Best Practice Guide for Sandwich Structures in Marine Applications

Prepared by the SAND.CORe Co-ordination Action on Advanced Sandwich Structures in the Transport Industries Under European Commission Contract No. FP6-506330

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SANDCORe

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1. Introduction

1.1. Background

Sandwich materials typically consist of two relatively thin, stiff facings separated by a thicker, lower density core material or structure. They have a number of characteristics that make them attractive for transport applications, including:

- High mass specific stiffness and strength for **lightweighting** (leading to improved vessel performance and/or lower life cycle costs).

- **Design integration** – the ability to combine different functionalities (e.g. mechanical properties such as stiffness / strength with thermal properties such as insulation) within a single material construction.

- Improved **surface quality** (“flatness”) compared to stiffened plates.

- Good **crashworthiness** characteristics.

- Good **vibration** (damping) characteristics.

- Reduced **assembly and outfitting** times / costs.

However, despite their technical advantages, there are a number of issues that are currently limiting the adoption of sandwich materials by the marine (and other) sectors. These include:

- **Comparative assessment** – at present, potential specifiers of sandwich materials often have insufficient knowledge and experience to fully assess their net benefits. The high initial purchase costs of sandwich structures (in comparison to traditional stiffened plates) need to be properly balanced against the corresponding savings in assembly and life cycle costs. Such comparisons are not always straightforward, particularly when the use of sandwich materials results in completely new design solutions.

- **Joining and assembly** – the implementation of prefabricated sandwich components within ship structures requires specialist joining and assembly expertise that is not always readily available to potential users.

- **Design complexity** – sandwich structures can exhibit a wide range of failure modes. Furthermore, numerical analyses tend to be computationally intensive and require specialist tools and skills. In addition, design data for sandwich materials (e.g. material properties, fire performance, etc.) is not always readily available.

- **Manufacturing** – the manufacturing of sandwich materials requires specialist skills and equipment. These are not often available within shipyards and their introduction would require investment. Prefabricated sandwich structures produced by third party specialists are not always available.

- **Planning** – there is generally a need to finalise certain design details (e.g. penetrations) earlier in the design process when sandwich technology is used. Furthermore, subsequent changes in the design / fabrication process tend to have a more significant impact. Additional time may also be required for approval by the necessary authorities, possibly including a need for testing of any novel details and aspects.

- **A lack of standardised procedures** – for aspects such as testing, inspection and repair.

- **New approaches to design and production** – the efficient application of sandwich structures often requires new design approaches. This might includes new perspectives on the product concept as well as non-conventional production processes.

- **Industry fragmentation** – historically, a number of industrial sectors (e.g. marine, rail, aerospace, construction, automotive, etc.) have tended to develop their own sandwich technologies, practices, specifications and regulations in isolation. To date, there has been little cross-sectorial consultation.

To address these issues, the **SAND.CORe co-ordination action** was initiated. Its aim was to foster the application of sandwich structures in the European transport sectors by benchmarking, harmonising and complementing previous research work, by making state of the art knowledge and experiences easily available, and by creating a sustainable infrastructure for inter-industry co-operation. This best practice guide represents one component of this initiative by providing an authoritative reference source on the design, manufacturing, assembly and operation of sandwich structures in the marine industry.

1.2. Scope

This document is intended to provide designers and engineers with reliable guidelines and recommendations on best practice for the following aspects of sandwich technology:

- Design of sandwich structures.
- Inspection and repair.
- Joining assembly and outfitting.
- Legislation and approval.

Where appropriate, the document also provides relevant background information to ensure that the recommendations are presented in the correct context. The objective is to provide sufficient information to allow the marine industry and other potential users to routinely assess the potential advantages of sandwich technology as an alternative to conventional construction techniques.

1.3. Structure of this Document

Following this introduction, this document provides an overview of some of the common types of sandwich structure, including those that are most relevant to the marine industry: all-**metal** (as defined in section 2.2), **hybrid metal** (as defined in section 2.3) and **composite** (as defined in section 2.4).

This is then followed by an extensive section on **design** which covers static analysis (elastic loading, ultimate strength and buckling), crash / impact response, fatigue analysis, vibration analysis, and joint design / analysis.

By way of background, a section on **manufacturing** then describes the techniques that are used to produce all-metal, hybrid metal and composite sandwich structures.

Three sections then follow that discuss practical aspects of sandwich use, namely: (i) **joining, assembly and outfitting** for the production of integrated structures, (ii) **inspection and repair** for the ongoing maintenance of sandwich structures, and (iii) **legislation and approval** for certification purposes.

Finally, a number of marine **application case studies** are described that illustrate the techniques and recommendations presented in the preceding sections.

1.4. Acknowledgements

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2. Types of Sandwich Structure

2.1. What is a Sandwich Structure?

2.1.1. The "Sandwich Effect"

A **sandwich structure** is a fabricated material that consists of two thin, stiff **facing sheets** joined to either side of a low density **core material or structure**. The separation of the facings by a lightweight core acts to significantly increase the second moment of area (and hence the bending stiffness) of the material cross-section with only a small increase in weight. This so-called "**sandwich effect**" is illustrated below:

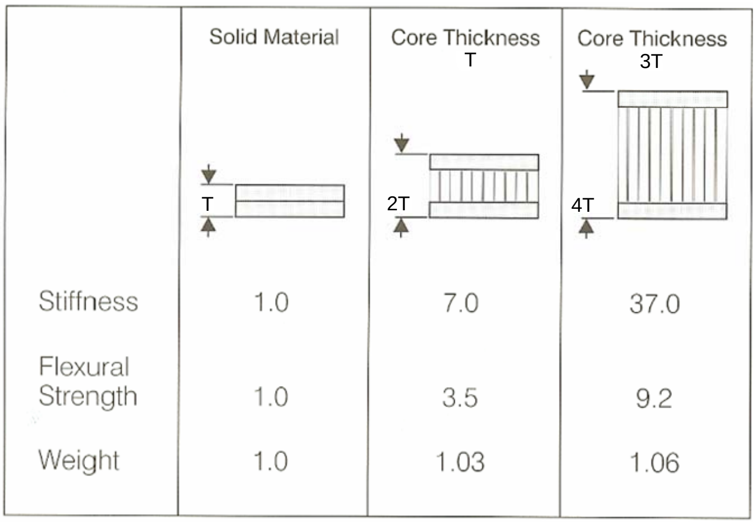


Figure 2.1-1 - illustration of the "sandwich effect" for a typical construction. It can be seen that it is possible to realise significant increases in bending stiffness and strength for minimal increases in weight compared to a single skin structure (from Hexcel Composites 2000).

In addition to the "sandwich effect", sandwich materials also offer a number of other potential benefits including possibilities for functional integration, space saving and modular construction. Such advantages, as well as the corresponding problems that sandwich structures can create, are discussed more fully in section 2.1.3 below.

2.1.2. Classification of Sandwich Structures

A wide range of materials can be used for sandwich facings and cores. Common facing materials include metals (e.g. steel or aluminium) and composites (e.g. fibre reinforced polymers). Common core materials or structures include metallic stiffeners, foams (polymer or metallic), honeycombs and balsa wood. The core-to-facing joint is normally achieved through adhesive bonding or welding.

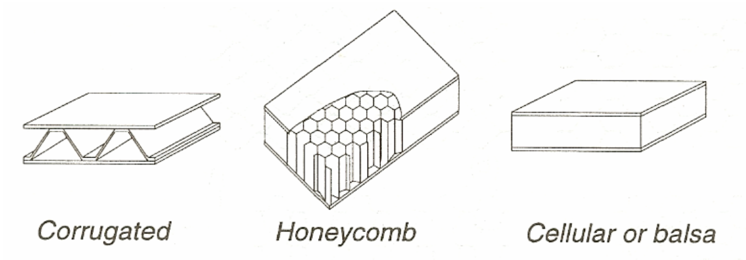


Figure 2.1-2 - some examples of typical sandwich configurations (from Zenkert 1995).

This best practice guide focuses primarily upon the types of sandwich structures that are of most interest to the marine industry, namely all-metal, hybrid metal, and composite. More detailed descriptions of these three types can be found in sections 2.2, 2.3 and 2.4 that follow. However, the table below summarises the primary options that available within each type of sandwich technology.

Sandwich Structures							
All-Metal			Hybrid Metal			Composite	
Core Stiffeners		Solid Core Layer	Core Stiffeners		Solid Core Layer	Core Stiffeners	Solid Core Layer
Unidirectional	Multi-Directional		Unidirectional	Multi-Directional			
Both the sandwich facings and core are metallic materials. The latter can consist of uni- or multi-directional core stiffeners, metallic foams, or honeycombs. The normal materials used for all-metal sandwich structures are steel and aluminium.			The sandwich contains a mixture of metallic and non-metallic materials. This usually means that the sandwich facings are metallic and the sandwich core contains some non-metallic materials (e.g. foam-filled cavities, non-metallic stiffeners, or elastomers).			Facing sheets are fibre reinforced polymers. Cores are normally polymer foams, honeycombs or balsa.	

2.1.3. Advantages and Problems Relating to the Application of Sandwich Structures

Although the various types of sandwich outlined above have some unique characteristics and considerations, all sandwich structures have some generic advantages and problematic aspects. These can be summarised as follows:

Typical advantages compared to traditional structural materials:

- High stiffness to weight ratio, making them suitable for lightweight design.
- Good buckling resistance compared to thin orthotropic plate structures.
- Good crashworthiness properties.
- Reduced constructional heights (compared to stiffened plates) for increased useful occupancy space.
- Large unsupported spans, thereby reducing the requirement for supporting elements and increasing architectural freedom.
- Reduced part counts through integrated design.
- Good dimensional accuracy and flatness due to prefabrication in workshops (as opposed to on-board fabrication).
- Reduced assembly times via modular approaches to construction.

Typical problem areas:

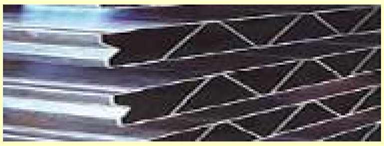
- High material costs.
- Complex design/validation procedures. Possibly a longer certification process.
- General lack of sandwich expertise and equipment in shipyards.
- The need to restructure process chains to facilitate cost-effective assembly and outfitting.
- Complex outfitting (e.g. penetrations, attachments).
- The detailed planning requirements of modular construction.
- Lack of data and information to support the proposed benefits of sandwich structures in comparison to traditional construction technologies.

Consequently, potential benefits, problem areas and experiences need to be carefully considered for each sandwich application. This document aims to provide some assistance to prospective sandwich users to increase the probability of technical and commercial success.

2.2. All-Metal Sandwich Structures

2.2.1. Classification of All-Metal Sandwich Structures

For the purposes of this guide, an **all-metal** sandwich structure is defined as one in which both the facings and the core are formed from metallic materials. In the marine industry, this normally means steel or aluminium. Aside from the constituent materials, all-metal sandwich structures can be further classified by the geometry of the core. Some typical examples are shown in the table below:

Sandwich Structure Material	Core Stiffeners	
	Unidirectional	**Multi-Directional**
All-Steel	 Corrugations	
	 Flat bars (I-Core™)	 Wire pyramids (COREX™)
	 Z-Profiles	
All-Aluminium	 Extrusions	 Aluminium Honeycomb
	 Corrugations (CORALDEC™)	

The core stiffeners are normally joined to the facings by welding, adhesive bonding or mechanical joining (e.g. riveting). The fabrication of all-metal sandwich structures is described in more detail in section 4.1 of this guide.

2.2.2. Comparative Performance of All-Metal Sandwich Structures

The table below highlights the main differences between the various types of all-metal sandwich structure as a guide to technology selection.

Criteria	All-Steel with Unidirectional Core Stiffeners	All-Steel with Multi-Directional Core Stiffeners	All-Aluminium
Weight saving	Low	Low – Medium	High
Price per m^2 of panel	Low	Medium	High
Resistance to transverse loads	Low - Medium	High	Low – Medium
Handling in shipyards	Easy	Easy	Medium
Risk of corrosion	Medium - High	Medium	Low
Robustness	High	Medium	High
Fire insulation requirements	Medium	Medium	High

2.2.3. Typical Applications of All-Metal Sandwich Structures

2.2.3.1. Laser Welded All-Metal Sandwich Structures

All-metal sandwich panels with unidirectional core stiffeners, such as corrugated core, flat bars (I-Core) or Z-profiles can be efficiently produced by laser welding (see section 4.1). Meyer Werft in Germany is the prime manufacturer of these panels on an industrial scale, whilst some other smaller companies and institutes also produce prototypes. Some typical applications are shown in figures 2.2-1 and 2.2-2.

Figure 2.1-1 - I-Core™ decks.

Figure 2.2-2 - I-Core™ stairs and staircase landings in cruise ships and deck houses.

2.2.3.2. Multi-Directionally Stiffened All-Metal Sandwich Panels (COREX)

COREX™ panels were developed by MacGregor Ltd, primarily for RoRo decks. The facing sheets (mostly stainless steel) are connected by "wire pyramids" that are welded from inside the panels using a special device. COREX has found applications in a number of areas (figure 2.2-3) and is commercially available.

Figure 2.2-3 - COREX™ RoRo decks.

2.2.3.3. Aluminium Extrusions and Corrugated Panels (CORALDEC)

Aluminium extrusions are widely used in modern shipbuilding. Extrusions are provided by a number of companies, such as Astech and Corus. No further reference is made to these products as they are widely known in the industry.

CORALDEC™ is a unidirectionally stiffened panel made from AluStar (AA 5059). It was developed by Corus in cooperation with Meyer Werft. Thin corrugated stiffening elements are laser welded to the face sheets to provide weight savings of around 30% compared to extruded profiles (figure 2.2-4).

Figure 2.2-4 - application of CORALDEC™ panels in the mega yacht Athena built in the Netherlands.

2.2.3. Guidelines on the Successful Application of All-Metal Sandwich Structures

- In comparison to other sandwich technologies, all-metal sandwich structures are not particularly "lightweight". If lightweighting is a primary design driver, composite material sandwich structures might be a better option.

- The main advantages of all-metal sandwich structures are space savings, increased unsupported spans and high pre-manufacturing accuracy.

- Other significant advantages of all-metal sandwich structures (in comparison to other sandwich technologies) are their relatively low cost and their ease of joining to conventional ship structures by welding.

- For reasons of robustness in the shipyard production process (e.g. handling of material, welding, etc.) it is recommended that the facings of all-metal sandwich panels should be at least 2 mm thick. Experience has shown that such panels can be handled within shipyards without them incurring significant damage. Thinner facings can be used, but these need to be handled more carefully.

2.3. Hybrid Metal Sandwich Structures

2.3.1. Classification of Hybrid Metal Sandwich Structures

For the purposes of this guide, a **hybrid metal** sandwich structure is defined as one that contains a mixture of both metallic and non-metallic materials. For example, the core cavities in an existing all-metal sandwich structure might be filled with other materials to improve local strength or fire resistance. Alternatively, the core materials themselves might be non-metallic. Some typical examples are shown in the table below:

Core Type		
Filled Metallic Stiffeners	**Non-Metallic Stiffeners**	**Non-Metallic Solid**
		
- Bonded solid blocks of cellular material (e.g. polymer foams such as polyurethane, balsa wood, Rockwool, metallic foams, etc.). - In-situ "liquid" filling using polymer foams, light concrete, etc.	- Non-metallic stiffeners adhesively bonded or mechanically joined to metallic face sheets.	- Non-metallic solid core layer, such as a polyurethane elastomer (as in the Sandwich Plate System – SPS) or light concrete, between metallic face sheets.

2.3.2. Comparative Performance of Hybrid Metal Sandwich Structures

The following table highlights the main differences between the various types of hybrid sandwich structure as a guide to technology selection.

Criteria	Filled Metallic Stiffeners	Non-Metallic Stiffeners	Non-Metallic Solid*
Weight saving	Medium	High	Low - High
Price per m^2 of panel	Medium	Not commercially available	Medium - High
Resistance to transverse loads	Low - Medium	Low	High
Handling in shipyards	Medium	Medium	Medium - Difficult
Risk of corrosion	Medium	Medium	Low
Fire resistance	Medium	Low	Low - High

** Very much dependent upon the core material used.*

2.3.3. Typical Applications of Hybrid Metal Sandwich Structures

Figure 2.3-1 - funnel casing with improved thermal insulation (SPS – steel facings and polyurethane elastomer core).

Figure 2.3-2 - mid-ship section of a barge (SPS – steel facings and polyurethane elastomer core).

2.3.4. Guidelines on the Successful Application of Hybrid Metal Sandwich Structures

- The introduction of non-metallic core filling materials into all-metal sandwich panels has no weight saving purpose. The real benefits are in terms of increased local strength, better thermal insulation, or improved crashworthiness.

- The addition of the filling materials means that, in general, the cost of hybrid metal panels is higher than that of all-metal panels. However, the total system cost is often lower because unfilled all-metal panels may require further modifications or additions (e.g. external insulation) to meet all the functional requirements of an application.

- Local filling of the core cavities in an all-metal panel is often a good compromise between cost and improved performance. Furthermore, in-situ "liquid" filling using polymer foams or light concrete is easily performed under shipyard conditions.

- Filling materials, and in particular combustible materials, can cause problems in assembly and outfitting, especially with respect to welding. Modifications to the production sequence can often solve such problems.

- Light concrete and mineral wool are cheap, efficient and easily applied for increases in local strength or thermal insulation respectively. Moreover, they don't represent a fire risk.

2.4. Composite Material Sandwich Structures

2.4.1. Classification of Composite Material Sandwich Structures

For the purposes of this guide, a **composite** sandwich structure is defined as one in which the facing sheets are formed from a composite material. A **composite material** is a combination of two or more physically different constituents, each of which largely retains its original structure and identity. The combined composite material usually provides an overall performance that is superior to each of the individual constituents alone. Composites encompass a vast range of materials, both natural (e.g. wood, bone, teeth) and man-made (e.g. concrete, fibreglass, paper).

Within the transport sectors, the most common type of man-made composite material is the **fibre reinforced polymer (FRP)**. As the name suggests, FRPs consist of fibre reinforcements embedded within a polymer matrix. The fibres, which may be discrete or continuous, directional or random, are often oriented such that they are aligned with the principal loading directions for optimum tensile performance. The mechanical properties of FRPs are therefore usually non-isotropic. The polymer matrix, which may be thermosetting or thermoplastic, acts to support the fibres and facilitates load transfer. FRPs often consist of several layers (or "plies") of material that have been stacked and bonded to form a laminate.

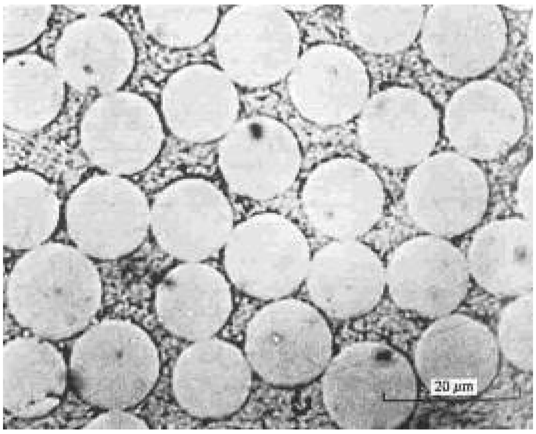


Figure 2.4-1 - micrograph of a section cut at right angles to the fibres in a unidirectional laminae of glass fibre reinforced polyester (Hull & Clyne 1996).

Examples of common fibre-matrix combinations that are employed within the transport sectors include:

- Carbon fibre reinforced epoxy – a high performance material system with excellent mass specific properties. Predominantly used for applications in which weight is at a premium such as in the performance yacht, aerospace and motorsport sectors.

- Glass fibre reinforced phenolic – phenolic based composites have good fire, smoke and toxicity properties. This makes them a good option for sectors with stringent fire requirements, such as the marine and rail industries.

- Glass reinforced polypropylene – unlike thermosetting matrices such as epoxy or phenolic that irreversibly "cure", thermoplastic resins such as polypropylene can be reversibly thermoformed. This makes them amenable to short cycle time, high volume manufacturing processes, and also makes them easier to recycle. As such, they are well suited to mass production sectors such as the automotive industry. However, the relatively poor elevated temperature and fire performance of polypropylene can be a limiting factor in many applications.

Being light and stiff, FRPs are excellent candidate materials for sandwich structure facings. They are most commonly used in conjunction with polymer foam, balsa wood, or honeycomb core materials. Some typical examples are shown in the table below:

Core Type		
Polymer Foam	**Honeycomb**	**Polymer Foam / FRP Stiffeners**
		
The example shown above consists of glass reinforced epoxy facings and a rigid polyurethane foam core	The example shown above consists of glass reinforced epoxy facings and a phenolic reinforced aramid paper honeycomb core	The example shown above consists of glass reinforced epoxy facings and a rigid polyurethane foam core with additional glass reinforced epoxy corrugated stiffeners.

2.4.2. Advantages and Disadvantages of Composite Material Sandwich Structures

In general terms, the **advantages of FRPs** (compared to steel and aluminium) can be summarised as:

- Good mass specific properties (e.g. stiffness, strength), making them suitable for lightweight design.
- Reduced part counts through integrated design.
- Improved styling – composites are moulded rather than formed, allowing for complex curvatures and geometries.
- Good crashworthiness – the controlled brittle failure of FRPs provides very efficient energy absorption mechanisms.
- Durability – good corrosion and fatigue resistance.

The potential **disadvantages of FRPs** (compared to steel and aluminium) are:

- High raw material costs.
- Complex (non-isotropic) design and validation procedures.

- Less well suited to the high volume manufacturing of structural parts (particularly thermosets).
- Difficult to recycle (particularly thermosets).

2.4.3. Typical Applications of Composite Material Sandwich Structures

Figure 2.4-2 - hull of the Visby class corvette – carbon fibre reinforced polymer facings and PVC foam core.

Figure 2.4-3 - hull of the Mirabella V yacht, the largest marine composite structure produced to date at 75 m long. The sandwich construction used for the hull and deck consists of glass reinforced vinylester facings and a polymer foam core. Carbon and aramid fibre reinforcements were also selectively employed.

Figure 2.4-4 - prototype grain bulkhead produced by the Technical University of Delft. A weight saving of 50-70% compared to an equivalent steel structure was realised.

Figure 2.4-5 - fire testing of a prototype composite sandwich helicopter hangar under the US Navy's Libra programme. Extensive trials demonstrated that fire was not a major problem provided that composite structures were well-protected.

3. Design of Sandwich Structures

3.1. Static Analysis

3.1.1. Linear Elastic Response

3.1.1.1. Analytical Methods

Analytical approaches to sandwich design are often used in the early design stages to obtain first approximations. This is because they are considerably less time-consuming than numerical approaches and therefore allow a wide range of scenarios to be explored relatively quickly. In marine applications, analytical techniques are often employed to obtain first estimates of sandwich dimensions and scantlings.

3.1.1.1a. Linear Elastic Analysis of Sandwich Structures Under Static Loads: Analytical Methods – General Overview

This section describes how to estimate the **elastic deflections** and **associated stresses** of simple sandwich beams and plates under standard **static** loading configurations. The expressions presented here are applicable to panels with isotropic facings and isotropic cores. This includes hybrid-metal sandwich structures with steel facings and isotropic polymer cores. Sections 3.1.1.1b, 3.1.1.1c and 3.1.1.1d that follow describe the additional complexities that need to be addressed when handling all-metal, other hybrid metal and composite sandwich structures respectively.

Elastic deflections of sandwich beams

A sandwich structure can be approximated as a "**beam**" when its width, *b*, is less than one third of its span, *l*.

The deflection, δ, of a sandwich beam will be comprised of a **bending** component and a **shear** component, i.e.:

$$\delta = \frac{k_b P l^3}{D} + \frac{k_s P l}{S} \qquad \textit{(equation 3.1.1.1a-1)}$$

where P is the applied load, l is the span of the sandwich beam, D is the flexural rigidity (bending stiffness) of the sandwich beam, S is the shear stiffness of the sandwich beam, and

k_b and k_s are deflection coefficients (see table below). Clearly, the relative importance of the shear-induced deflections will increase as the core shear stiffness decreases.

In equation 3.1.1.1a-1, the flexural rigidity, *D*, of the sandwich beam can be calculated by:

$$D = E_f \frac{bt^3}{6} + E_f \frac{btd^2}{2} + E_c \frac{bc^3}{12} \qquad \textit{(equation 3.1.1.1a-2)}$$

where E_f is the Young's modulus of the sandwich facings, E_c is the Young's modulus of the sandwich core, *b* is the width of the sandwich beam, *t* is the thickness of the sandwich facings (assumed equal), *c* is the thickness of the sandwich core, and *d* is the distance between the centrelines of opposing facings (= *t* + *c*). Note, that if the thickness of the facings is very much less than the thickness of the core, then the first term of equation 3.1.1.1a-2 can be neglected without incurring a significant error (the first term is less than 1% of the second when $d/t > 5.77$). Similarly, if the Young's modulus of the core is very much less than the Young's modulus of the facings, then the third term can be neglected. Specifically, the third term is less than 1% of the second when:

$$\frac{6E_f td^2}{E_c t_c^3} > 100 \qquad \textit{(equation 3.1.1.1a-3)}$$

In equation 3.1.1.1a-1, the shear stiffness, *S*, of the sandwich beam can be approximated by:

$$S = bdG_c \qquad \textit{(equation 3.1.1.1a-4)}$$

where G_c is the shear modulus of the core.

In equation 3.1.1.1a-1, the deflection coefficients k_b and k_s will vary according to the loading configuration. Some example values for standard loadings are presented in the following table:

Loading Configuration		Deflection Coefficients		Maximum Shear Force	Maximum Bending Moment
End Supports	Loading	k_b	k_s	F	M
Both Simple	Uniformly Distributed	$\frac{5}{384}$	$\frac{1}{8}$	$\frac{P}{2}$	$\frac{Pl}{8}$
Both Fixed	Uniformly Distributed	$\frac{1}{384}$	$\frac{1}{8}$	$\frac{P}{2}$	$\frac{Pl}{12}$
Both Simple	Centre Point	$\frac{1}{48}$	$\frac{1}{4}$	$\frac{P}{2}$	$\frac{Pl}{4}$
Both Fixed	Centre Point	$\frac{1}{192}$	$\frac{1}{4}$	$\frac{P}{2}$	$\frac{Pl}{8}$
One Fixed (Cantilever)	Uniformly Distributed	$\frac{1}{8}$	$\frac{1}{2}$	P	$\frac{Pl}{2}$
One Fixed (Cantilever)	End Point	$\frac{1}{3}$	1	P	Pl

Using the expressions for the maximum shear force, F, and the maximum bending moment, M, in the above table, it is also possible to estimate the sandwich facing stress, σ_f, and the sandwich core shear stress, τ_c, as follows:

$$\sigma_f = \frac{M}{dtb} \qquad \textit{(equation 3.1.1.1a-5)}$$

$$\tau_c = \frac{F}{db} \qquad \textit{(equation 3.1.1.1a-6)}$$

<u>**Elastic deflections of sandwich plates**</u>

A sandwich structure can be approximated as a "**plate**" when its width, b, is greater than one third of its length, a.

For a sandwich plate that is simply-supported on all four sides and which is being subjected to a uniformly distributed load, the deflection, δ, can be estimated by:

$$\delta = \frac{qb^5}{D}\left(\beta_1 + \rho\beta_2\right) \qquad \textit{(equation 3.1.1.1a-7)}$$

where q is the load per unit area, D is the flexural rigidity of the sandwich plate, and β_1, β_2 and ρ are coefficients defined below.

In equation 3.1.1.1a-7, the flexural rigidity, D, of the sandwich plate can be estimated using:

$$D = E_f \frac{btd^2}{2\left(1-\nu_f^{\,2}\right)} \qquad \textit{(equation 3.1.1.1a-8)}$$

where E_f and t are the Young's modulus and thickness of the sandwich facings respectively, d is the distance between the centrelines of opposing facings, and ν_f is the Poisson's ratio of the sandwich facing material. Note that equation 3.1.1.1a-8 is equivalent to the reduced form of equation 3.1.1.1a-2, but with an additional $(1-\nu_f^2)$ term. This term arises because a "wide" plate is being considered rather than a "narrow" beam.

The constant ρ is calculated by:

$$\rho = \frac{\pi^2 E_f td}{2b^2 G_c\left(1-\nu_f^{\,2}\right)} \qquad \textit{(equation 3.1.1.1a-9)}$$

where G_c is the shear modulus of the core. ρ represents the ratio of the flexural rigidity (bending stiffness) to the shear stiffness.

The parameters β_1 and β_2 in equation 3.1.1.1a-7 are functions of the plate length (a) / width (b) ratio and can be read from the figure below:

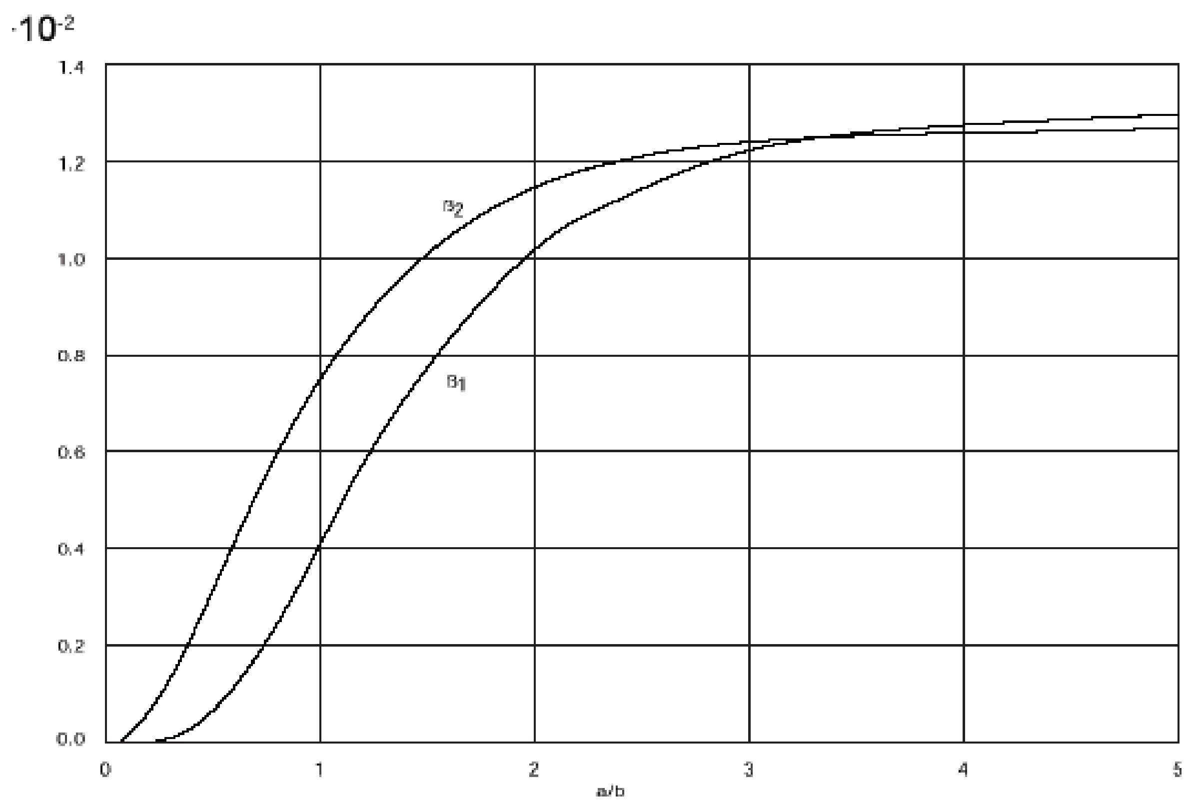


Figure 3.1.1.1a-1 - coefficients β_1 and β_2 for a simply supported isotropic sandwich with thin faces (from DIAB).

For a sandwich plate under a uniformly distributed load that is simply supported on just two opposite sides, the expressions outlined previously for sandwich beams can be employed provided that the term E_f is replaced by the term $E_f/(1-\nu_f^2)$. This modification allows for the fact that the plate is "wide" rather than "narrow".

Guidelines on the elastic analysis of sandwich structures under static loads: analytical methods

- The expressions presented here are generally applicable to sandwich panels with thin, equal isotropic facings and isotropic cores. For non-isotropic sandwich materials, consult the specialist texts listed in the References / Bibliography. See also the sections on all-metal (3.1.1.2b), hybrid metal (3.1.1.1c) and composite (3.1.1.1d) sandwich structures elsewhere in this guide. Some non-homogenous cores, such as honeycombs, can often be approximated as isotropic for preliminary estimates. In such instances, it is advisable to employ the properties of the core in the weakest direction to obtain conservative predictions. The beam equations can also be used to approximate the performance of unidirectionally stiffened all-metal sandwiches along the direction of the stiffeners (and only in that direction).

- Similarly, the above expressions only represent some common examples of the wide range of analytical expressions that are available. Again, consult the further information texts for expressions to cover other scenarios.

- In general, exact solutions such as those presented above can be readily derived for any simply-supported sandwich beam or plate. However, other boundary conditions are often statically indeterminate and analytical solutions are much more difficult to obtain. In these cases, alternative approaches such as finite element analysis should be considered.

- For anything other than flat structures with well defined loadings and constraints, it is recommended that the analytical techniques described here are only used for preliminary dimensioning purposes. For the detailed design of more complex components, numerical methods such as finite element analysis should be considered.

3.1.1.1b. Linear Elastic Analysis of All-Metal Sandwich Structures Under Static Loads: Analytical Methods

From an analysis perspective, **all-metal** sandwich structures are considerably more complex than the isotropic facing / isotropic core constructions described in Section 3.1.1.1a. This is because:

- If the core stiffeners are unidirectional (as is the case with I-Core™, CORALDEC™, etc.), then the sandwich is highly orthotropic.

- The facings are unsupported between the stiffeners.

For these reasons, practical analytical solutions for all-metal sandwich structures are rarely available. Instead, purely numerical, or a combination of analytical and numerical, approaches are the norm. These are discussed in section 3.1.1.2b.

3.1.1.1c. Linear Elastic Analysis of Hybrid Metal Sandwich Structures Under Static Loads: Analytical Methods

As discussed in section 2.3, **hybrid metal** sandwich structures, as defined by this guide, encompass three types of construction:

- **Type 1** - all-metal sandwich structures in which the core cavities have been filled with a non-metallic material such as a polymer foam.

- **Type 2** - sandwich structures with metal facings and non-metallic core stiffeners.

- **Type 3** - sandwich structures with metal facings and a solid non-metallic core, such as an elastomer.

These are all very different types of construction. Therefore, it is not possible to describe a common set of procedures for their analysis. However, in most instances, the analyst will be able to employ the techniques outlined previously in this part of the guide, namely in the "General Overview" section (3.1.1.1a) and the "All-Metal" section (3.1.1.2b), according to the following guidelines:

- **Type 1** hybrid metal sandwich structures (filled all-metal) are the most problematic because the core filler may modify the behaviour of the all-metal sandwich. This will depend upon the properties of the filler material. If the filler material is non-structural (e.g. Rockwool insulation), or if the filler is a very low density foam (< 30 kg/m^3), then it is unlikely that it will have a significant influence on structural performance. Therefore, in this instance the methods for all-metal sandwich structures can be employed. However, if the core material does contribute to the overall mechanical performance of the sandwich (e.g. by increasing the shear stiffness or through-thickness compression stiffness), then the methods for all-metal sandwich structures are likely to underestimate mechanical performance. A full analytical treatment of filled all-metal sandwich structures would be very complex and beyond the scope of this guide. However, as a first approximation, the all-metal methods could be used to provide a conservative underestimate of performance.

- For **type 2** hybrid metal sandwich structures (metal facings and non-metallic core stiffeners), the methods for all-metal sandwich structures (section 3.1.1.2b) can be broadly employed with the substitution of the appropriate core material properties.

- For **type 3** hybrid metal sandwich structures (metal facings and a solid non-metallic core), the methods outlined in the "General Overview" (section 3.1.1.1a) can be employed provided that the core is isotropic.

Guidelines on the elastic analysis of hybrid metal sandwich structures under static loads: analytical methods

With respect to **type 1** hybrid metal sandwich structures (filled all-metal), it should be noted that:

- Core filling may have the effect of increasing the elastic range of an all-metal panel by delaying the onset of buckling failure modes.

- The effect of core filling may have a greater impact upon the **strength** of an all-metal sandwich structure rather than on its **elastic** properties (see section 3.1.2.2c).

- Note that whilst core filling may improve the absolute mechanical performance of an all-metal sandwich structure, it will obviously do so with an increase in mass. Indeed, the mass specific properties of the panel (e.g. flexural stiffness per unit mass) may actually fall.

3.1.1.1d. Linear Elastic Analysis of Composite Sandwich Structures Under Static Loads: Analytical Methods

Composite material sandwich structures with **fibre reinforced polymer (FRP)** facings can be analysed for **stiffness under static loads** in much the same way as any conventional sandwich structure (see section 3.1.1.1a). The only specialist aspect relates to the analytical treatment of the FRP facing laminates. The approach adopted will depend upon the availability of material property data and the extent to which the analyst wishes to optimise the lay-up of the FRP facing. Three situations are considered below:

- If the overall mechanical properties of a quasi-isotropic FRP facing laminate are known (e.g. through testing).
- If only the individual ply (laminae) properties of an FRP facing are known, or if a designer wishes to optimise the lay-up of an FRP facing laminate.
- If only the fibre and matrix properties of an FRP facing are known.

If the overall mechanical properties of a quasi-isotropic FRP facing laminate are known …

If the overall mechanical properties of a quasi-isotropic FRP facing laminate are known (e.g. through testing), then sandwich deflections under static loads can be calculated using the normal analytical procedures as outlined in section 3.1.1.1a. Typical material properties for the facings and cores of composite sandwich structures can be found in section 3.1.1.3d.

If only the ply properties of an FRP facing are known …

If only the ply (laminae) properties of an FRP are known, or if a designer wishes to optimise the lay-up of an FRP sandwich facing, then it is possible to estimate the stiffness of an overall laminate based on the arbitrary orientation and sequencing of a series of individual known laminae (figure 3.1.1.1d-1).

This approach is known as **classical laminate theory (CLT)** and it is applicable to flat, thin, perfectly-bonded laminates in which edge effects are neglected. A detailed description of CLT is beyond the scope of this best practice guide. However Matthews & Rawlins 1994 (listed in the further information section) provides a good overview, as well as worked examples. There are also software packages available that will perform classical laminate theory calculations, such as CoDA and CCSM.

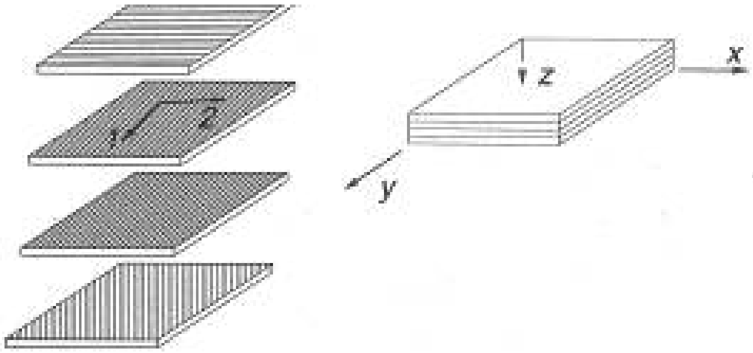


Figure 3.1.1.1d-1 - the overall stiffness of a laminate (e.g. in the global x and y directions) can be estimated from knowledge of the properties of the individual plies (e.g. in the local 1 and 2 directions) and their respective orientation (figure from Zenkert 1995).

If only the fibre and matrix properties of an FRP facing are known …

If only the fibre and matrix properties of an FRP facing are known, then it is possible to estimate the properties of a ply (lamina) using a rule of mixtures approach. For example, the stiffness, *E*, of a unidirectional lamina in the direction parallel to the fibres can be estimated by:

$$E = vE_{fi} + (1 - v)E_{ma} \qquad \text{(equation 3.1.1.1d-1)}$$

where v is the fibre volume fraction within the lamina, E_{fi} is the Young's modulus of the fibres, and E_{ma} is the Young's modulus of the matrix.

Again, the interested reader is directed to the references in the further information section for more details (e.g. estimating ply stiffness perpendicular to the fibre direction, estimating the ply shear modulus, etc.), particularly the texts by Hull & Clyne 1996, Matthews & Rawlins 1994 and Zenkert 1997.

Guidelines on the elastic analysis of composite sandwich structures under static loads: analytical methods

- FRPs generally exhibit a wider variation in mechanical properties than isotropic materials. This is normally due to slight manufacturing inconsistencies that lead to, for example, small variations in fibre alignment or content. Wherever possible, reliable experimentally-derived material property data should be used in calculations.

- The expressions presented in section 3.1.1.1a are applicable to quasi-isotropic FRP facing laminates only. For the treatment of non-isotropic facings, consult a specialist text (e.g. Zenkert 1995).

- The above expressions also assume that the core is isotropic. If this is not the case (e.g. it is a honeycomb), then use the core material properties in the weakest direction.

- If using classical laminate theory to derive the properties of a laminate, remember its underlying assumptions: that the laminate is flat, thin, perfectly bonded (i.e. no delamination) and infinite (i.e. no edge effects). Caution should be exercised when deviating from these assumptions - consider the use of alternative techniques such as numerical methods (see section 3.1.1.2d).

- For anything other than flat panels with well defined loadings and constraints, it is recommended that the analytical techniques described here are only used for preliminary dimensioning purposes. For the detailed design of more complex components, numerical methods such as finite element analysis should be considered (see section 3.1.1.2d).

- As with all composite material structures, experimental validation of analytical results is strongly recommended.

3.1.1.2. Numerical Methods

Whilst the analytical approaches to sandwich design described in Section 3.1.1.1 are generally quick and easy to apply, their applicability is often restricted in terms of the geometry of the panel, its boundary conditions and its constituent materials. To overcome these restrictions, **numerical methods**, such as finite element analysis (FEA), can be employed. Whilst it becomes possible to perform very detailed studies using FEA, the compromise is usually the increased time and cost associated with formulating and solving the models.

3.1.1.2a. Linear Elastic Analysis of Sandwich Structures Under Static Loads: Numerical Methods – General Overview

This section describes how to analyse the **elastic deflections** and associated **stresses** of sandwich structures by means of the **finite element** method. The approaches presented here are applicable to panels with isotropic facings and an isotropic core. This includes some hybrid metal sandwiches such as those with metal facings and isotropic polymer cores. Sections 3.1.1.2b, 3.1.1.3c and 3.1.1.2d that follow describe the additional complexities that need to be addressed when handling non-isotropic all-metal, hybrid metal and composite sandwich structures respectively.

Constitutive law

All strains due to in-service loads are assumed to be small. Furthermore, as stated previously, the properties of the facings and the core are assumed to be isotropic. Therefore, linear stress-strain relationships can be used for both materials. This requires the use of just four parameters to describe the material's behaviour – the elastic moduli of the facings and the core, E_f and E_c, and their corresponding Poisson's rations, ν_f and ν_c.

Element selection and modelling

If continuum (solid) elements are used to model the whole sandwich structure, it is possible to accurately predict all the modes of deformation, i.e.:

- Overall bending of the sandwich structure.
- Bending of the facings.
- Compression/tension of the core in the through-thickness direction.
- Shear deformations.

However, relatively fine meshing will be required to capture all of these deformation modes.

As an example, figure 3.1.1.2a-1 shows an analysis of a sandwich beam with one end clamped and the other end simply-supported. As shown in (a), the beam has been subjected to a uniformly-distributed load. In (b) the bending stresses in the facings can be seen. In particular, the lower facing experiences a lot of local bending. (c) shows the distribution of the through-thickness stresses that arise because the load is applied to the unsupported upper facing. Again, the effects are only significant around the sandwich beam's supports. Therefore, discrete modelling of the facings and the core is only required if the local stresses around connection details are of interest.

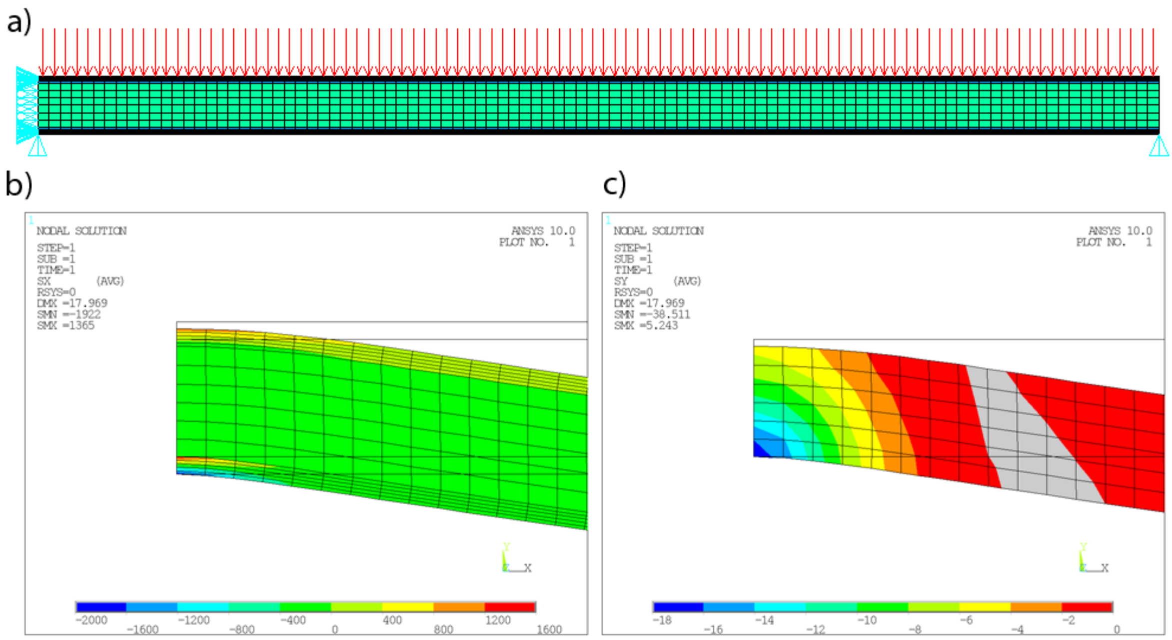


Figure 3.1.1.2a -1 - example finite element analysis of a sandwich beam: (a) applied loads and supports, (b) bending stresses, and (c) through-thickness stresses.

Often (i.e. in those cases where the global deflections and associated stresses are primarily of interest), it is sufficient to model a sandwich structure using shell elements. However, the layered composition of a sandwich must be reflected in the element formulation. In some commercial finite element codes there are elements that are specially designed for modelling layered structures (e.g. SHELL 91 and SHELL 181 in ANSYS).

Usually the element formulation allows for bending deformation as shown in figure 3.1.1.2a-2 (a). However, for sandwich structures with thin facings and relatively low shear stiffness cores, the deformations will be as shown in figure 3.1.1.2a-2 (b). In ANSYS, the type (b) behaviour can be accommodated by selecting the sandwich option of element type SHELL 91. This option is well suited for sandwich structures with a core thickness of at least 10 times the thickness of the facings. If the facings cannot be considered thin, or the finite element code being used does not have a sandwich option, then the user must ensure that there are sufficient through-thickness integration points (at least 3-5 for each layer).

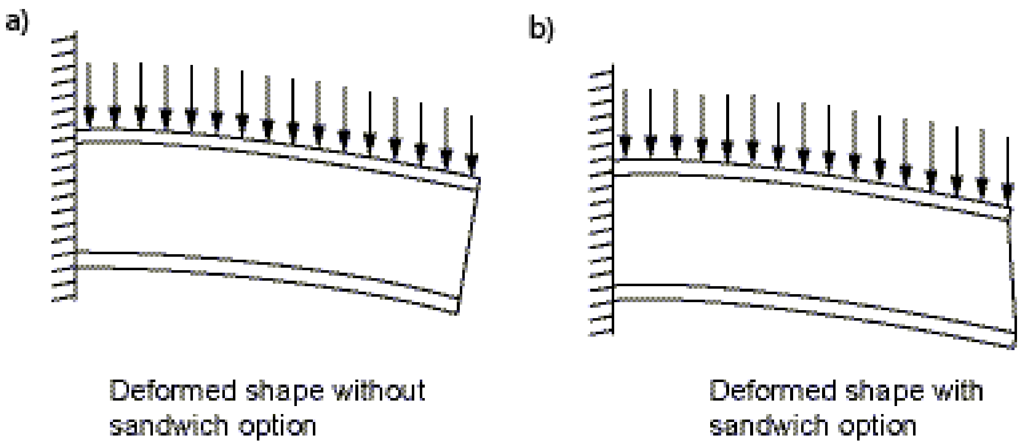


Figure 3.1.1.2a-2 - the effect of using specialist sandwich elements to predict bending deformations.

Almost all shell finite elements neglect the through-thickness stresses. Similarly, core compressibility is neglected (i.e. the facings are assumed to remain a constant distance apart). Shell elements that can accommodate these complexities have been developed recently, but are not yet available in commercial finite element codes.

To illustrate the different approaches, figure 3.1.1.2a-3 compares the predicted deflections of a sandwich beam using a variety of element types, together with an analytical solution.

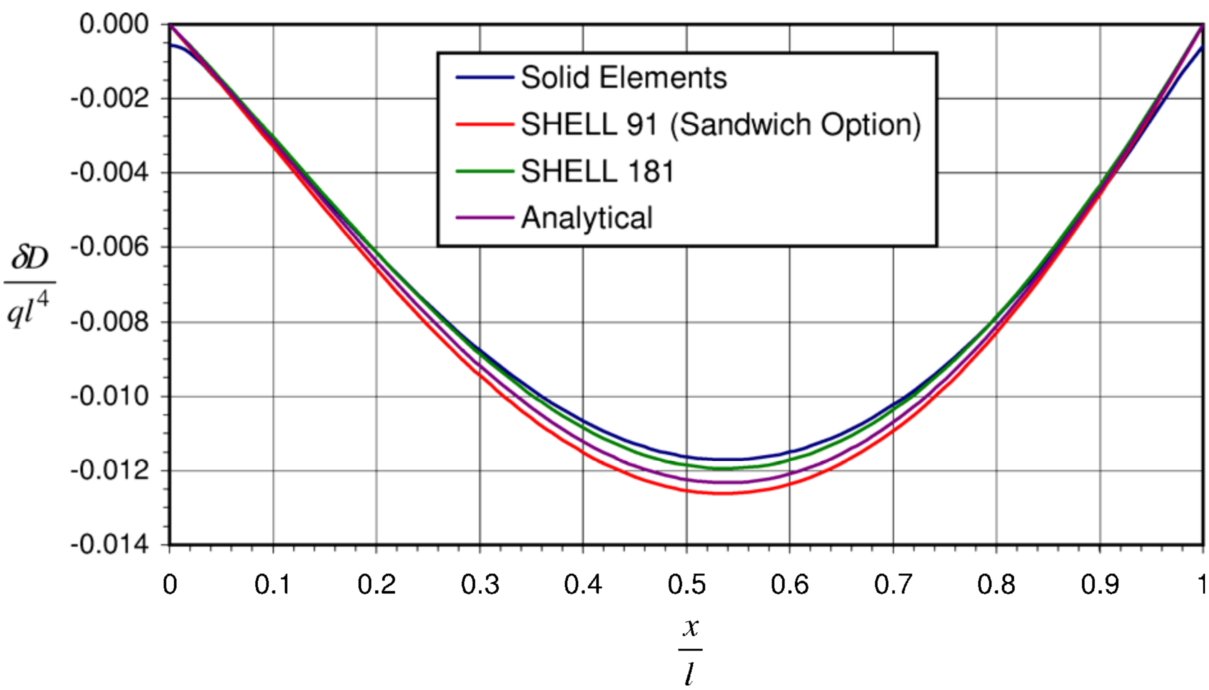


Figure 3.1.1.2a-3 - predicted deflections according to different element formulations for a sandwich beam under a uniformly distributed load with one end clamped and the other end simply supported.

Post-processing

Post-processing elastic numerical analyses of sandwich structures is straightforward for both solid element and shell element models. However, special care should be taken when post processing the normal (bending) stresses in solid models. Whilst the normal strains have to be continuous at the interface between the core and facings, the stresses are not. Conversely, the transverse shear stresses are continuous at the interface, but shear strains are not. Stress averaging at nodes adjacent to elements with different material properties must be discarded.

When post-processing results from shell element models, stresses from the top, mid-plane and bottom of an element should not be confused.

Guidelines on the static analysis of sandwich structures under elastic loading: numerical methods

- For normal in-service loads, material behaviour can usually be taken as linear elastic.
- If local stresses and deflections at connection details, supports and other discontinuities are of interest, use solid elements.
- If global deflections and their associated stresses are of interest, shell elements can be used.
- If the sandwich structure has thin facings and a relatively weak core, activate the sandwich option (if available). Ensure that there are at least 3 to 5 integration points over the thickness of each layer.
- When post-processing the through-thickness stresses in solid models, discard nodal averaging at nodes adjacent to elements with different material properties.
- Be sure to select the right layer when post-processing stresses in shell models.

3.1.1.2b. Linear Elastic Analysis of All-Metal Sandwich Structures Under Static Loads: Numerical Methods

In the analysis of **all-metal** sandwich structures, the designer must be aware that these structures:

- Can be highly orthotropic (e.g. corrugated stiffeners in one direction only).

- Have facing sheets that are unsupported between the stiffeners.

Due to the first property, purely analytical solutions exist for only a few cases. Design approaches usually consist of analytical pre and post processing, with a numerical solution of the differential equations. Due to the high orthotropy of many all-metal sandwich panels, it is recommended to treat them always with plate theory (i.e. never as beams).

Due to the second property, the facing sheets can bend under applied loads. This bending can be significant when the overall deflections and stresses of a panel are considered (Figure 3.1.1.2b-1).

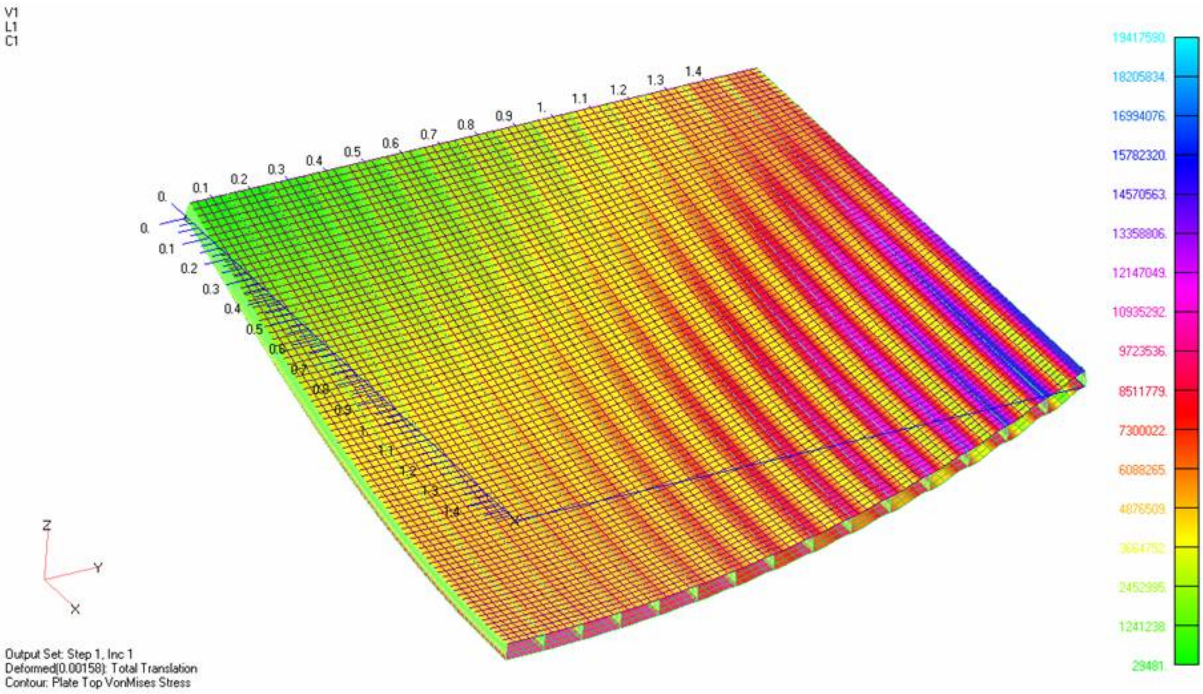


Figure 3.1.1.2b-1 - the response of a square all-metal sandwich plate under uniform pressure loading. The secondary bending stresses (both compressive and tensile) in the facing sheets due to shear induced bending can be seen on the right hand side of the picture.

The analysis of all-metal sandwich panels is most easily performed using plate theory in which the periodic core geometry of the sandwich structure has been homogenised. In these circumstances, the design approaches applicable for non-isotropic sandwich structures become valid. The homogenisation is performed using a rule of mixtures approach in order to obtain the so-called *ABD*-matrix.

The shear stiffness in the stiffener direction is derived using beam theory. The shear stiffness perpendicular to the stiffener direction is much more difficult to define, but is, for example, for an I-Core^{TM} panel:

$$S_y = \frac{12D_w}{s^2\left(k_Q\left(\frac{D_w}{D_b}+6\frac{d}{s}\right)+12\frac{D_w}{k_\theta^b s}-2\frac{d}{s}\right)}$$ *(equation 3.1.1.2b-1)*

where:

$$D_i = \frac{E_i t_i^3}{12\left(1-\mu_i^2\right)},\; i = t,w,b$$

(equations 3.1.1.2b-2)

$$k_\theta^i = Qs/\theta_c^i$$

and:

$$k_Q = \frac{1+12\frac{D_t}{s}\left(\frac{1}{k_\theta^t}-\frac{1}{k_\theta^b}\right)+6\frac{D_t}{D_w}\frac{d}{s}}{1+12\frac{D_t}{D_w}\frac{d}{s}+\frac{D_t}{D_b}}$$ *(equation 3.1.1.2b-3)*

The stiffness formulations for other all-metal sandwich cross-sections can be found in Romanoff & Klanac 2004.

Parameter k_θ^i defines the rotation between the core and the facing sheet. This parameter can be taken as infinite if the facing sheets are many times thinner than the web plates and the weld thickness is larger than the facing sheet thickness. For example, for a 1 mm thick facing sheet and a 4 mm thick web plate k_θ^i can be taken as infinite as long as the weld thickness is greater than 1 mm. For greater plate thicknesses, detailed finite element analysis (FEA) or experimental stiffness testing of this connection is recommended as presented in Romanoff & Kujala 2003.

Stiffness modelling and calculation of stresses: combined analytical and numerical methods

In homogenous sandwich plate analysis, the stiffness parameters can be derived analytically as presented above. The numerical solution for a given set of load and boundary conditions can then be obtained in a similar manner as for homogenous sandwich plates. The analytical stress analysis should always start with the resultant reactions. Once these reactions are known, the analyst should look again at the stiffness formulations and calculate the stresses based on the stiffness derivation. Details of these formulations are given by Romanoff & Klanac 2004.

The stress output of commercial FEA packages does not usually work for all-metal sandwich panels, unless the software has a special "all-metal sandwich" option. Two packages that do accommodate all-metal sandwiches correctly are ESAComp-MSE and the SANDWICH Design Tool.

Stiffness modelling and calculation of stresses: purely numerical methods

In three-dimensional FEA modelling with shell elements, the only stiffness parameter that needs to be defined is the rotational stiffness between the facings and the web plates. It should also be noted that in geometries in which the flange of the core stiffener is in contact with the facing sheet, rigid links or beam elements with appropriate stiffness should be used. The stress prediction can be done with the FEA package's own post-processor. It is important to make sure that there are enough (> 4 parabolic) elements in the smallest dimension of the web plate or in the facing plate between two web plates. The maximum stress usually occurs right next to the web plate (as shown in Figure 3.1.1.2b-1 above).

In homogenous sandwich plate analysis, the stiffness parameters can also be derived numerically. The numerical determination of the stiffness is presented, for example, in Buannic et al. 2003. The basic idea is that a unit cell of all-metal sandwich panel is modelled and subjected to basic load cases such as extension, bending, torsion and shear. Then the resulting deformations are recorded and further stiffness is derived from:

$$k = \frac{F}{u} \qquad \textit{(equation 3.1.1.2b-4)}$$

where F is the axial load, moment or shear force, and u is the axial displacement, curvature or shear angle. The stress analysis should be carried out taking the real resultant reactions occurring in the structure and using these values to scale the stresses in the stiffness models.

3.1.1.2c. Linear Elastic Analysis of Hybrid Metal Sandwich Structures Under Static Loads: Numerical Methods

Hybrid metal sandwich structures can be categorised according to the type of core (see section 2.3.1):

- **Type 1** - filled metallic stiffeners.
- **Type 2** - non-metallic stiffeners.

- **Type 3** - Non-metallic solid.

As the latter has a core with isotropic properties, the information provided in the general overview section (3.1.1.2a) is applicable to this type of sandwich.

For information on the static analysis of sandwich structures of type 1 or 2, please refer to section 3.1.1.2b.

Filling the cavities of all-metal sandwiches mainly changes the shear stiffness perpendicular to the stiffeners. Modelling the whole panel (including the filler material) with solid elements is one way to estimate the effect of the filling. However, the computational cost is high. The increased shear stiffness can also be incorporated into the stiffness of an orthotropic, layered shell element.

3.1.1.2d. Linear Elastic Analysis of Composite Sandwich Structures Under Static Loads: Numerical Methods

Finite element analysis (FEA) tools are normally used when analytical solutions prove inadequate. In the case of **composite** sandwich structures, such inadequacies may arise because of one or more of the following reasons:

- The boundary conditions do not allow an analytical solution to the governing equations of equilibrium because of either a non-symmetric lay-up of the facing laminates, or because of non-identical facings.

- The material disposition is non-uniform and variable, which is possible when the facing composition or thickness varies and/or the core density/thickness varies in a spatial sense.

- Non-linearity is to be studied either in terms of geometry or in terms of material behaviour (e.g. in some PVC foam cores).

- Orthotropy of the facing material (for woven roving or angle/cross ply materials) proves to be difficult to model in closed form solutions.

FEA packages for use with composite sandwich structures

The following commercial packages are reported to have been successful in practical contexts:

- ANSYS.
- ABAQUS.
- NISA.
- MSC Nastran.
- MAESTRO.
- ESACOMP.
- HyperSizer.

Element selection

- **Bar elements** can be used to model the facings of two dimensional sandwich structures in which the flexural stiffnesses of the facings about their own neutral axes are not significant (see Zenkert 1997). This generally implies that the material properties of the facings in the two principal in-plane directions are the same.

- **Beam elements** can be used for facings in two dimensional sandwich structures when the local bending stiffness is relatively high, e.g. when facings are relatively thick. Again, there is an implication that the composite facings are isotropic in-plane. If the facings are highly bi-directional and the properties are orthotropic, then beam- and bar-based two dimensional analyses should be avoided.

- **Brick elements** can be used for core materials. Note that these could have directional properties for materials such as end-grained balsa or honeycombs. Generally, foam cores can be treated as isotropic, although users should be aware of the potential for varying density in the through-thickness direction due to core processing limitations.

- **Layered brick elements** can be used for both facings and core. Normally one layer is used per lamina or ply. In so doing, it is important to check the convergence of results vis-à-vis the aspect ratio of the elements.

- **Layered shell elements** can be used for full three dimensional analyses. Layered elements can use a variety of plate theories such as classical laminate theory (CLT), first order shear deformation theory, higher order shear deformation theory, etc. (see Nayak & Shenoi 2005 for details of formulations). Normally, elements based on higher order plate theory should be used when span-to-depth ratios are less than about 15 and when core shear becomes an important issue in determining response limits.

- **Plain strain elements** can be used for two-dimensional analyses in situations such as bulkhead-to-shell connections (see section 3.5.1.3). Again, generally these should be capable of accounting for the layers in the boundary angle over-laminate that forms the connection since the lay-up can vary from ply to ply.

Note that element formulations vary from package to package and hence care must be exercised when comparing results obtained using one package with those obtained using another. The choice of elements for a particular problem thus depends not just on the analysis type (e.g. linear elastic or non-linear elastic) but also on the chosen package.

Material models

The choice of materials input data depends on the sophistication of the analysis being conducted, its criticality from a design, production or operations viewpoint, and the level of detail being sought in the analysis.

- If the analysis is for **preliminary or benchmarking purposes** then it is adequate for the composite facings to be modelled as a single entity, with gross elastic properties being defined for all plies together. These properties could be derived using some empirical formulation such as the rule-of-mixtures. Alternatively, they could be derived from experimental programmes. Core properties may be taken from suppliers' data sheets. If foam cores are used then it is reasonable to assume isotropy. If, on the other hand, end-grained balsa or honeycomb materials are used then the analyst needs to be aware of the directionality of properties and the manner in which the core is laid into the sandwich.

- If the analysis is to be used for more **specific, detailed purposes** then it may be desirable, or even essential, to use detailed material property input data. Details such as the lamina-by-lamina definition of the principal in-plane, transverse shear, interlaminar shear, etc. moduli will be required. Some of these properties, such as in-plane direct stress and in-plane shear properties may be derived using rule-of-mixtures formulations. It is recommended though that the designer obtains all properties through rigorous experimentation. Core material properties may exhibit non-linearity, especially PVC foams. It is therefore necessary to input the full stress-strain curve to failure. Note that in such cases, the analysis should be conducted to take into account both geometric and material non-linearity.

- In some cases, it may be important to input details of the **adhesive layer** between the facings and the core, as well as between layers of a core material (which is likely to be the case for some PVC and balsa sheets).

Pre- and post-processing issues

- Note that lamina properties are generally defined with respect to the principal directions of that lamina. This can be at variance with the structural or global coordinate system. Hence care must be taken in the coordinate system used to specify material properties in the finite element software.

- Given that element meshes can be dense in order to cater for layer-by-layer properties, it is important to ensure nodal and elemental consistency in geometrical terms.

- When post-processing, try and query results in the strain domain rather than the stress domain. Because of large variations in the elastic modulus between layers (in a directional sense), it is possible that stresses in two adjacent elements may have a large variation. For example, the stresses in a core element at the facing-core interface will be very much smaller than the stresses in the facing element at a common node owing to the difference in elasticity. Similar differences can be present between layers/plies of a facing due to directionality of the lay-up. By working in the strain domain, it ensures that the strain values at common nodes between elements are the same. Thus, the strain in a core element at a facing-core interface will be the same as the strain in the facing element owing to compatibility requirements.

3.1.1.3. Test Data

This section provides some example **test data** relating to the **linear elastic** response of sandwich structures. Clearly, the response of any sandwich structure is going to be strongly dependent upon its materials, geometry, loading and support conditions. Therefore, extreme caution should be exercise when extrapolating any of the information that is presented here. However, the examples cited are indicative of the performance levels that can be achieved with similar panels. Furthermore, the numerical data is a useful resource for benchmarking and validation purposes.

3.1.1.3b. Linear Elastic Test Data for All-Metal Sandwich Structures Under Static Loads

The following section describes **large scale bending tests** performed on **laser welded all-steel** sandwich panels.

Test specimens

The specimens tested had areal dimensions of 3000 mm x 1500 mm. Two different core geometries were investigated:

- I-Core – i.e. stiffeners perpendicular to the facings.
- V-Core – i.e. corrugated stiffeners.

These two core types are illustrated in figure 3.1.1.3b-1.

For the I-Core panels, the distance between the stiffeners was kept constant at 80 mm. The thickness of the stiffeners was also kept constant at 4 mm. However the following panel parameters were varied to gauge their influence:

- Facing thickness, t = 1 mm, 2 mm and 3 mm.
- Stiffener height, c = 20 mm, 40 mm and 60 mm.

For the V-core panels, the core geometries of the two types of panel tested are defined in figure 3.1.1.3b-1.

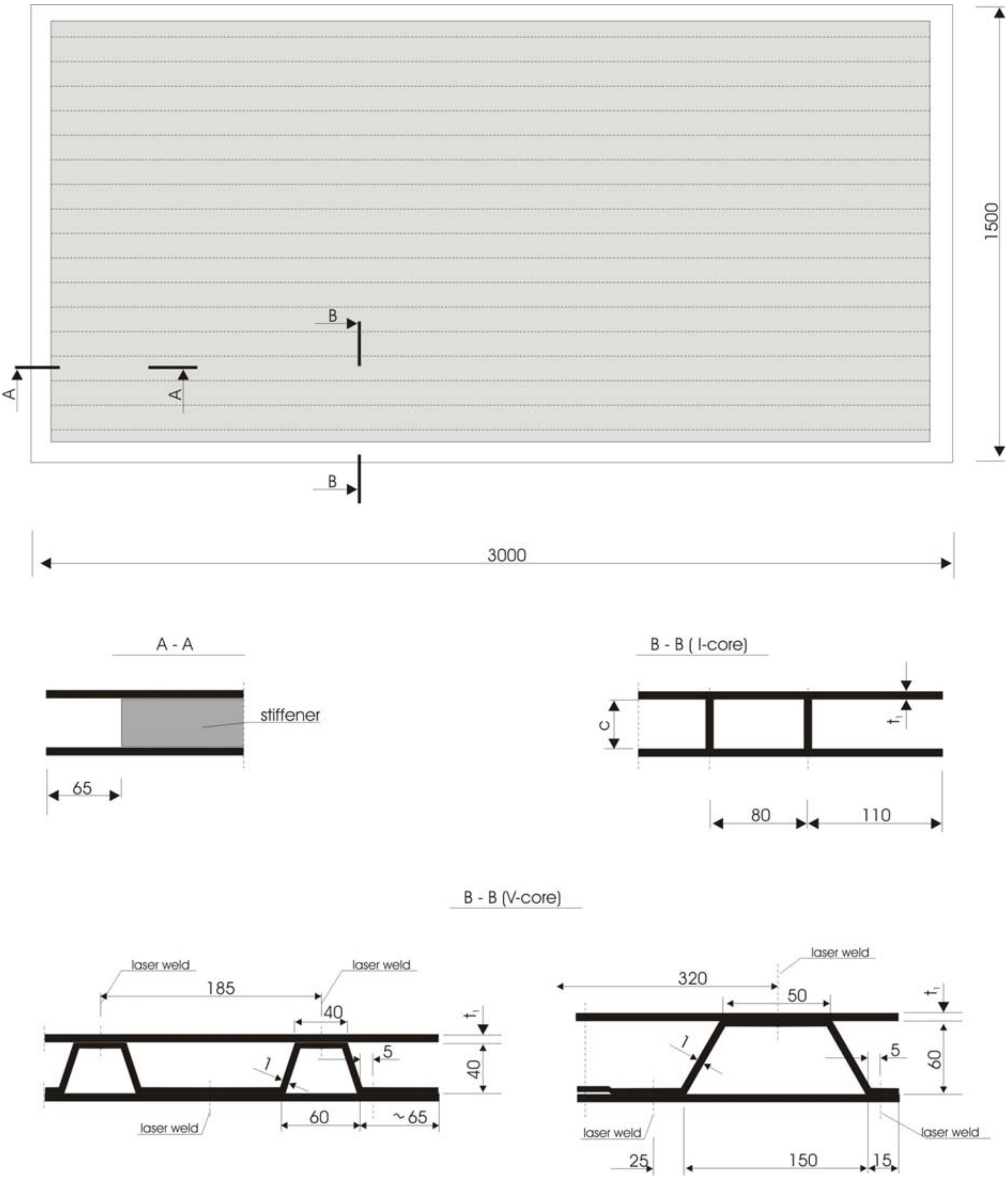


Figure 3.1.1.3b-1 - geometrical details of the test specimens. Dimensions in mm.

Loading and support conditions

Figures 3.1.1.3b-2 and 3.1.13b-3 show the loading and support conditions respectively that were employed for the tests. Photographs of some of the apparatus used to perform the tests are shown in figure 3.1.1.3b-4.

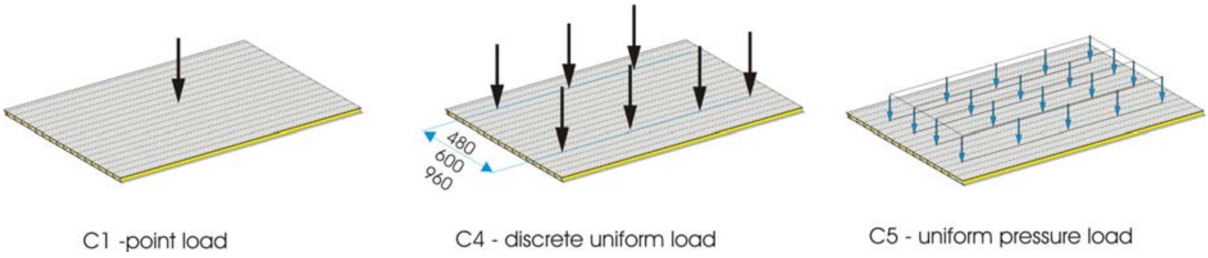


Figure 3.1.1.3b-2 – specimen loading conditions.

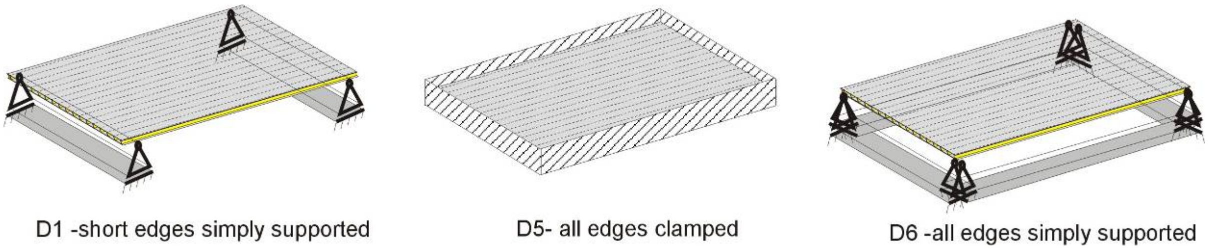


Figure 3.1.1.3b-2 – specimen support conditions.

Figure 3.1.1.3b-4 – some of the apparatus used to perform the bending tests. Left: set-up for loading / support configuration C4&D6. Right: set-up for loading / support configuration C5&D5.

Test results

The following specimen nomenclature is used for the presentation of the test results:

stiffener height (mm) x facing thickness (mm) x E (for empty, i.e. the core was unfilled).

So, for example, a specimen designated 20x2xE had a stiffener height of 20 mm, a facing thickness of 2 mm, and had no core filling. Test results for filled (i.e. hybrid metal) panels can be found in section 3.1.1.3c.

Using the nomenclature and loading / support definitions above, the following graphs present the results of the bending tests for the I-Core and V-Core panels in terms of load – displacement relationships. The data relates to the outer surface of the lower facing at the middle of panel.

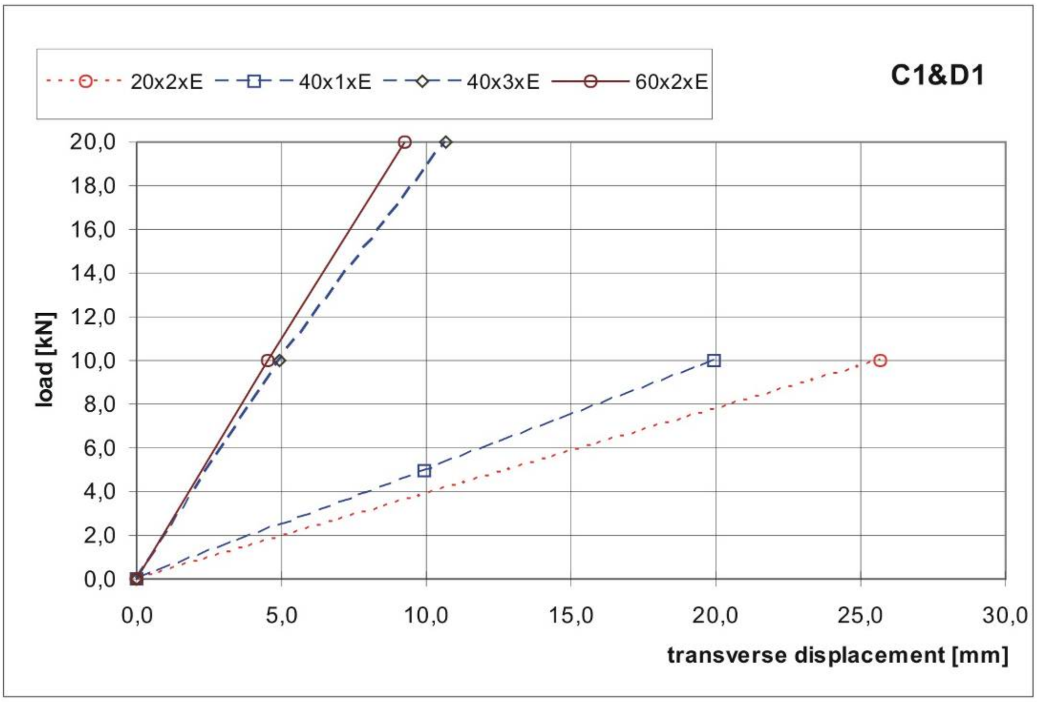


Figure 3.1.1.3b-5 – I-Core panels, central point load, short edges simply supported.

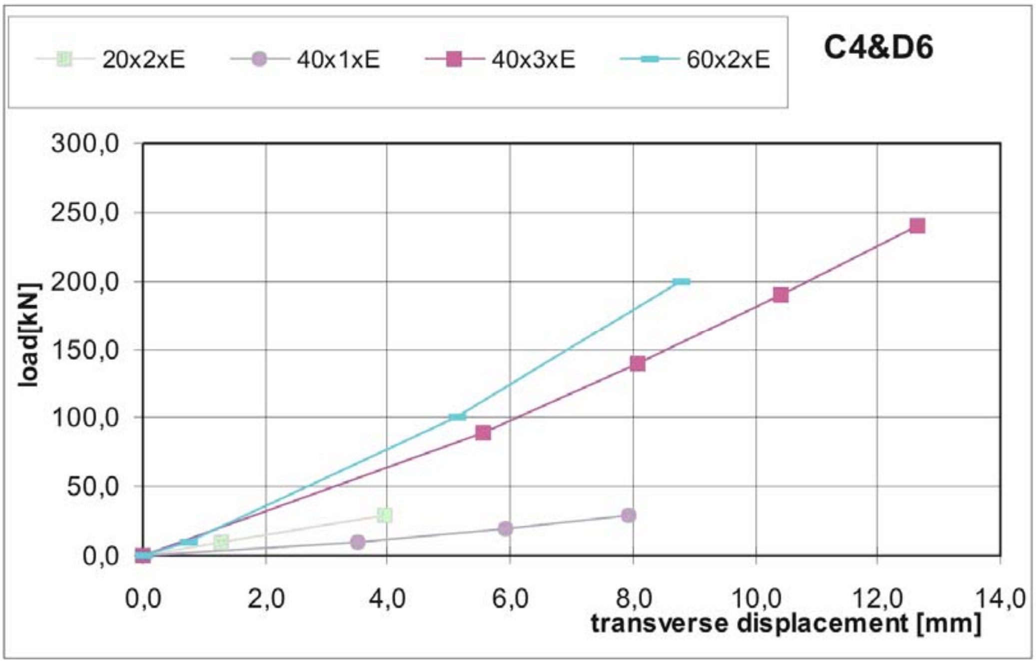


Figure 3.1.1.3b-6 – I-Core panels, discrete uniform load, all edges simply supported. The distance between the two lines of applied load was 960 mm (figure 3.1.1.3b-2).

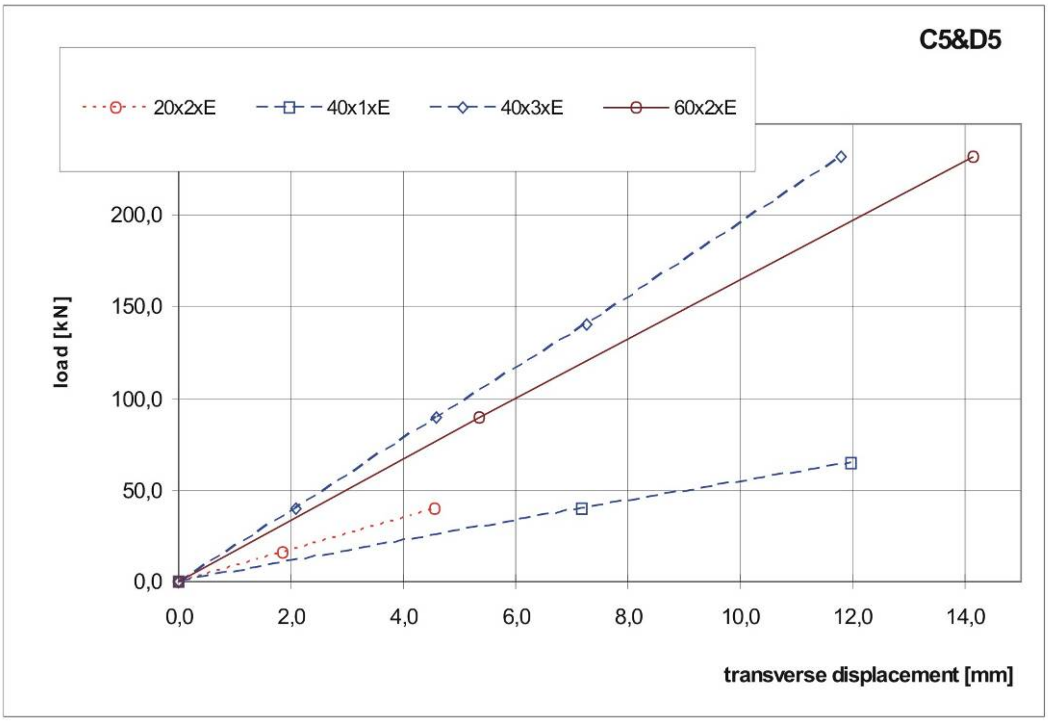


Figure 3.1.1.3b-7 – I-Core panels, uniform pressure load, all edges clamped.

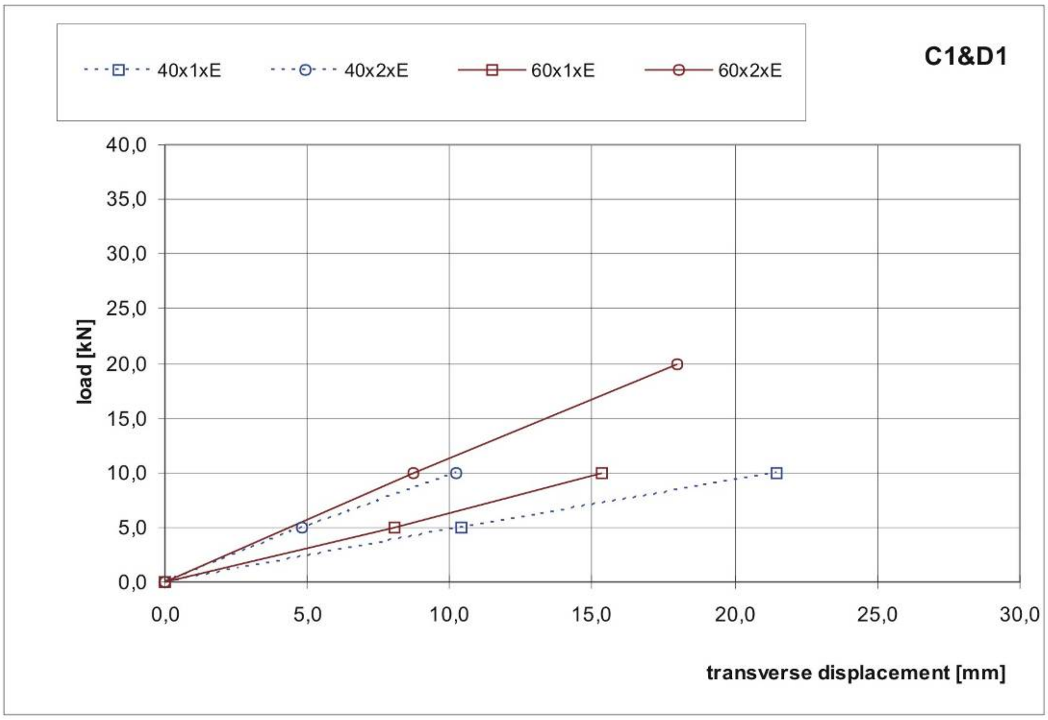


Figure 3.1.1.3b-8 – V-core panels, central point load, short edges simply supported.

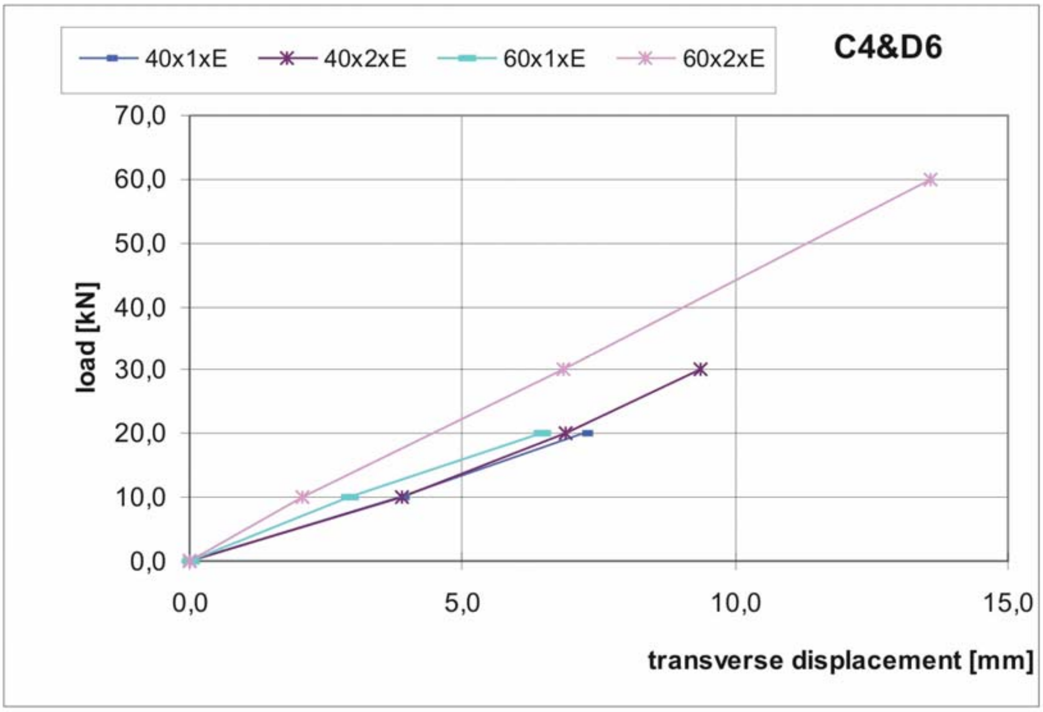


Figure 3.1.1.3b-9 – V-core panels, discrete uniform load, all edges simply supported. The distance between the two lines of applied load was 600 mm (figure 3.1.1.3b-2).

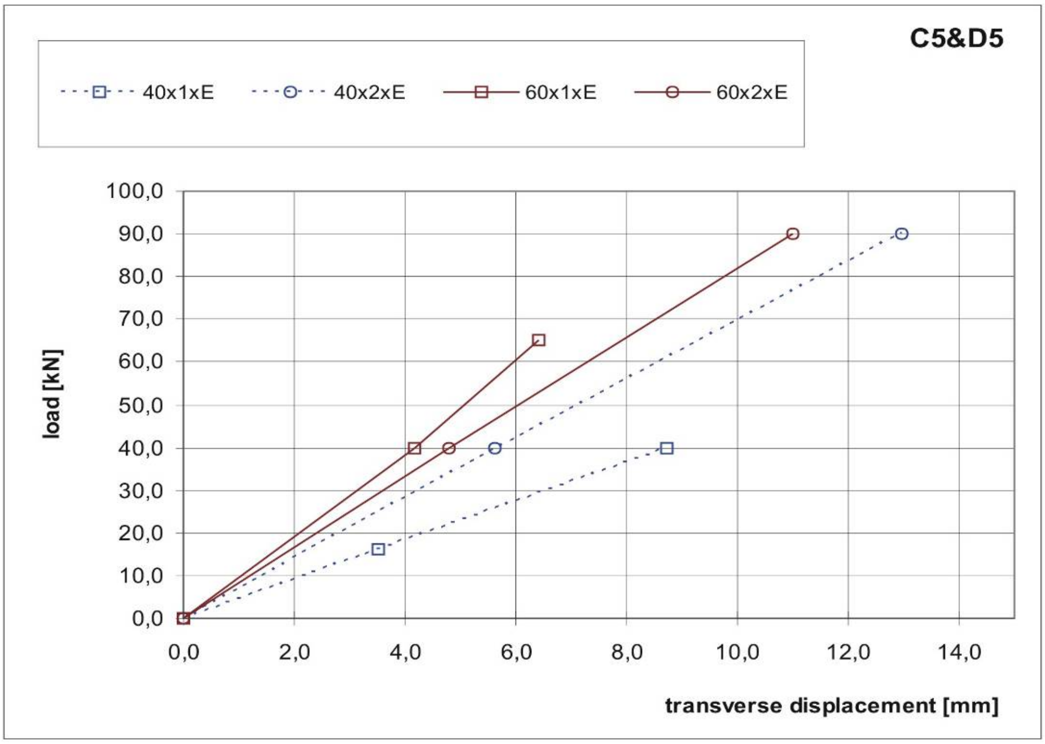


Figure 3.1.1.3b-10 – V-core panels, uniform pressure load, all edges clamped.

Guidelines and lessons learned

- It can be observed that both the height of the stiffeners and the facing thickness contribute to the overall stiffness of the sandwich.
- It can also be observed that the I-Core system has a better stiffness performance than the V-core system.
- The results also demonstrate the relatively high mechanical flexibility of sandwich structures. From a design perspective, this might necessitate the introduction of a "maximum allowable deflection" criterion for sandwich panels in addition to the maximum allowable strength criterion that is normally sufficient for single skin, steel-stiffened panels.

3.1.1.3c. Linear Elastic Test Data for Hybrid-Metal Sandwich Structures Under Static Loads

Similarly to section 3.1.1.3b (above), this section provides typical **test data** for **hybrid**, filled steel I-Core and V-Core panels. The nomenclature employed and test configurations are exactly the same as those described in section 3.1.1.3b. The only difference is that the core cavities of the panels tested were filled with either **low density polyurethane foam** (designated "L") or **high density balsa wood** (designated "H").

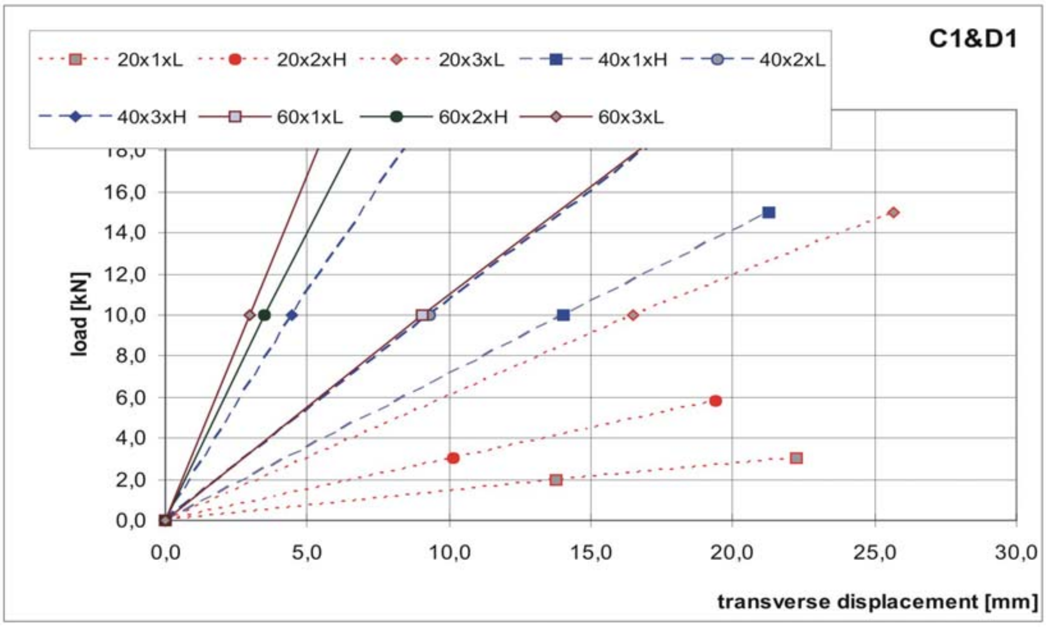


Figure 3.1.1.3c-1 – I-Core panels, central point load, short edges simply supported.

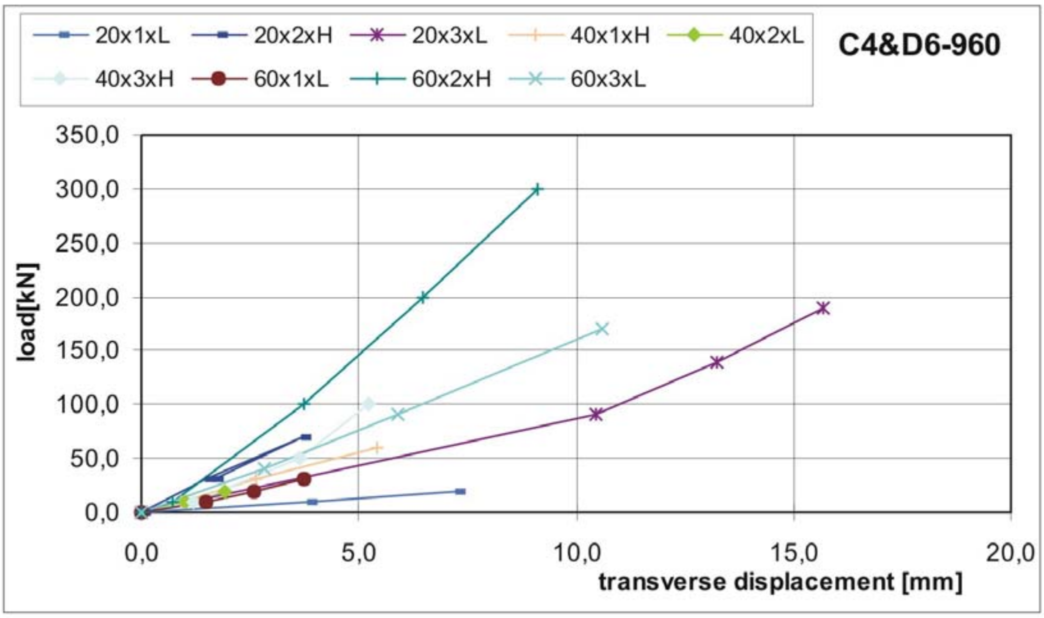


Figure 3.1.1.3c-2 – I-Core panels, discrete uniform load, all edges simply supported. The distance between the two lines of applied load was 960 mm (figure 3.1.1.3b-2).

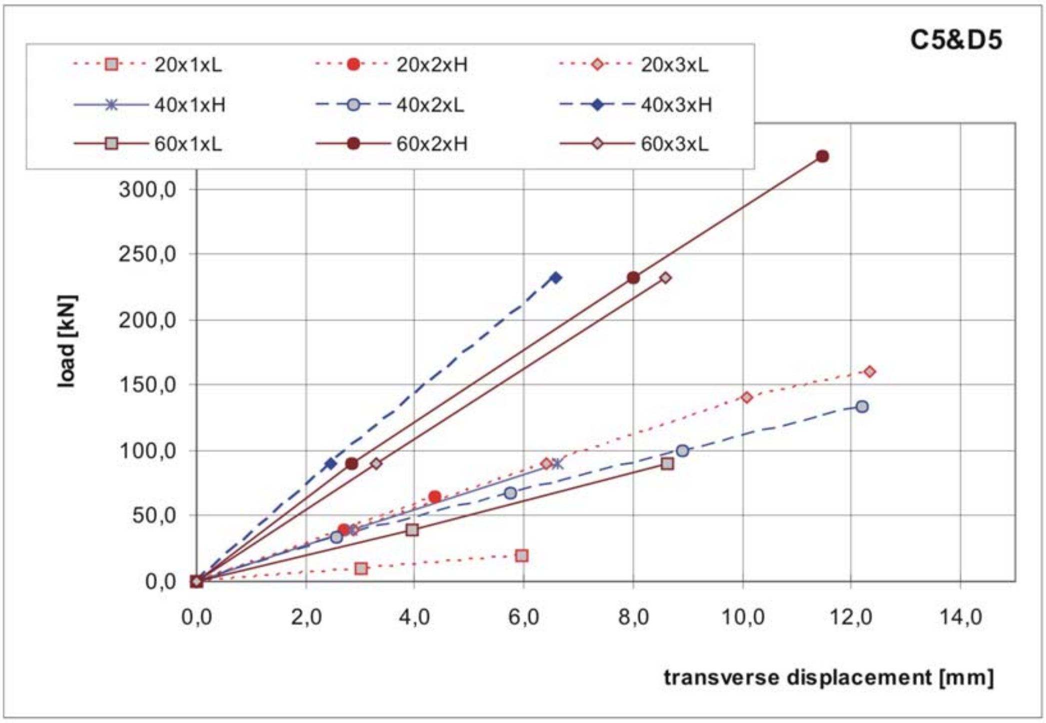


Figure 3.1.1.3c-3 – I-Core panels, uniform pressure load, all edges clamped.

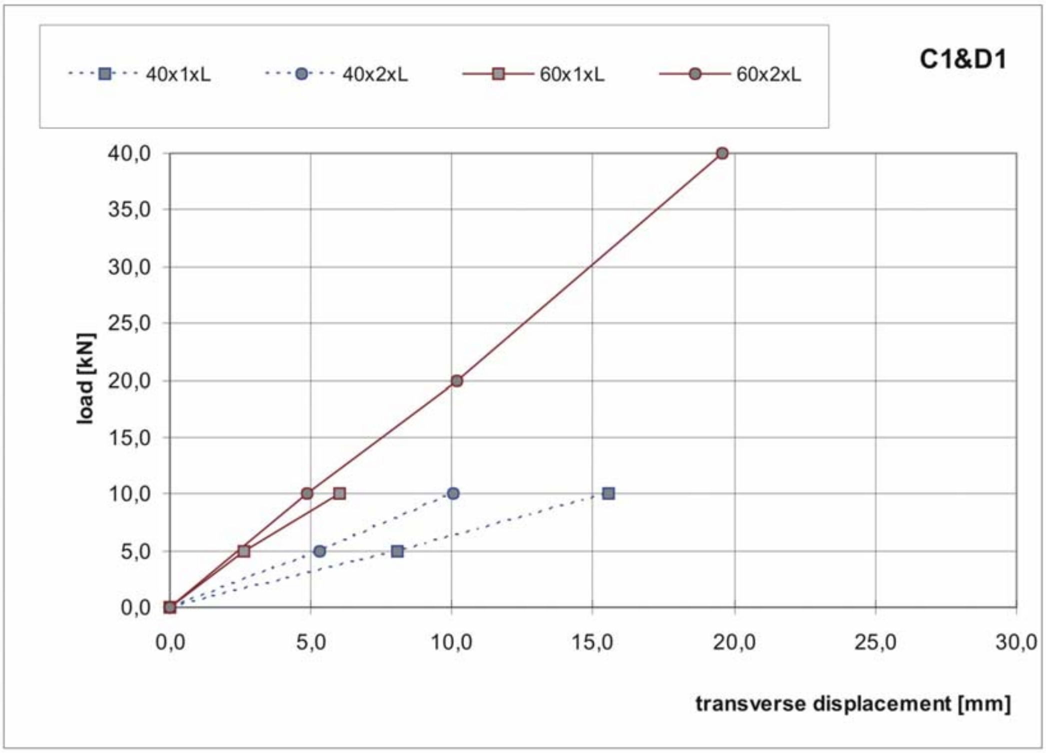


Figure 3.1.1.3c-4 – V-core panels, central point load, short edges simply supported.

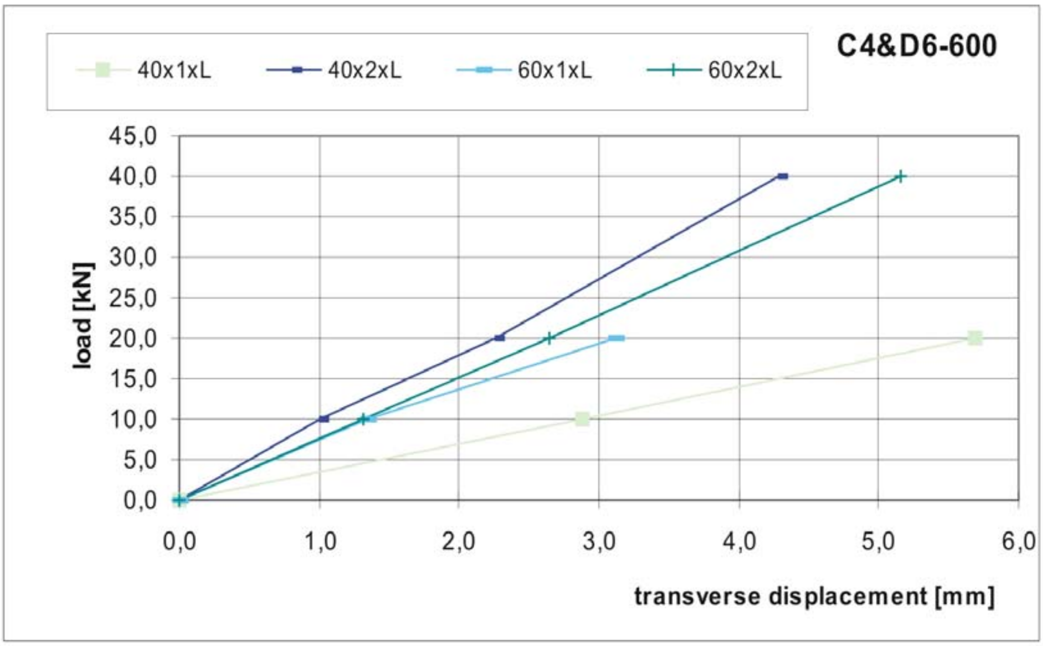


Figure 3.1.1.3c-5 – V-core panels, discrete uniform load, all edges simply supported. The distance between the two lines of applied load was 600 mm (figure 3.1.1.3b-2).

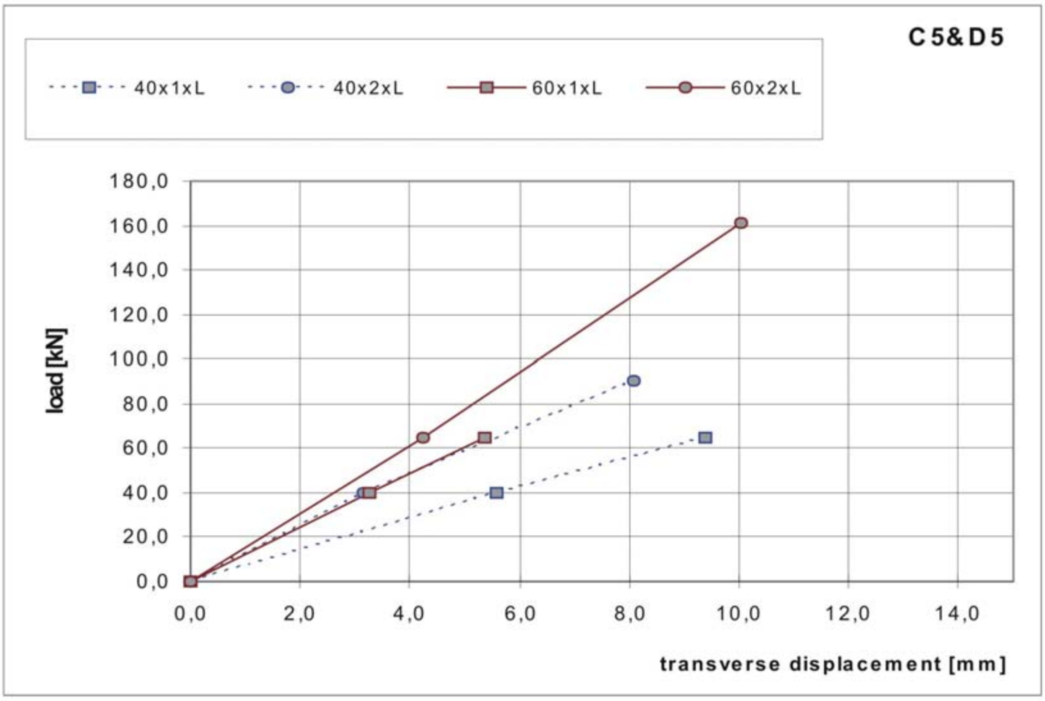


Figure 3.1.1.3c-6 – V-core panels, uniform pressure load, all edges clamped.

Guidelines and lessons learned

- The results from the testing indicate that a combination of stiffener height and filling material density has a major influence on the stiffness properties of hybrid metal sandwich panels. However, this relationship is not simple, and the stiffness exhibited by the test specimens was also found to be strongly related to the loading regime and boundary conditions.

- The effect of the core filling material was found to vary for different panel geometries. It had a stronger influence on panels with lower facing thicknesses. For some panels, the high density balsa wood filling was found to almost double the overall stiffness of the sandwich.

3.1.1.3d. Linear Elastic Test Data for Composite Sandwich Structures Under Static Loads

Analyses of **composite** sandwich structures typically require information about the mechanical characteristics of the materials that make up the construction. The purpose of this section is to list typical data concerning materials used in composite sandwich structures within the **elastic** range, and to suggest further reading for the direct determination of such properties for specific applications.

Generally the data required for characterising elastic behaviour includes mass density, elastic moduli of different kinds, Poisson's ratio, thermal properties, etc. Some key data is listed in the tables that follow. Other data can be found in classic texts or industry data books (e.g. Hancox & Mayer 1994 and Shenoi & Wellicome 1993)

Typical properties of thermosetting resins

Material	Specific Gravity	Young's Modulus (GPa)	Poisson's Ratio	Heat Distortion Temperature (°C)
Polyester (orthophthalic)	1.23	3.2	0.36	65
Polyester (isophthalic)	1.21	3.6	0.36	95
Vinyl ester (Derakene 411-45)	1.12	3.4		110
Epoxy	1.20	3.0	0.37	110
Phenolic	1.15	3.0		120

Typical properties of reinforcing fibres

Material	Specific Gravity	Young's Modulus (GPa)	Poisson's Ratio	Coefficient of Expansion, Axial ($x10^{-6}$ / °C)	Thermal Conductivity, Axial (W / m°C)
E-glass	2.55	72	0.2	5.0	1.05
S-glass	2.50	88	0.2	5.6	
High strength carbon	1.81	300		-0.5	140
High modulus carbon	2.18	825		-1.2	150
Aramid (Kevlar)	1.49	125		-2.0	0.04

Typical properties of fibre reinforced laminates (sandwich facing materials)

Material	Fibre Volume Fraction	Specific Gravity	Young's Modulus (GPa)	Shear Modulus (GPa)
E-glass - polyester (chopped strand mat)	0.18	1.5	8	3.0
E-glass - polyester (balanced woven roving)	0.34	1.7	15	3.5
E-glass - polyester (unidirectional fibres)	0.43	1.8	30	3.5
Carbon - epoxy (high strength, balanced fabric)	0.50	1.5	55	12.0
Carbon - epoxy (high strength, unidirectional fibres)	0.62	1.6	140	15.0
Aramid - epoxy (unidirectional fibres)	0.62	1.4	50	8.0

Typical properties of sandwich core materials

Material	Specific Gravity	Shear Modulus (MPa)	Through-Thickness Young's Modulus (MPa)
PVC foam*	0.075-0.19	25-50	50-160
End grain balsa*	0.10-0.18	110-300	800-1400
Aluminium honeycomb**	0.13	895/365	2340
GRP honeycomb**	0.08	117/52	580
Nomex honeycomb**	0.065	53/32	193

** The ranges reflect a range of densities of the core, from about 80 kg/m^3 to 200 kg/m^3.*

*** Pairs of numbers refer to the longitudinal and transverse directions of a hexagonal honeycomb.*

Additional data requirements, test standards and check list

Note, that in addition to the basic data reported in the above tables, there may be a requirement for specific information concerning a particular facing laminate or core material. In such cases, the potential suppliers of such materials should be consulted for a preliminary estimation of the values needed for an analysis. It is also highly advisable to consider the following options:

- Conduct experimentation oneself for the data items.

- Check with standards organisations such as ASTM, ISO, DIN, BSI, EN, etc. and also with the concerned classification society about the procedures to be followed for material data generation. Sims 2005 provides guidance on possible test standards.

- Be aware that composite material property data can vary with material supplier, process route (e.g. hand lay-up, prepreg consolidation, vacuum infusion, etc. – see section 4.3), and the test method employed.

- Note that, on occasion, it may be desirable and even essential to characterise the totality of the composite sandwich configuration rather than just the individual material constituents. Sims 2005 is especially relevant in this context.

Guidelines on whole structure characterisation

Any results for whole structural components from published sources should be treated with great caution. Particular attention should be paid to the following:

- Test boundary conditions and loading.

- Geometry of the structure.

- Material make-up of the structure.

- Manufacturing processes involved.

- Purpose of the testing.

- Instrumentation used in the testing.

Users should be certain that, even if all these bits of information are available, then they are pertinent to the users' own application. In particular, care should be taken not to over-generalise the results from one test. Note that there could be considerable variation in certain material properties. For instance, it is known that the standard deviation in quoted values of core shear strength can be up to 20%. Similarly, for composite facing laminates produced by hand lay-up, standard deviations can be as high as 15% for experienced laminators. There is also the issue of process-dependent variability – this will typically be greater for hand lay-up and less so for vacuum infusion, resin transfer moulding and prepreg consolidation.

3.1.2. Ultimate Strength

3.1.2.1. Analytical Methods

3.1.2.1a. Ultimate Strength of Sandwich Structures Under Static Loads: Analytical Methods – General Overview

This section describes how to estimate the **ultimate strength** of sandwich panels under **static loads**. The expressions presented here are applicable to panels with isotropic facings and isotropic cores, including hybrid metal panels with metal facings and solid isotropic cores. Sections 3.1.2.1b, 3.1.2.1c and 3.1.2.1d that follow describe the additional complexities that need to be addressed when handling all-metal, other hybrid metal and composite sandwich panels respectively.

When analysing any sandwich panel for strength, one needs to have knowledge of the loading and support configuration. For example:

- For a sandwich panel loaded in bending, the likely failure modes are tensile / compressive failure of the facings or shear failure of the core.

- For a sandwich panel loaded in flatwise (through-thickness) compression, the likely failure mode is core compression / local indentation. It should be noted that through-thickness stresses not only arise through direct normal loads such as those shown in (h) in the figure below, but also at structural discontinuities such as joints and inserts.

- For a sandwich panel loaded in edgewise (in-plane) compression, possible failure modes include panel buckling, panel shear crimping, facing wrinkling, and (for non-continuous cores such as metallic stiffeners and honeycombs) facing intra-cell buckling (dimpling).

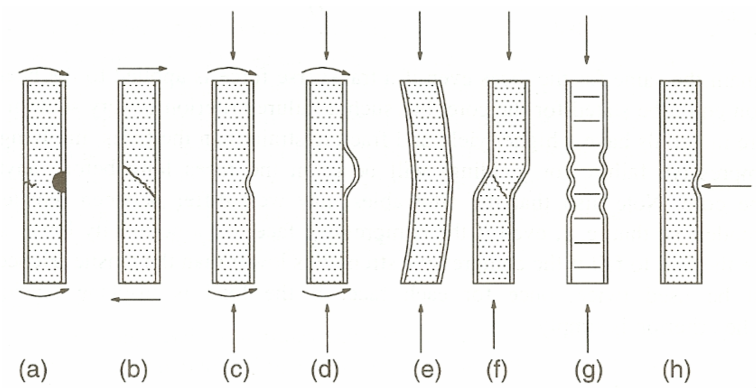


Figure 3.1.2.1a-1 - failure modes in sandwich beams (from Zenkert 1995) – (a) tensile / compressive failure of the facings, (b) shear failure of the core, (c) and (d) facing wrinkling, (e) buckling, (f) shear crimping, (g) facing intra-cell buckling (dimpling), and (h) local indentation.

The following table provides some simple expressions that can be used for checking for sandwich failure depending on the type of loading. In the expressions presented, σ_f is the stress in the facings, $\hat{\sigma}_f$ is the strength of the facing material, τ_c is the shear stress in the core, $\hat{\tau}_c$ is the shear strength of the core material, q is the applied load per unit area, $\hat{\sigma}_c$ is the compressive strength of the core material, G_c is the shear modulus of the core material, E_c is the Young's modulus of the core material, E_f is the Young's modulus of the facing material, P is the applied load, t is the thickness of the sandwich facing, b is the width of the sandwich panel, and s is the core cell size (e.g. of a honeycomb).

Loading Configuration	Failure Mode	Check: Failure Occurs If …
Bending	Facing Tensile / Compressive Failure	$\sigma_f \geq \hat{\sigma}_f$ σ_f can be estimated using the guidelines provided in Section 3.1.1.1a.
	Core Shear Failure	$\tau_c \geq \hat{\tau}_c$ τ_c can be estimated using the guidelines provided in Section 3.1.1.1a.
Flatwise (Through-Thickness Compression)	Core Compression	$q \geq \hat{\sigma}_c$
Edgewise (In-Plane Compression)	Facing Wrinkling	$\sigma_f \geq 0.5(G_c E_c E_f)^{1/3}$
	Panel Shear Crimping	$P \geq tG_c b$
	Facing Intra-Cell Buckling (e.g. with honeycomb cores)	$\sigma_f \geq 2E_f\left(\frac{t}{s}\right)^2$

Guidelines on the ultimate strength of sandwich structures under static loads: analytical methods

- The expressions presented here are only applicable to sandwich panels with thin, equal isotropic facings and isotropic cores. For non-isotropic sandwich materials, consult the specialist texts listed in the further information section below, as well as the sections on the strength of all-metal (3.1.2.1b), hybrid metal (3.1.2.1c) and composite (3.1.2.1d) sandwich panels elsewhere in this guide. Honeycomb cores can be treated as isotropic as a first estimate, although unless the orientation of the panel is clear, it is advisable to use the honeycomb properties in the weakest direction to obtain conservative predictions.

- The above expressions also assume a strong bond between the facing and the core. However, for some sandwich structures, particularly those with lightweight polymer foam cores, a weak core-to-facing bond can be a limiting factor in terms of strength. For example, in bending, the core and the facings might separate before the strength of the facings is reached. To evaluate the strength of the core-to-facing bond, four-point bending or peel tests can be used.

- In practice, failure most commonly occurs at stress concentrations – joints, corners, holes, discontinuities, etc. More detailed studies (e.g. using numerical methods such as finite element analysis) may be required in the presence of such features.

- The ultimate strength of large complex structures that consist of an assembly of sandwich panels and non-sandwich stiffeners is normally studied by considering the progressive failure of the individual elements under increasing loads. This means that the ultimate strength of individual panels plays an essential role. However, the derivation of the full load-displacement characteristics for individual panels (including elastic and non-elastic behaviour), which in some approaches must be taken into account, is not considered in this guide.

3.1.2.1b. Ultimate Strength of All-Metal Sandwich Structures Under Static Loads: Analytical Methods

The ultimate strength of **all-metal** sandwich panels can be separated into two aspects. One is global panel collapse. The second is local collapse of a panel's facings and/or core. Naturally, a local failure can lead to a global collapse, so it is important that both aspects are considered.

The local failure of an all-metal panel might occur in any of the three parts of the structure, i.e. the **top faceplate**, the **core stiffeners**, or the **bottom faceplate**. Axial (in-plane) loading is usually considered to spread throughout the cross section of a panel. On the other hand, lateral (through-thickness) loading is assumed to be in contact with the top faceplate only.

Top faceplate

Due to axial (in-plane) compressive stresses, plastic buckling can be initiated in the top faceplate along the direction of the core and transverse to it as seen in figure 3.1.2.1b-1a. In general, the transverse strength is approximately four times lower than the longitudinal strength. In the case of very large sheet thicknesses with short unsupported spans between stiffeners, yielding might occur without buckling.

Due to high local lateral (through-thickness) loads, a faceplate might yield locally forming a permanent indentation as shown in figure 3.1.2.1b-1b. However, such confined damage is not regarded as a failure. That said, if the local damage of the plate is extensive and left untreated, it could lead to buckling of the panel and subsequent collapse. The load needed to initiate a permanent indentation is the sum of the limit load evoking plastic deformation, and the load needed to develop a dent.

a) b)

Figure 3.1.2.1b-1: a) buckling and b) denting of the top faceplate.

The following table lists the basic analytical expressions for the determination of critical loadings for the top faceplate:

Failure Mode	Loading Condition	Equations
Elastic Buckling*	For the case where the buckling stress is less than half the yield stress ...	
	In Bending or in Membrane	$\hat{\sigma}_{e,t} = 0{,}9 \cdot k \cdot E_t \cdot \left(\frac{t_t}{b_{b,t}} \right)^2$
	In Shear	$\hat{\tau}_{e,t} = 4.8 \cdot E_t \cdot \left(\frac{t_t}{b_{b,t}} \right)^2$
	Buckling coefficient, k	
	Parallel to the Core Stiffeners	$k = 4$
	Transverse to the Core Stiffeners	$k = 1$

**Elastic buckling cannot strictly be treated as a failure.*

Continued overleaf...

Plastic Buckling	For the case where the buckling stress is more than half the yield stress, the elastic buckling formulations have to be corrected ...	
	In Bending or in Membrane	$$\hat{\sigma}_{b,t} = \sigma_{y,t} - \frac{\sigma_{y,t}^2}{4\cdot\hat{\sigma}_{e,t}}$$
	In Shear	$$\hat{\tau}_{b,t} = \tau_{y,t} - \frac{\tau_{y,t}^2}{4\cdot\hat{\tau}_{e,t}}$$
	Bi-axial Compression and Shear	$$\frac{\sigma_{X,t}}{\hat{\sigma}_{b,X,t}\cdot\eta_{XY,t}} - k\cdot\frac{\sigma_{X,t}\cdot\sigma_{Y,t}}{\hat{\sigma}_{b,X,t}\cdot\hat{\sigma}_{b,Y,t}\cdot\eta_{XY,t}} + \left(\frac{\sigma_{Y,t}}{\hat{\sigma}_{b,Y,t}\cdot\eta_{XY,t}}\right)^{1.2} \le 1$$ where: $$\eta_{XY,t} = 1 - \left(\frac{\tau_{XY,t}}{\hat{\tau}_{B,XY,t}}\right)^2$$ $$k = 0.8\cdot\beta_t^{0.04}$$ $$\beta_t = \frac{b_{b,t}}{t_t}\cdot\sqrt{\frac{\sigma_{y,t}}{E_t}}$$
Local Indentation – Limit Load	Patch Loading	$$P_{\text{limit}} = \begin{cases} 2\cdot\sigma_{y,t}\cdot t_t^2\cdot\frac{c_Y}{b_{b,t}}\cdot\left(2+\frac{c_X}{b_{b,t}}\right), c_Y \le b_{b,t} \\ 2\cdot\sigma_{y,t}\cdot t_t^2\cdot\left(2+\frac{c_X}{b_{b,t}}\right), c_Y > b_{b,t} \end{cases}$$
	Drop of a Sharp Object	$$P_{\text{limit}} = \begin{cases} 0.231\cdot\frac{c_X}{b_{b,t}}\cdot\frac{m_{DNV}\cdot\sigma\cdot(t_t-t_k)^2}{k_w}, c_Y > b_{b,t} \\ 0.231\cdot\frac{c_X}{c_b}\cdot\frac{m_{DNV}\cdot\sigma\cdot(t_t-t_k)^2}{k_w}, c_Y \le b_{b,t} \end{cases}$$ where: $$m_{DNV} = \begin{cases} \frac{38}{\left(\frac{c_Y}{b_{b,t}}\right)^2 - 4.7\cdot\frac{c_Y}{b_{b,t}} + 6.5}, \frac{c_Y}{b_{b,t}} \le 1.0 \\ 13.57, \frac{c_Y}{b_{b,t}} > 1.0 \end{cases}$$ $$\sigma = 235 \le \sigma_y < 265 = 320$$ $$\sigma = 265 \le \sigma_y < 315 = 345$$ $$\sigma = 315 \le \sigma_y < 355 = 409$$ $$\sigma = 355 \le \sigma_y < 390 = 444$$ $$\sigma = 390 \le \sigma_y = 457$$
Local Indentation – Load to Cause Dent	Apply formulations for hybrid panels with metallic stiffeners as described in section 3.1.2.1c.	

where E is Young's modulus, P is point loading, σ_y is yield strength, τ_y is yielding strength in shear, $\hat{\sigma}$ is critical normal buckling stress, $\hat{\tau}$ is critical buckling stress in shear, t is thickness, b_b is the unsupported span of a plate in buckling, h_c is the height of the stiffeners, p is the panel pitch, c_x is the length of a patch load parallel to the stiffeners, and c_y is the breadth of a patch load parallel to the stiffeners. The subscripts employed refer to the following aspects: t to the top plate, c to the core, b to values critical for buckling, *bend* to values related to bending loading, *memb* to values related to membrane loading *plc* to plastic collapse, and *X, Y* and *Z* to the longitudinal, transverse and through-thickness directions of a panel.

Core stiffeners

Core stiffeners are prone to failure by buckling and yielding. Depending upon the loading conditions, the core stiffeners might buckle due to shear, bending, or maybe a combination of the two. In addition, for high local loads such as tyre prints, the core plate might simply plastically collapse as seen in figure 3.1.2.1b-2.

a) b)

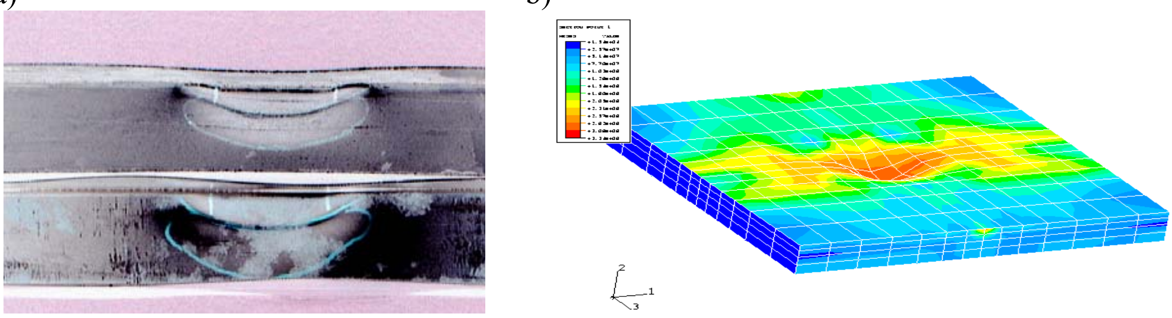


Figure 3.1.2.1b-2 – core web plate plastic collapse: a) inside a panel, b) top view of a damaged sandwich panel predicted numerically.

The following table lists some analytical expressions for predicting the critical loadings of core stiffeners:

Failure mode	Loading Condition	Equations
Elastic Buckling	For the case where the buckling stress is less than half the yield stress ...	
Elastic Buckling	Membrane	Use formulation as for a top faceplate in bending
Elastic Buckling	In Bending	$\hat{\sigma}_{e,c} = 21.6 \cdot E_c \cdot \left(\frac{t_c}{b_{b,c}}\right)^2$
Elastic Buckling	In Shear	$\hat{\tau}_{e,c} = 3.8 \cdot E_c \cdot \left(\frac{t_t}{b_{b,c}}\right)^2$

<table>
<tr><td rowspan="4">Plastic Buckling</td><td colspan="2">For the case where the buckling stress is more than half the yield stress, use the formulations as for a top faceplate</td></tr>
<tr><td>Membrane Compression and shear</td><td>$$\frac{\sigma_{memb,c}}{\hat{\sigma}_{b,c}}+\left(\frac{\tau_c}{\hat{\tau}_{b,c}}\right)^2\le 1$$</td></tr>
<tr><td>Bending and Shear</td><td>$$\left(\frac{\sigma_{bend,c}}{\hat{\sigma}_{b,c}}\right)^2+\left(\frac{\tau_c}{\hat{\tau}_{b,c}}\right)^2\le 1$$</td></tr>
<tr><td>Uni-axial, Bending and Shear</td><td>$$\frac{\sigma_{memb,c}}{\hat{\sigma}_{b,c}}+\left(\frac{\sigma_{bend,c}}{\hat{\sigma}_{b,c}}\right)^2+\left(\frac{\tau_c}{\hat{\tau}_{b,c}}\right)^2\le 1$$</td></tr>
<tr><td rowspan="2">Plastic Collapse of Core</td><td>I-, C-, O- and Z-core Panels</td><td>$$P_{plc}=\frac{1.1\cdot t_c^2\cdot\sqrt{E_c\cdot\sigma_{y,c}}}{k}\cdot\sqrt[4]{\frac{t_t}{t_c}}\cdot\left(1+\frac{c\cdot t_c}{h_c\cdot t_t}\right)\cdot\sqrt{1-\left(\frac{\sigma_{X,t}}{\sigma_{y,c}}\right)^2}$$</td></tr>
<tr><td>V- and Vf-core Panels</td><td>$$P_{plc}=\left(4\cdot\frac{M_t}{\beta}+4\cdot\frac{M_w}{\beta}\cdot\left(\frac{k_1\cdot\beta\cdot c+\frac{M_t}{2\cdot M_w}}{1+k_1\cdot k_3\cdot t_w}\right)\right)\cdot\sqrt{1-\left(\frac{\sigma_{X,t}}{\sigma_{y,w}}\right)^2}$$
where:
$$c=\min\left(c_X,c_Y\right)$$
$$M_t=\frac{\sigma_{y,t}\cdot p\cdot t_t^2}{2}$$
$$M_c=\frac{\sigma_{y,c}\cdot t_c^2}{4}$$
$$I_t=\frac{p\cdot t_t^3}{6}$$
$$k_2=\frac{M_t^2}{12\cdot E\cdot I_t\cdot M_c}$$
$$\phi=\tan^{-1}\left(\frac{2\cdot k_2\cdot\sin^2\theta}{\sin^2\theta-k_2^2}\right)$$
$$k_1=\frac{\sigma_{y,t}}{40\cdot t_c\cdot\sigma_{y,c}}\cdot\frac{\sqrt{\sin^2\theta-\sin^2\phi}}{\sin\phi\cdot\cos\phi}$$
$$\beta=\sqrt{\frac{M_t}{4\cdot M_c\cdot k_1}}$$
$$k_3=\sqrt{\sin^2\theta+\frac{27}{4}\cdot\cos^2\theta}$$</td></tr>
</table>

Bottom faceplate

The bottom faceplate is usually considered to be the one not receiving any lateral (through-thickness) loads. Therefore, the plate might buckle in the case of axial (in-plane) loading, or yield in general. However, if the bottom faceplate is also subjected to lateral loads, then its ultimate strength needs to be assessed in the same manner as for the top faceplate. The buckling and yielding mechanisms of the bottom faceplate will be the same as for the top faceplate.

Global collapse

The global collapse of a panel most often occurs following a significant local failure of the faceplates and/or core. In the case of the total global collapse of a panel, plastic buckling is the dominant failure initiation mechanism, followed by the severe formation of hinges either in the mid-span of the panel, as seen in figure 3.1.2.1b-3, or in the vicinity of joints or other boundary conditions. Reliable analytical methods to evaluate the global collapse of all-metal sandwich panels do not yet exist. It is therefore recommended that numerical methods are employed for such instances.

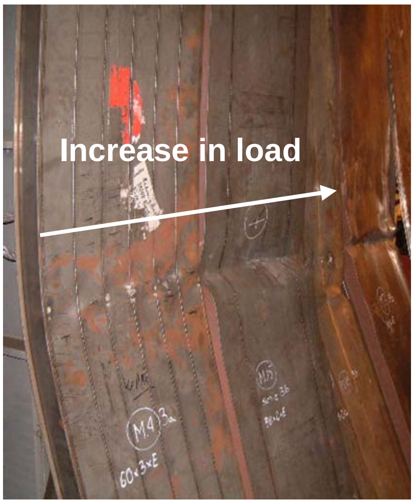


Figure 3.1.2.1b-3 – panel in different stages of collapse.

General remarks

- A designer should be aware that all-metal panels are made up of very thin sheets of material. As such, they are prone to incidental damage that might affect their ultimate strength. Hence, one has to provide sufficient robustness in service and production to assure safety and the proper function of the structure.

- For further information on the presented modes of failure and analytical expressions the reader is urged to refer to the reports by Romanoff & Kujala 2002 and Romanoff & Klanac 2004.

3.1.2.1c. Ultimate Strength of Hybrid Metal Sandwich Structures Under Static Loads: Analytical Methods

Similarly to the approach described in section 3.1.1.1c for the elastic analysis of **hybrid metal** sandwich structures, the methods employed for estimating their **ultimate strength** will depend upon the nature of the construction (as defined in section 2.3):

- **All-metal sandwich, core cavity filled with a non-metallic material** - here the approach will depend upon the relative influence of the filler material. If the filler material is non-structural (e.g. Rockwool insulation), or if the filler is a very low density foam (< 30 kg/m^3), any significant influence on structural performance is unlikely. Consequently, for these cases the methods for all-metal sandwich structures can be employed (section 3.1.2.1b). On the other hand, if the core material does contribute to the overall mechanical performance of the sandwich (e.g. by increasing the shear strength or through-thickness compression strength), then the methods for all-metal sandwich structures are likely to underestimate mechanical performance. The presence of a core filler material may also alter the critical failure modes of a sandwich structure (e.g. by inhibiting certain failure modes such as faceplate wrinkling or local indentation).

- **Metal facings, non-metallic core stiffeners** - for these types of hybrid metal sandwich, the methods outlined in section 3.1.2.1b (ultimate strength of all-metal sandwich structures) can be employed with the substitution of the appropriate core material properties.

- **Metal facings, non-metallic solid core** - in this case, the methods outlined in section 3.1.2.1a (ultimate strength of isotropic facing – isotropic core sandwich structures) can be employed, provided that the core is isotropic.

In light of the above, this section focuses on providing analytical expressions for predicting local failures in all-metal sandwich panels that are filled with a non-metallic material that cannot be considered as structural insignificant.

Top faceplate

Common failure modes for the top faceplate of a hybrid metal sandwich include buckling, yielding, and denting. In addition, in the case of very thin faceplate thicknesses (< 1 mm), wrinkling of the faceplate can take place as a result of the elastic support from the filling material.

The filling material mostly influences the local behaviour of a panel. The magnitude of the local load needed for the development of a dent is increased depending on the nature of the filling. However, an analytical expression for the magnitude of the limit load to initiate plastic deformation has proven difficult to derive. As a result, a proper evaluation of the limit load for filled panels can only be performed on a case by case basis, either through finite element analysis or testing. It should also be noted that the analytical expressions presented in section 3.1.2.1b yield conservative estimates for the limit load.

The following table lists the basic analytical expressions for the determination of critical loadings for the top faceplate of a hybrid metal sandwich:

Failure mode	Loading Condition	Equations
Elastic Buckling*		For the case where the buckling stress is less than half the yield stress ...
	In Bending or in Membrane	$\hat{\sigma}_{e,X,t} = 0,9 \cdot k \cdot E_t \cdot \left(\frac{t_t}{b_{b,t}} \right)^2$ $\hat{\sigma}_{e,Y,t} = 0,9 \cdot k \cdot E_t \cdot \left(\frac{t_t}{b_{b,t}} \right)^2 + 0.82 \cdot E_t \cdot \sqrt{\frac{E_c}{E_t} \cdot \frac{t_t}{h_c}}$
	In Shear	$\hat{\tau}_{e,t} = 4.8 \cdot E_t \cdot \left(\frac{t_t}{b_{b,t}} \right)^2$
		Buckling coefficient, k
	Parallel to the Core Stiffeners	$k = 2 \cdot \left(1 + \sqrt{1 + \kappa}\right)$ where: $\kappa = \frac{12}{\pi^2} \times \frac{k_z \times b_{b,t}}{E_t} \times \left[\frac{b_{b,t}}{t_t} \right]^3$ $k_Z = \max \left[\frac{E_{v,Z}}{h_c}, \quad 0.28 \times E_{v,Z} \sqrt{\frac{E_{v,Z}}{D_t}} \right]$
	Transverse to the Core Stiffeners	$k = 1$

**Elastic buckling cannot strictly be treated as a failure.*

Continued overleaf...

Plastic Buckling	For the case where the buckling stress is more than half the yield stress, use the equations for the top faceplate of an all-metal sandwich as presented in section 3.1.2.1b.	
Wrinkling	Thick Core Criterion	$\left(\frac{t_t}{h_c}\right)\cdot\left(\frac{E_t}{E_{v,Z}}\right)^{1/3} \le 0.21\left(\frac{1}{1+\nu_{v,XZ}}\right)^{2/3}$
	Thin Core	$\hat{\sigma}_{w,t} = 0.82\cdot E_t\sqrt{\frac{E_{v,Z}}{E_t}\cdot\frac{t_t}{h_c}} + 0.387\cdot G_{v,XZ}\cdot\frac{h_c}{t_t}$
	Thick Core	$\hat{\sigma}_{w,t} = 0.5\cdot\left(\frac{E_t\cdot E_{v,Z}\cdot G_{v,XZ}}{1-\nu_t^2}\right)^{1/3}$
Local Indentation – Limit Load	Use the equations for all-metal sandwiches in section 3.1.2.1b, or perform finite element analyses or tests.	
Local Indentation – Load to Cause Dent	Use One Giving Smaller Loads	$P_{dent} = \begin{cases} 2\cdot\sigma_{y,t}\cdot t_t^2\cdot\left(3\cdot\frac{c_X}{b_{b,t}}+2\right)\cdot\frac{\delta}{t_t}, & \frac{\delta}{t_t}\le 1 \\ 8\cdot\sigma_{y,t}\cdot t_t^2\cdot\left(\frac{c_X}{b_{b,t}}+1\right)\cdot\frac{\delta}{t_t}, & \frac{\delta}{t_t}>1 \end{cases}$
		$P_{dent} = k_{sup}\cdot\left[2\cdot\sigma_{y,t}\cdot t_t\cdot\left(\frac{c_X}{b_c}+\frac{c_Y}{a_c}+\frac{\pi}{2}\right)+k_z\cdot\left(c_X\cdot c_Y+a_c\cdot b_c\right)\right]\cdot\delta$ where: $k_{sup}\cong 1$ for O-, Vf- and V-panels $k_{sup} = \frac{1}{1+\frac{2\cdot k_{1,1}}{\left(\frac{B}{2\cdot p}-1\right)\cdot k_{1,2}+\left(\frac{B}{2\cdot p}+1\right)\cdot k_{2,i}}}$ for other panels $k_{1,1} = 2\cdot\frac{E_t\cdot t_t}{2\cdot p}$ $k_{1,2} = \frac{E_t\cdot t_t}{2\cdot p}$ $k_{2,i} = \frac{E_w\cdot t_w^3}{4\cdot h_c^3}$ $k_{2,i} = \frac{k_Y}{\lambda}\cdot\frac{\cosh^2(\lambda\cdot h_c)+\cos^2(\lambda\cdot h_c)}{\sinh(2\cdot\lambda\cdot h_c)-\sin(2\cdot\lambda\cdot h_c)}$ $\lambda = \sqrt[4]{\frac{3\cdot k_Y}{E_w\cdot t_w^3}}$ $a_{min} = \sqrt{8\cdot\frac{\sigma_{y,t}\cdot t_t\cdot c_Y}{k_Z\cdot(L-c_X)}}$ $a_c = \begin{cases} a_{min}, & a_{min}\le\frac{L-c_X}{2} \\ \frac{L-c_X}{2}, & a_{min}\ge\frac{L-c_X}{2} \end{cases}$

		$b_{\min} = \sqrt{8 \cdot \frac{\sigma_{y,t} \cdot t_t \cdot c_X}{k_Y \cdot (b_{b,t} - c_Y)}}$ $b_c = \begin{cases} b_{\min}, & b_{\min} \le \frac{(b_{b,t} - c_Y)}{2} \\ \frac{(b_{b,t} - c_Y)}{2}, & b_{\min} \ge \frac{(b_{b,t} - c_Y)}{2} \end{cases}$

where E is Young's modulus, G is shear modulus, P is point loading, D is stiffness, ν is Poisson's ratio, σ_y is yield strength, $\hat{\sigma}$ is critical normal buckling stress, $\hat{\tau}$ is critical buckling stress in shear, L is panel length, t is thickness, b_b is the unsupported span of a plate in buckling, h_c is the height of the stiffeners, p is the panel pitch, f is the core stiffener overlap distance, g is the gap between core stiffeners, k is the elastic foundation stiffness of the filling material, c_x is the length of a patch load parallel to the stiffeners, c_y is the breadth of a patch load parallel to the stiffeners, and δ is the permanent deflection. The subscripts employed refer to the following aspects: t to the top plate, c to the core, v to the filling material, w to the web stiffeners, plc to plastic collapse, ult to ultimate strength, and X, Y and Z to the longitudinal, transverse and through-thickness directions of a panel.

Core stiffeners

In a hybrid (filled all-metal) sandwich, the core stiffeners are normally supported by the filling material. As a result, their strength is higher than for all-metal panels. The failure modes nevertheless are similar, and in the case of very thin plates, the core stiffener may also buckle. In addition, the filling material itself can fail. In the case where the filling is bonded in place, the material can sustain a shear failure by either yielding (if the material is ductile) or by fracturing in brittle manner.

The following table lists some analytical expressions for predicting the critical loadings of filled core stiffeners:

Failure mode	Condition	Equations
Elastic Buckling		For the case where the buckling stress is less than half the yield stress...
	Membrane	The same expression as given for a top faceplate in bending can be used, but with the foundation modulus, $k_{Z,}$ replaced with: $k_Y = 2 \times \frac{E_{v,Y}}{h_{c,Y}}$ $k_Y = 0.56 \cdot E_{v,Y} \sqrt{\frac{E_{v,Y}}{D_w}}$ accounting for tension and compression of the filling material, where $h_{c,Y}$ is as follows: For I-, C- and Z-core panels: p For O-core panels: $\left(\frac{1}{f - 2 \cdot t_w} + \frac{1}{g} \right)^{-1}$ For V- and Vf-core panels: $\left(\frac{1}{f_b + b_c} + \frac{1}{b_c + 2 \cdot f_t + g} \right)^{-1}$
	In Bending	Same as for all-metal panels (section 3.1.2.1b)
	In Shear	Same as for all-metal panels (section 3.1.2.1b)
Plastic Buckling	For the case where the buckling stress is more than half the yield stress, the equations given for all-metal sandwich panels in section 3.1.2.1b can be used.	
Wrinkling	$\hat{\sigma}_{w,w} = 2 \cdot \hat{\sigma}_{w,t}$	

Continued overleaf...

<table>
<tr><td rowspan="3">Plastic Collapse of Core</td><td>I-, C-, O- and Z-core Panels</td><td>$$P_{plc}=\left[\sigma_{ult,c}\frac{\pi}{12}\left(3c^2+6L_D c+4L_D^2\right)+\frac{h_D^2 k_Y}{3}\left(3c+2L_D\right)\right]\times\sqrt{1-\left(\frac{\sigma_{X,t}}{\sigma_{y,w}}\right)^2}$$
where:
$$L_D=\sqrt{\frac{\sigma_{y,t}^3\cdot g^2\cdot t_t^3\cdot h_D}{2\cdot E_w\cdot\sigma_{y,w}^2\cdot t_w^4}}$$
$$h_{d,1}=20\cdot t_w\cdot\frac{\sigma_{y,w}}{\sigma_{y,t}}$$
$$h_d=\begin{cases}h_{d,1}, h_{d,1}\le\frac{h_c}{2}\\ \frac{h_c}{2}, h_{d,1}>\frac{h_c}{2}\end{cases}$$</td></tr>
<tr><td>V/Vf-core Panels</td><td>$$P_{plc}=\left[\sigma_{ult,c}\frac{\pi}{12}\left(3c^2+6L_D c+4L_D^2\right)+\frac{2h_D^2 k_Y}{3}\left(3c+2L_D\right)\right]\times\sqrt{1-\left(\frac{\sigma_{X,t}}{\sigma_{y,w}}\right)^2}$$</td></tr>
<tr><td>Note</td><td>The filling material provides additional support. Therefore, the critical plastic collapse forces presented here have to be added to those presented for all-metal sandwich panels (section 3.1.2.1b) in order to obtain the total permissible force P_{plc} on core stiffeners.</td></tr>
</table>

Bottom faceplate

The failure criteria for the bottom faceplate of hybrid (filled all-metal) sandwiches are similar to those of all-metal panels. The analytical expressions for the determination of the critical loads given for the top faceplate can also be used in this case.

Global collapse

Global collapse is similar to that of all-metal panels since the effect of the presence of the filling material is local.

3.1.2.1d. Ultimate Strength of Composite Sandwich Structures Under Static Loads: Analytical Methods

Detailed studies of the **ultimate strength** of **composite** sandwich structures using **analytical** approaches are generally not practical. This is because composite sandwich facings tend to be both brittle and layered. Damage therefore usually accumulates in a progressive fashion, which is most effectively studied using numerical techniques (see section 3.1.2.2d). The iterative nature of **progressive damage modelling** makes it too cumbersome for analytical approaches.

However, analytical techniques can be effectively used for preliminary dimensioning purposes. In this case it is recommended that composite facings are treated as single entities with bulk properties (rather than as a series of separate plies). These properties can be obtained from data books or through testing (see sections 3.1.1.3d and 3.1.2.3d). The general guidelines for ultimate strength analysis provided in section 3.1.2.1a can then be applied to obtain a first order estimate of a composite sandwich's limit capacity. The analyst should check both the gross capacity of the facings in bending, and the capacity of the core in shear.

Guidelines on the strength analysis of composite sandwich structures

- Fibre reinforced plastic (FRP) facing laminates are usually stronger under tensile loading than they are under compressive loading. Therefore, the strength performance of a sandwich beam with FRP facings under bending is more likely to be limited by the compressive strength of the facing material than the tensile strength.

- Most analytical expressions assume a strong bond between the facing and the core. However, for some composite sandwich structures, particularly those with lightweight polymer foam cores, a weak core-to-facing bond can be a limiting factor in terms of strength. For example, in bending, the core and the facings might separate before the strength of the facings is reached. To evaluate the strength of the core-to-facing bond, four-point bending or peel tests can be used.

- Caution should be exercised when using manufacturers' or data book material property values relating to strength. These properties are often determined in "ideal" conditions. However, subsequent processing to produce real structures is likely to introduce variations in these properties (e.g. variable resin content or thickness, holes, etc.).

- In practice, failure most commonly occurs at stress concentrations – joints, corners, holes, discontinuities, etc. More detailed analysis (e.g. using numerical methods such as finite element analysis) may be required in the presence of such features.

3.1.2.2. Numerical Methods

3.1.2.2a. Ultimate Strength of Sandwich Structures Under Static Loads: Numerical Methods – General Overview

The **numerical methods** for **ultimate strength** prediction that are presented in this section are applicable to panels with **isotropic facings** and **isotropic cores**. The additional complexities that arise with non-orthotropic cores and facings (e.g. with all-metal and composite sandwich structures) are dealt with in sections 3.1.2.2b, 3.1.2.2c and 3.1.2.2d that follow.

For normal in-service loads, deformations and strains are generally assumed to be small. In such cases, linear theory can be employed. However, for an **ultimate strength** analysis, this premise is not valid. A finite element analysis (FEA) must therefore account for any geometrical non-linearity. Similarly, the constitutive equations must accurately reflect the non-linear material behaviour up to the failure strain.

Constitutive law

For the **metallic** parts of a sandwich, the constitutive law is usually an elastic-plastic material law. Such material laws are well documented. The yield criterion is based on an equivalent stress (normally von Mises). Plastic straining is always perpendicular to the yield surface. Material behaviour may also change with the loading rate. This effect, often referred to as strain rate sensitivity, should be taken into account with transient loads (see, for example, section 3.2 on crashworthiness), but is neglected in this section.

The constitutive law for **polymeric** materials that undergo large deformations is more complex. Some polymers show elastic - nevertheless non-linear - behaviour, i.e. the deformations are fully recoverable if the load is removed. The stress-strain relation is then normally described on the basis of the strain energy potential. This material behaviour is often referred to as **hyperelasticity**. It can be combined with viscoelastic models to address time dependent effects like creep or relaxation. Other materials become plastic, i.e. only a (small) portion of the deformation recovers while some plastic deformation remains. Contrary to the plasticity of metals, the yield condition is not a function of a single stress value (equivalent stress) but has to be described as a function of the three invariants of the stress tensor. In particular, the yielding of foams is very much dependent on the hydrostatic stress. It can also be described in terms of the first invariant of the stress tensor.

The identification of parameters for either of the above mentioned types of constitutive laws can be a complex task. Furthermore, there is no standardised procedure for obtaining these parameters. Generally, it is necessary to have stress strain data from experiments that apply to the different states of material deformation (tension, shear, bi-axial tension, etc.) The parameters of the material law must then be fitted to the experimental results. A consistent set of parameters can be determined by means of least square fit algorithms.

Wrinkling

The ultimate load of a sandwich panel is often governed by buckling or wrinkling of the facings. All-metal sandwich panels in particular are prone to this kind of failure mechanism. Hybrid metal and composite sandwich structures can also show such behaviour when the core material is weak. The ultimate strength analysis is then closely related to a buckling analysis (see section 3.1.2.1b, 3.1.2.2b and 3.1.3.2). Figure 3.1.2.2a-1 shows the buckling of a hybrid metal sandwich with a polymer foam core. One faceplate is subjected to compression and starts buckling.

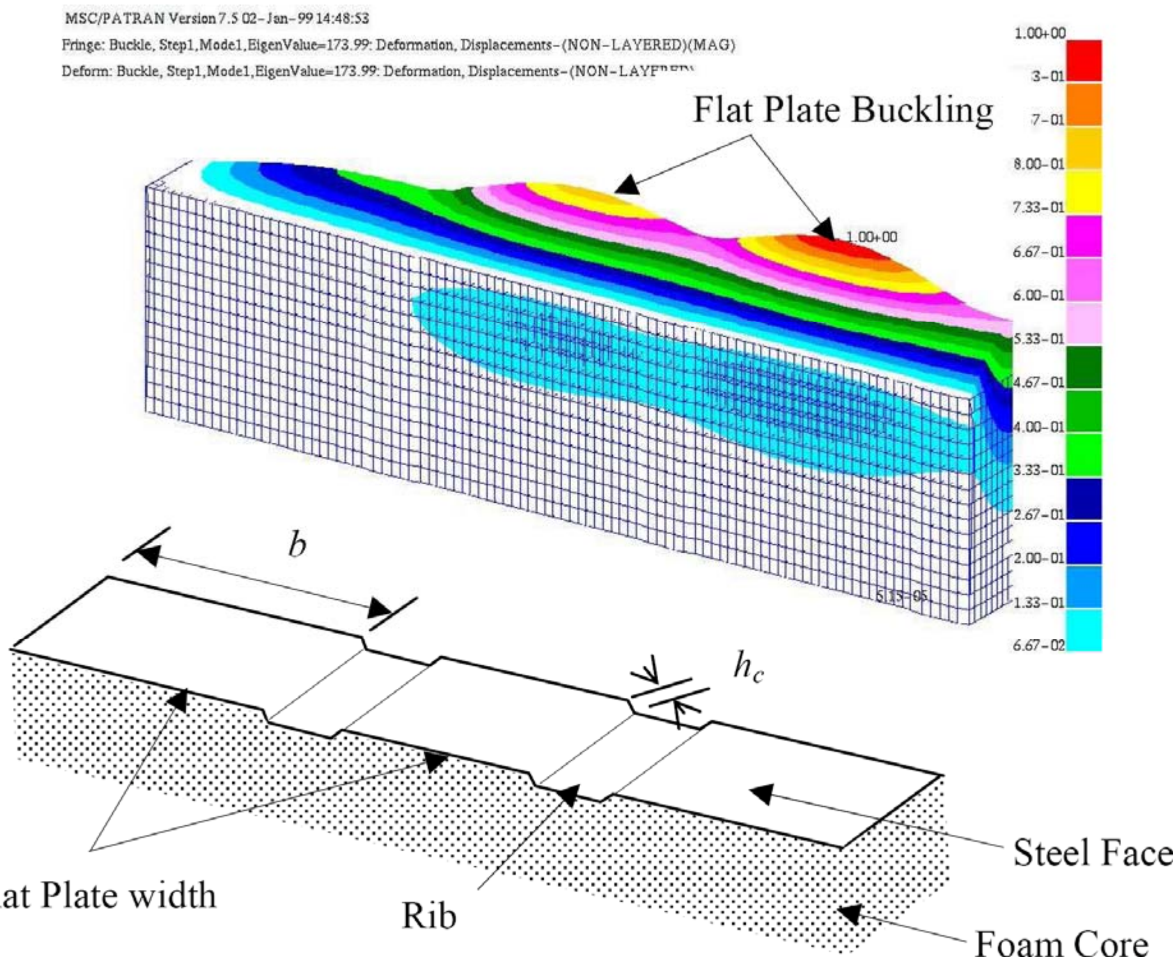


Figure 3.1.2.2a-1 - local buckling and wrinkling of lightly profiled panels (from Pokharel & Mahendran 2005)

Failure criteria

The total collapse of a sandwich structure can also be governed by the formation of cracks. It might therefore be important to establish failure criteria, i.e. states of stress or strain in a finite element at which the material experiences rupture. Clearly different criteria will be necessary for the different materials in a sandwich. Furthermore, a third criterion for the de-bonding of the facings might be reasonable.

In the simplest case, a failure criterion can be defined as a limit value of the equivalent stress or equivalent strain. This is usually not sufficient for polymeric materials. The state of stress (or strain) should rather be divided into a volumetric (hydrostatic stress) and a deviatoric part. The latter is also reasonable for a debonding criterion.

In some finite element codes there are contact algorithms that can be employed for modelling debonding (sometimes referred to as **tie-break contacts** or **adhesive zone elements**). Alternatively, the modelling of debonding can be done through the use of coupled degrees of freedom. Whether the coupling has to be released can be checked after every (sub-) step of the analysis. In this case it is important to use small time steps.

Modelling guidelines

The huge variety of panel types leads to a great number of different failure mechanisms. Many of these are of a local nature. Any finite element model employed should therefore have the necessary level of detail. For example, the use of shell elements for the complete cross section of a panel, as used for linear static analyses (see section 3.1.1.2), is usually not applicable since they do not account for local failure of the faceplates or the core. The finite element model must be capable of predicting all the possible (or at least the most important) failure modes.

There are no general rules on how to model sandwich panels in an ultimate load analysis, but a list of recommendations based on experience is as follows:

- Mind the general rules for modelling structures with finite elements (section 3.1.1.2).

- Make sure that all possible failure modes of the structure can be represented by the finite element model.

- Large strain / large displacement elements should be included in the analysis (geometrical non-linearity)

- Non-linear material behaviour should be included in the analysis. Parameters for elastic - plastic material models for metals are often available in the literature, whereas plastic or hyperelastic parameters for polymeric materials are not always available. Where required, material tests to obtain such parameters should be performed.

- If the ultimate load is governed by some kind of failure mechanism, failure criteria must be included in the finite element model.

3.1.2.2b. Ultimate Strength of All-Metal Sandwich Structures Under Static Loads: Numerical Methods

In spite of its high computational cost for non-linear analyses, finite element analysis is the most accurate method for predicting the **ultimate strength** of an **all-metal** sandwich panel. The collapse of all-metal sandwich panels can be caused by web plate buckling or by yielding of either the faceplates or the core. If a panel has relatively thin faceplates (less than 3 mm thick) a buckling collapse mode is more likely (figure 3.1.2.2b-1). Increasing the faceplate thickness means that the proportional limit of the constituent sandwich material is reached before the onset of elastic buckling. The addition of a filling material into the core cavities has a similar influence.

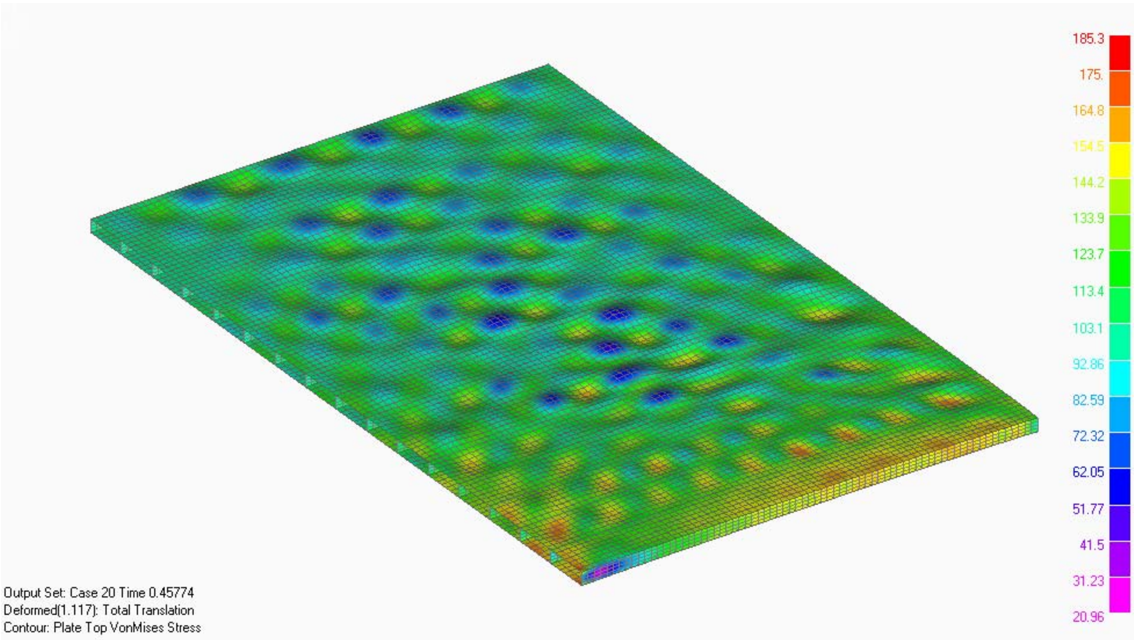


Figure 3.1.2.2b-1 - Von Mises stress plotted for an I-Core panel under a biaxial load.

Modelling requirements

The accuracy of the prediction of the ultimate strength of all-metal sandwich panels will be dependent upon the type of finite elements used to build the model, the mesh density, and the selected non-linear solution search algorithm.

Kolsters & Zenkert 2003 suggest the use of finite strain shell elements (4 nodes) for modelling plates. The use of small strain finite elements (8 nodes) can introduce errors because their thickness doesn't change during the analysis (if global strain is larger than 2%). Furthermore, model preparation can play key role in ultimate strength calculations. A few guidelines an analyst should be aware of when preparing a model are as follows:

- At least four elements should be used to model the characteristic part of the plate (stiffening elements or core element).

- The aspect ratio of elements should not exceed 2.

- When analysing I-Core panels in uni-axial compression, some initial imperfection should be applied to simulate a buckling effect under loading (some commercial finite element solvers do not incorporate this requirement). As an initial deformation field, deformation shapes of an appropriate linear buckling analysis mode are usually applied (Kajaste-Rudnitski & Kujala 2000). The selected amplitude should not exceed 10^{-4} of the panel characteristic length.

- Neglecting the strain hardening behaviour of a material and modelling it as elastic - ideally plastic will provide more conservative estimates of ultimate strength.

Solution search algorithms

Although solution search algorithms vary between finite element software packages, most use the modified Newton-Raphson method and arc-length method for post-buckling analysis (Lee 1992). It is a matter of experience and the characteristics of a particular model when it comes to selecting the search algorithm parameters to obtain convergence at the ultimate strength. In general, a value of *a/1000,* where *a* is a characteristic model length (for example, the distance between stiffening elements), can be taken as a tolerance for displacement convergence. In the case of the Newton-Raphson method or its variants, at least 10 iterations for one load step are suggested. It is also preferable to apply the load in several stages.

Ultimate strength criteria

For certain models in which a sudden loss of structural integrity occurs and the ultimate limit state is reached, it is necessary to define a criteria for ultimate strength. Hughes 2004 suggests that collapse occurs when yield has spread from the middle of the concave faceplate to the mid-length of the unloaded sides of the faceplate (figure 3.1.2.2b-2). In many cases convergence of mathematical models stops when large increments of deformation occur, allowing the modeller to take that load as the ultimate load.

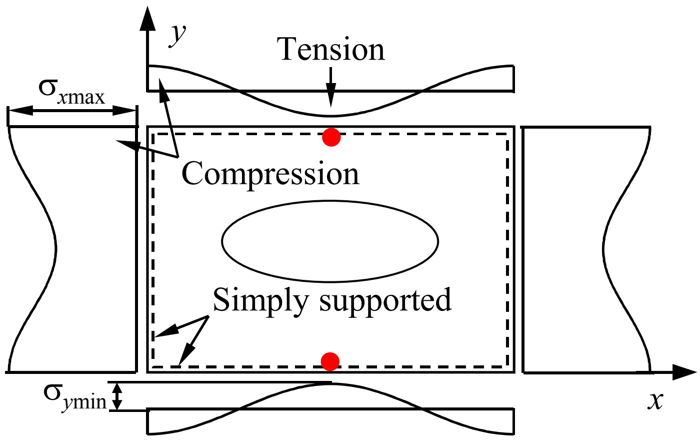


Figure 3.1.2.2b-2 - sandwich panel in compression.

Computational costs

The time needed for one solution increases exponentially with the increase of the number of elemental degrees of freedom. As an example, non-linear analysis calculations of the metal sandwich panel shown in Figure 3.1.2.2b-1 (20,221 nodes and 21,024 elements), using a notebook personal computer and MSC NASTRAN for Windows version 2001, takes about 30 minutes if there is no core filling material. If the whole sandwich panel is modelled with 3D brick elements, then about 12 hours will be needed using the same computer.

3.1.2.2c. Ultimate Strength of Hybrid Metal Sandwich Structures Under Static Loads: Numerical Methods

As discussed previously, **hybrid metal** sandwich structures (section 2.3) are categorised for the purposes of this guide as follows:

- **Type 1** - all-metal sandwich structures in which the core cavities have been filled with a non-metallic material such as a polymer foam.

- **Type 2** – sandwich structures with metal facings and non-metallic core stiffeners.

- **Type 3** – sandwich structures with metal facings and a solid non-metallic core, such as an elastomer.

As the latter has a core with isotropic properties, the information provided in the general overview section (3.1.2.2a) is applicable to this type of sandwich structure.

For information on numerical ultimate strength analyses of sandwich structures of types 1 or 2, the reader is referred to section 3.1.2.2b.

One effect (as mentioned in section 3.1.1.2c) of filling the core cavities of an all-metal sandwich is an increase in shear stiffness perpendicular to the core stiffeners. Furthermore, the filling also provides an elastic foundation for both stiffeners and faceplates. This results in an increased resistance to local buckling and wrinkling. Taking this effect into account requires the implementation of solid element models for the steel panel, including the core filler. Material non-linearity of the filler must also be accounted for.

There are numerous materials that can be used as core fillers and consequently many different material models. Most commercial finite element codes provide material models for foam materials (compressible hyperelastic models). Material behaviour of rubber-like polymers is usually modelled using incompressible hyperelastic models. There are also special material models for (light) concrete.

3.1.2.2d. Ultimate Strength of Composite Sandwich Structures Under Static Loads: Numerical Methods

Numerical strength analyses of **composite material** sandwich structures can be performed in much the same way as outlined in section 3.1.2.2a for general sandwich structures. The only specialist aspect relates to the treatment of strength for the **fibre reinforced plastic (FRP)** facings. For these, a finite element model needs to be capable of capturing the progressive build up of damage that is typical of FRPs (**progressive damage modelling**), as well as the ultimate **brittle fracture**.

The modelling of the core and the core-to-facing bond in composite sandwich structures can be treated in the normal way as described in section 3.1.2.2a.

Ply strength

As for isotropic materials, failure criteria can be used to predict the strength of FRPs. However, because of the layered nature of many FRPs, these criteria are normally applied at the **ply** (lamina) level. So, for example, a unidirectional ply that is aligned at an angle to the loading direction will usually fail before a similar ply that is aligned parallel to the direction of loading. In finite element models of FRP facings, each ply is normally assigned to a through-thickness integration point of an element. Therefore, an element representing an eight-ply laminate will have eight through-thickness integration points.

In terms of specific failure criteria, those that are common for metals, such as von Mises, are generally not appropriate for fibre composites because they do not take into account their inherent anisotropy. Instead there are a number of alternative criteria that have been developed specifically for FRPs. Unfortunately, there are many such criteria, with no universally accepted best approach. Common criteria include the relatively straightforward **maximum stress** and **maximum strain** theories, as well as more complex interactive criteria with multiple stress terms, **Tsai-Hill** being an oft-quoted example. These criteria are presented briefly below, although the interested reader is directed elsewhere for more detailed explanations. Hull & Clyne 1996 and Matthews & Rawlins 1994 both provide good introductions to the subject, whilst Soden et al. 1998 compare the performance of a wide range of current criteria that have been developed by various researchers. Most finite element codes with a composite modelling capability provide at least some of the more common FRP failure criteria.

Maximum stress and maximum strain criteria for ply failure

The **maximum stress criterion** simply states that a ply is considered to have failed if the stresses in any of the principal material directions exceed the corresponding strengths. In mathematical terms, failure occurs if:

$$\sigma_1 \geq \hat{\sigma}_{1T} \quad \text{or} \quad \sigma_1 \geq \hat{\sigma}_{1C} \quad \text{or} \quad \sigma_2 \geq \hat{\sigma}_{2T} \quad \text{or} \quad \sigma_2 \geq \hat{\sigma}_{2T} \quad \text{or} \quad \tau_{12} \geq \hat{\tau}_{12}$$

(equations 3.1.2.2d-1)

where σ and τ are the direct and shear stresses respectively in the lamina, $\hat{\sigma}$ and $\hat{\tau}$ are the corresponding lamina strengths, subscripts *1* and *2* denote the principal material directions (e.g. parallel and perpendicular to the fibre direction in a unidirectional lamina), and subscripts *T* and *C* denote the tensile and compressive loading directions respectively.

The **maximum strain criterion** is directly equivalent to the above, but with strain (ε, γ) substituted for stress (σ, τ).

Tsai-Hill criterion for ply failure

The **Tsai-Hill** criterion for ply failure attempts to accommodate multi-axial stress states by including interactive components. Tsai-Hill predicts failure if:

$$\left(\frac{\sigma_1}{\hat{\sigma}_1}\right)^2 - \frac{\sigma_1\sigma_2}{\hat{\sigma}_1{}^2} + \left(\frac{\sigma_2}{\hat{\sigma}_2}\right)^2 + \left(\frac{\tau_{12}}{\hat{\tau}_{12}}\right)^2 \geq 1 \qquad \textit{(equation 3.1.2.2d-2)}$$

where the terms in the Tsai-Hill equation are the same as those defined for the maximum stress criterion above. The strength values used in the Tsai-Hill expression are selected according to the nature of the loading. So, for example, if stress σ_1 is tensile, $\hat{\sigma}_{1T}$ is used for the corresponding strength.

Strength of laminates (progressive damage modelling)

All of the criteria outlined above are applied at a ply level. To determine the strength of an overall facing laminate, the combined effect of the ply-level stresses needs to be considered. A multi-ply laminate, in which the individual plies have different orientations, will generally accumulate damage in a progressive manner. Some plies (e.g. those with the fibres aligned transversely to the loading direction) are likely to reach their limiting stresses before others (e.g. those with the fibres aligned parallel to the loading direction). Plies that are deemed to have failed (according to whatever strength criterion is being used) typically have their stiffness properties reduced. The level of reduction is somewhat arbitrary and generally dependent on the specific fibre-matrix combination. However, a reduction of 50% – 100% would be typical. The loss of stiffness in the failed ply must of course be accommodated by the remaining non-failed laminae. Therefore, an iterative approach to stiffness and strength predictions is adopted by recalculating to include the reduced properties of the failed ply. This continues until all plies are deemed to have failed, which defines the ultimate strength of the laminate. It is the iterative nature of this process that makes the strength prediction of composites much better suited to numerical approaches than analytical approaches (section 3.1.2.1d).

Brittle fracture

When all the plies in an FRP facing laminate are deemed to have failed, the result will normally be brittle fracture. This is usually simulated in finite element models through the deletion of failed elements. Brittle fracture and its implementation in finite element codes is discussed in more detail in section 3.2.3 – “crash / impact response of composite sandwich structures”.

Guidelines on the numerical strength analysis of composite sandwich structures

- Assuming that the cores and facings of a composite sandwich are meshed as distinct entities, specialist failure criteria (as outlined in this section), coupled to progressive damage modelling, need to be employed for FRP facings. Cores and the core-to-facing bond can be handled as described in Section 3.1.2.2a.

- By assigning one through-thickness integration point to each facing ply, the scale of a composite finite element analysis can easily get quite large, leading to long solution times. For simplified, quicker analyses in which, for example, the entire sandwich construction (core and facings) are represented by a common element, specialist FRP failure criteria are less relevant. In these instances failure may have to be determined by comparing the predicted stresses in the sandwich against experimental failure data.

- Ply-to-ply delamination can be very difficult to model efficiently. Theoretically, interface elements or tie-break contacts such as those used to model core-to-facing bonds (section 3.1.2.2a) can be used, but the computational cost is likely to be massive. Alternatively, some finite element codes (e.g. LUSAS) have developed alternative delamination modelling techniques based on energy approaches.

3.1.2.3. Test Data

3.1.2.3b. Ultimate Strength Test Data for All-Metal Sandwich Structures Under Static Loads

This section provides some typical **ultimate strength test data** for the large scale bending of **all-metal** sandwich structures. The same nomenclature that was defined in section 3.1.1.3b is employed. All the panels described here are steel I-Core constructions. Data for three different core geometries is provided:

- Stiffener height = 20 mm, facing thickness = 2 mm (20x2xE).

- Stiffener height = 40 mm, facing thickness = 1 mm (40x1xE).

- Stiffener height = 60 mm, facing thickness = 2 mm (60x2xE).

All the panels were simply supported along their shorter edges and subjected to a central point loading (figure 3.1.2.3b-1). A photograph of a specimen undergoing testing is shown in figure 3.1.2.3b-2. For further details of the specimen geometry and testing configurations, the reader is referred to section 3.1.1.3b.

Figure 3.1.2.3b-1 – specimen support and loading conditions for the ultimate strength testing.

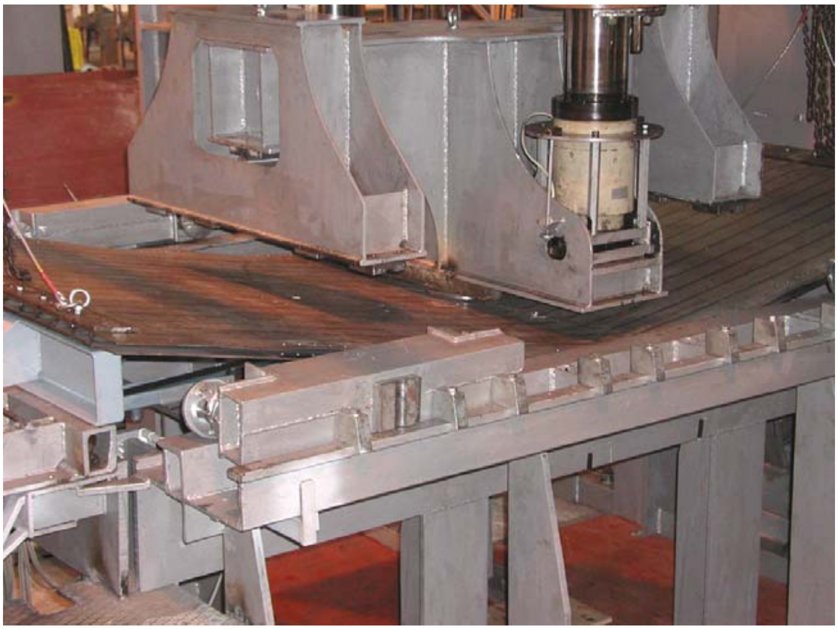


Figure 3.1.2.3b-2 – specimen under test.

Some typical test results are presented in figure 3.1.2.3b-3. A photograph of failed specimen following testing is shown in figure 3.1.2.3b-4.

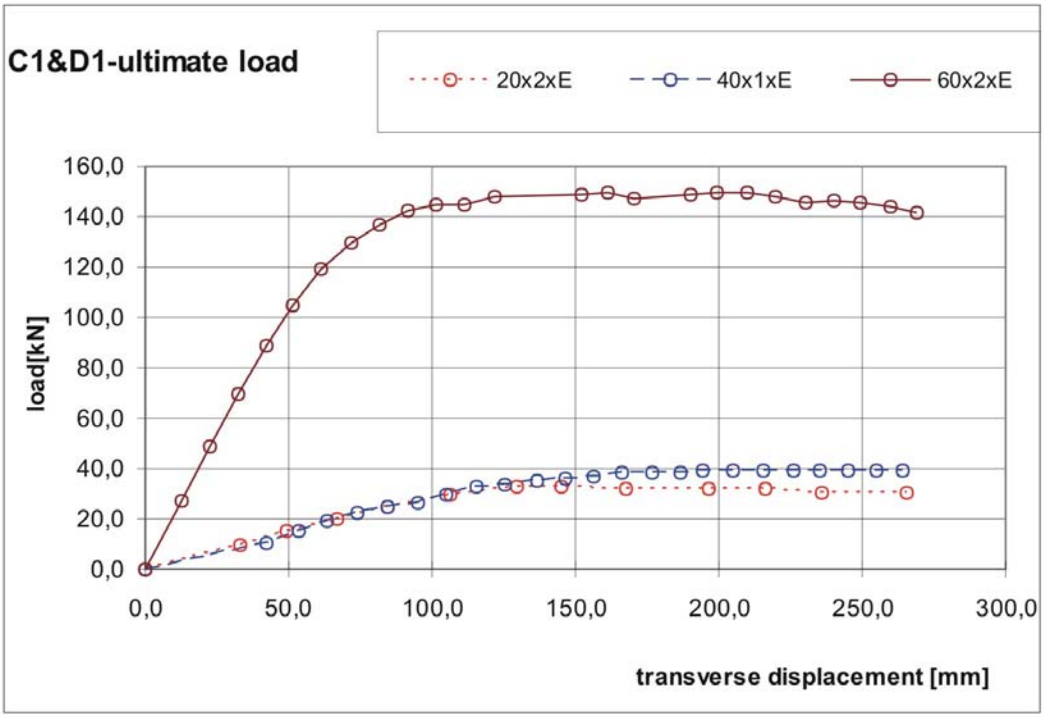


Figure 3.1.2.3b-3 – I-Core panels, central point load, short edges simply supported.

Figure 3.1.2.3b-4 – I-Core panel following testing showing mode of failure.

Guidelines and lessons learned

- The tests indicate that the failure mechanisms of steel sandwich structures under bending are dependent upon the geometrical properties of the panel cross-section.

Failure typically initiates through a loss of stability of the compressed facing in the middle of the panel. However, the extent of the damage, as well as the nature of the buckling of the compressed facing, is strongly influenced by the height of the core stiffeners and the facing thickness.

- The tests also reveal that, independent of any particular differences in the geometrical properties of the panels, steel sandwich structures provide a very high margin of load carrying capacity at the level of the maximum collapse force. From figure 3.1.2.3b-3, it can be seen that the total deflection at the point of ultimate failure is almost eight times higher than the deflection at the end of the linear response of the structure. Between the end of the linear region and the point of ultimate collapse, the load is maintained at a nearly constant level.

3.1.2.3c. Ultimate Strength Test Data for Hybrid Metal Sandwich Structures Under Static Loads

Similarly to section 3.1.2.3b (above), this section presents some **ultimate strength test data** for **hybrid metal** sandwich structures. The specimen loading and support configuration employed was exactly the same as that described in section 3.1.2.3b (figure 3.1.2.3b-1). Figure 3.1.2.3c-1 presents data for seven panel types, all based on filled steel I-Core constructions:

- Stiffener height = 20 mm, facing thickness = 1 mm, low density polyurethane foam filling (20x1xL).
- Stiffener height = 20 mm, facing thickness = 2 mm, high density balsa wood filling (20x2xH).
- Stiffener height = 20 mm, facing thickness = 3 mm, low density polyurethane foam filling (20x3xL).
- Stiffener height = 40 mm, facing thickness = 1 mm, high density balsa wood filling (40x1xH).
- Stiffener height = 60 mm, facing thickness = 1 mm, low density polyurethane foam filling, (60x1xL).
- Stiffener height = 60 mm, facing thickness = 2 mm, high density balsa wood filling, (60x2xH).

- Stiffener height = 60 mm, facing thickness = 3 mm, low density polyurethane foam filling, (60x3xL).

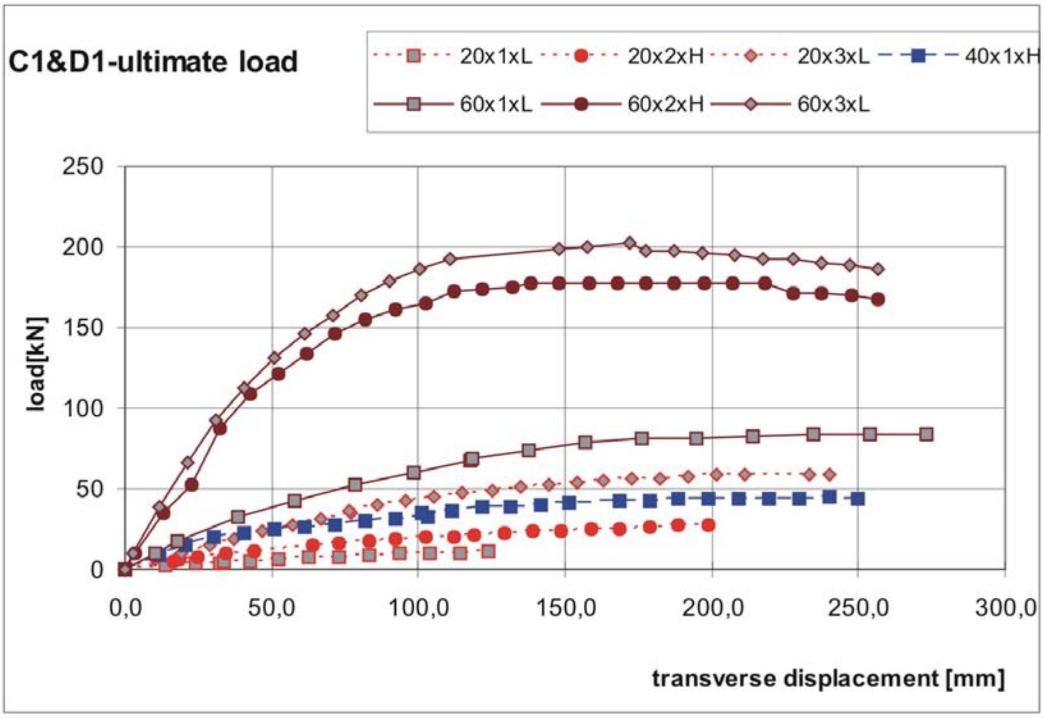


Figure 3.1.2.3c-1 – Filled I-Core panels, central point load, short edges simply supported.

3.1.2.3d. Ultimate Strength Test Data for Composite Sandwich Structures Under Static Loads

This section lists typical data concerning the **limiting stress and strain** of materials used in **composite** sandwich structures. It also suggests further reading relating to the direct determination of such properties for specific applications. Furthermore, guidance is given to whole structure testing.

Generally, the data required for the **ultimate strength** evaluation of **composite** sandwich structures consists of the limiting values of in-plane, through-thickness, interlaminar and intralaminar stresses and strains. Some key data is listed in the tables that follow. Other data can be found in industry data books or classic texts (e.g. Hancox & Mayer 1994 and Shenoi & Wellicome 1993).

Typical properties of thermosetting resins

Material	Tensile Strength (MPa)	Tensile Failure Strain (%)	Compressive Strength (MPa)
Polyester (orthophthalic)	65	2	130
Polyester (isophthalic)	60	2.5	130
Vinyl ester (Derakene 411-45)	83	5	120
Epoxy	85	5	130
Phenolic	50	2	

Typical properties of reinforcing fibres

Material	Tensile Strength (GPa)	Failure Strain (%)
E-glass	2.4	3.0
S-glass	3.4	3.5
High strength carbon	4.1	1.4
High modulus carbon	2.2	0.3
Aramid (Kevlar)	2.8	2.5

Typical properties of fibre reinforced laminates (sandwich facing materials)*

Material	Tensile Strength (MPa)	Compressive Strength (MPa)	Shear Strength (MPa)
E-glass - polyester (chopped strand mat)	100	140	75
E-glass - polyester (balanced woven roving)	250	210	100
E-glass - polyester (unidirectional fibres)	750	600	
Carbon - epoxy (high strength, balanced fabric)	360	300	110
Carbon - epoxy (high strength, unidirectional fibres)	1500	1300	
Aramid - epoxy (unidirectional fibres)	1600	230	

** Note that the properties are illustrative only. They are dependent on fibre volume ratios. Note also that, on occasion, the properties of individual laminae (as opposed to laminates) may be required. For unidirectional laminates, the properties in the transverse direction are governed by resin properties; as a conservative assumption, it is not unreasonable to take the resin modulus or the resin strength as a first estimate for the transverse properties of a unidirectional laminate.*

Typical properties of sandwich core materials

Material	Shear Strength (MPa)	Through-Thickness Compressive Strength (MPa)
PVC foam*	0.8-2.4	1.1-4.0
End grain balsa*	1.4-2.5	6-13
Aluminium honeycomb**	2.2/1.4	9.8
GRP honeycomb**	2.3/1.4	5.7
Nomex honeycomb**	1.7/1.0	3.9

** The ranges reflect a range of densities of the core, from about 80 kg/m^3 to 200 kg/m^3.*
*** Pairs of numbers refer to the longitudinal and transverse directions of a hexagonal honeycomb.*

For further guidance on the determination and application of material property data for composite sandwich structures, see section 3.1.1.3d.

Example test approach

One example of the manner and purpose of testing to determine the ultimate limits of a composite sandwich is described by Davies et al. 2003. Figure 3.1.2.3d-1 illustrates the possible failure modes for stiffened composite sandwich panels under transverse load conditions. The grid is employed by the experimenters to serve as a base for optical measurements of strains. (a) illustrates the stiffener debonding from the base panel, (b) shows a facing failure, (c) shows excessive distortion of the core and (d) shows a core shear fracture leading to a facing-core de-bond.

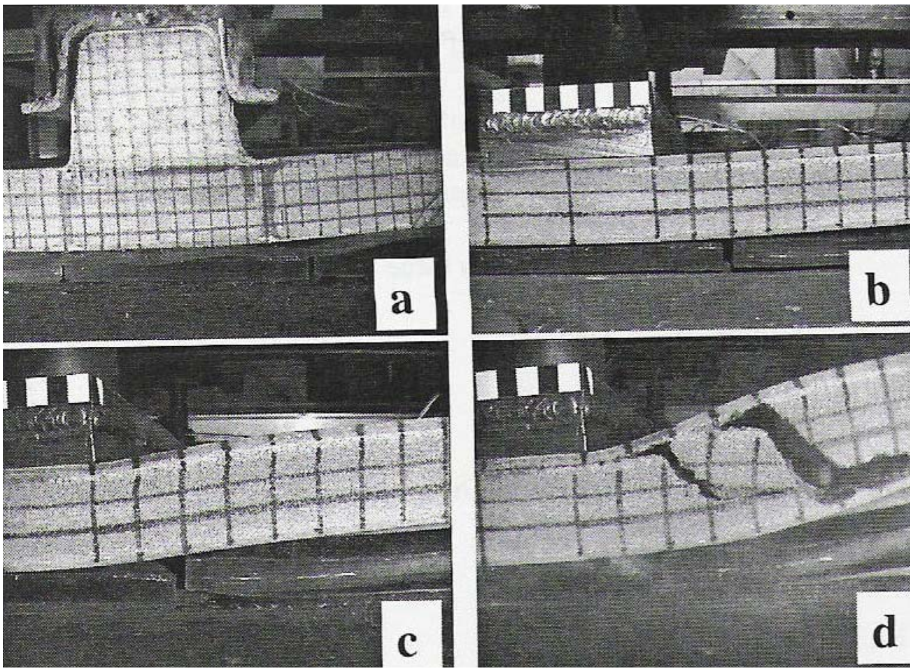


Figure 3.1.2.3d-1 – Ultimate strength testing of a stiffened composite sandwich panel.

It is important to note that in many instances of composite sandwich behaviour, the dominant failure is initiated by a mechanism of combined shear and compression in the core. This is commonly neglected in finite element studies and often ignored in test data generation. Davies et al. 2003 showed how it is possible to evaluate compression behaviour in foam cores - see figure 3.1.2.3d-2. The displacement contours are used to ascertain axial strains and lateral Poisson effects.

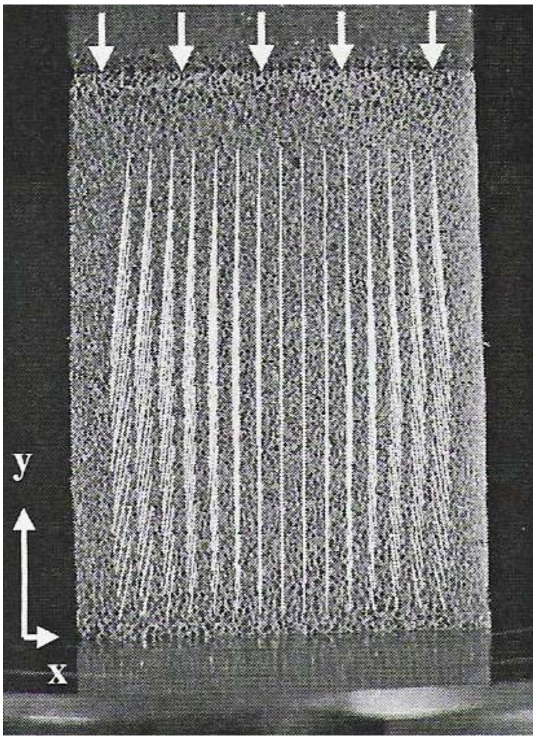


Figure 3.1.2.3d-2 – displacement contours of a foam core without rigid body movement.

3.1.3. Buckling

3.1.3.1. Buckling of Sandwich Structures: Analytical Methods

Analytical methods for evaluating the **buckling strength** of sandwich panels can be divided into two groups: those that investigate **overall (global) buckling**, and those that consider the different types of **local buckling** modes. The analytical formulae used for calculating the buckling strength of sandwich panels find their origins in the basic theories of elasticity (beam column and plate theory):

- The **overall** buckling strength of a sandwich panel is estimated by either modelling it as a beam column with its length and cross sectional characteristics as variables, or by analysing it as an orthotropic plate with equivalent bending and shear stiffnesses.

- The **local** buckling strength of a sandwich panel is estimated by analysing each component of the sandwich panel (faceplates and core) separately, taking into account local boundary conditions and core-to-faceplate interactions.

In this section, analytical formulae for estimating the buckling strength of different types of sandwich panels are provided.

3.1.3.1a. Overall Buckling

A sandwich panel with an aspect ratio *a/b>4 (*where *a* is the panel length and *b* is the panel width) and with free unloaded edges can be treated as a **beam column**. The critical overall elastic buckling load can then be estimated using the following formula (Romanoff & Klanac 2004):

$$N_x = \frac{\dfrac{n^2\pi^2 D_{11}}{k^2 a^2}}{1+\dfrac{n^2\pi^2 D_{11}}{D_{12}k^2a^2}} \qquad \textit{(equation 3.1.3.1-1)}$$

where:

N_x = critical buckling load in *x* direction.
k = buckling coefficient for appropriate load combination and boundary conditions (k = 1 for both ends simply supported; k = 2 for one end clamped and other end free; k = 0.5 for both ends clamped; k = 0.7 for one end simply supported and other end clamped).
a = length of panel.
n = number of half wave length.
D_{ij} = elements of flexural stiffness matrix (for composite sandwich panels calculated using classical laminate theory – see section 3.1.1.1d).

If a sandwich panel has a small aspect ratio and/or it has all edges loaded or restrained, then it should be treated as an **orthotropic plate**. The critical overall elastic buckling strength of such panels can be calculated using the following formula (ESDU Report No. 80023 1995):

$$N_x = K_0 \frac{\sqrt{D_{11}D_{22}}}{b^2} + \frac{C\pi^2 D_0}{b^2} \qquad \textit{(equation 3.1.3.1-2)}$$

where:

- N_x = critical buckling load in x direction.
- K_0 = buckling coefficient for appropriate load combination and boundary conditions (see figure 3.1.3.1-1).
- C = coefficient depending on type of support (C = 2.0 for sides simply-supported; C = 2.46 for clamped sides).
- a = length of panel.
- b = width of panel.
- D_{ij} = elements of flexural stiffness matrix (for composite sandwich panels calculated using classical laminate theory).
- D_0 = $D_{12} + 2D_{33}$

The flexural stiffness matrix for orthotropic **all-metal** sandwich panels can be calculated using the following formula:

$$D_{ij} = \begin{bmatrix} \dfrac{EI_1 h^3}{12a\left(1-\nu^2\right)} & \dfrac{\nu EI_1 h^3}{12a\left(1-\nu^2\right)} & 0 \\ \dfrac{\nu EI_1 h^3}{12a\left(1-\nu^2\right)} & \dfrac{EI_2 h^3}{12b\left(1-\nu^2\right)} & 0 \\ 0 & 0 & \dfrac{\nu E h^2 t}{2\left(1+\nu\right)} \end{bmatrix} \qquad \text{(equation 3.1.3.1-3)}$$

where:

- E = Young's modulus of faceplates and core material.
- t = equivalent thickness = $t = \left(2t_t t_b\right)/\left(t_t + t_b\right)$, where t_t = thickness of top faceplate and t_b = thickness of bottom faceplate.
- I_1 = moment of inertia about longitudinal axis.
- I_2 = moment of inertia about transverse axis.

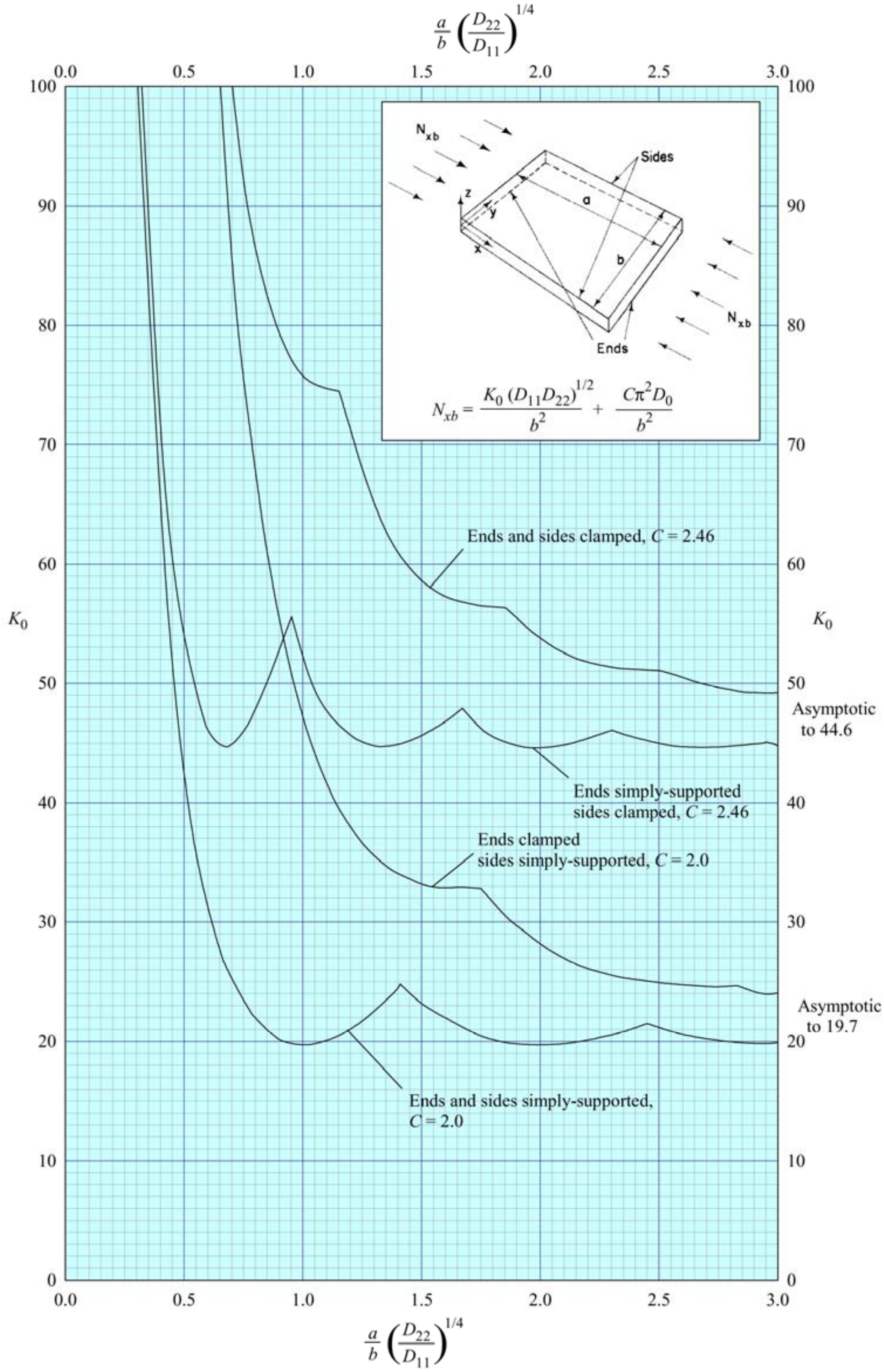


Figure 3.1.3.1-1 - buckling coefficient for an orthotropic plate.

3.1.3.1b. Local Buckling

Local buckling in **metal** sandwich panels, irrespective of whether they are filled or not, can occur in the top faceplate, the bottom faceplate, or within the core plate. Here the most commonly used formula for predicting the critical local buckling stress is presented. It is based on the "equivalent plate segment" that can be found between the stiffening elements and the stiffening elements themselves.

Buckling in the top faceplate, bottom faceplate and core plate can be caused by loads parallel or perpendicular to the core direction. Also, a shear load in the plane of the top (or bottom) faceplate and a combination of the previous load cases can cause localised buckling.

If the load is **parallel to the core direction**, the critical buckling stress of the top faceplate can be calculated according to the following formula (DNV, Pt. 3, Ch. 1, Sec. 14, 2002):

$$\sigma_{crit} = \begin{Bmatrix} \sigma_e = 0.9kE\left(\frac{t}{b}\right)^2, \cdots \frac{\sigma_e}{\sigma_0} \leq 0.5 \\ \sigma_0 - \frac{\sigma_0^2}{4\sigma_e}, \cdots \frac{\sigma_e}{\sigma_0} > 0.5 \end{Bmatrix} \qquad \textit{(equation 3.1.3.1-4)}$$

where:

- σ_{crit} = critical buckling stress.
- σ_e = elastic buckling stress.
- σ_0 = plate material yield stress.
- k = buckling coefficient (taking k = 4 gives the lowest (most conservative) critical buckling stress).
- E = Young's modulus of plate material (for composite panels calculated using classical laminate theory).
- t = plate thickness.
- b = width of plates between two core elements.

If the in-plane load is perpendicular to the core direction, the influence of any core filling can be taken into account using the following formula (Romanoff & Klanac 2004):

$$\sigma_e = 0.9kE\left(\frac{t}{b}\right)^2 + 0.82E\sqrt{\frac{E_c}{E}\frac{t}{h}} \qquad \textit{(equation 3.1.3.1-5)}$$

where:

- E_c = Young's modulus of homogenised core.
- h = core height.

In the case of an unfilled I-Core panel, the Young's modulus for the homogenised core is given by the following formula (Romanoff & Klanac 2004):

$$E_c = \frac{t_w}{2p} E_w \qquad \textit{(equation 3.1.3.1-6)}$$

where:

$E_w =$ Young's modulus of web plate.
$p =$ spacing between webs.

In case of combined loading, an interaction formula is used. See, for example, DNV, Pt. 3, Ch. 1, Sec. 14, 2002.

3.1.3.1c. Guidelines on the Buckling Analysis of Sandwich Structures under Static Loads: Analytical Methods

- When evaluating the overall buckling strength of sandwich panels, beam theory should be applied for slender structures (length-to-width ratio greater than 4) and plate theory for others.

- Applying simply supported boundary conditions for a local buckling analysis of a sandwich structure will give a lower predicted critical buckling stress (i.e. a conservative estimate).

- The formulae presented in this chapter do not take into account the quality of any joints (e.g. welds in laser-welded panels, adhesive bonds in hybrid and composite panels, or the delamination behaviour of composite sandwich structures).

3.1.3.2. Buckling of Sandwich Structures: Numerical methods

This section describes a methodology for analysing the **buckling mode shape and associated buckling load** of sandwich plates and columns under in-plane loads by means of **finite element analysis** (FEA).

Two techniques are available within the finite element method for predicting the buckling load and buckling mode shape of a structure: **non-linear buckling analysis** and **eigenvalue (or linear) buckling analysis**. As the name implies, the latter formulates an eigenvalue problem in which the eigenvalue is the buckling load and the associated eigenvector describes the mode shape. Non-linear buckling analysis is simply a non-linear static analysis and is usually the more accurate approach since initial imperfections (and lateral loads), non-linear material behaviour, and large deflection response can be included. However, the computational cost of a non-linear analysis is much higher. This should be considered when choosing one approach over the other. Furthermore, the choice of element types should be carefully considered with respect to the possible mode shapes.

3.1.3.2a. Mode Shapes

Just like elastic bending deflections, the global mode shapes under buckling are dependent on both the bending rigidity of the panel and the shear rigidity of the core. As the core gets weaker (i.e. E_c gets lower), or the slenderness of the beam (or plate) decreases, the shear deformation becomes more dominant in the mode shape as shown by the examples in figure 3.1.3.2-1.

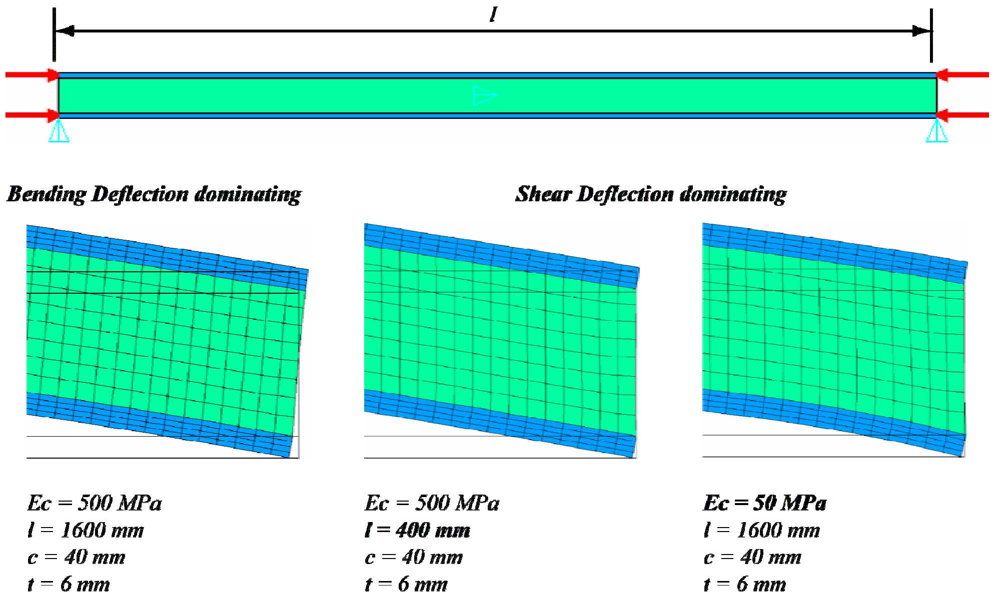


Figure 3.1.3.2-1 – comparison of the mode shapes of three sandwich columns, simply supported at both ends, under axial compression.

Besides the fact that sandwich panels can exhibit significant shear deformation, their global mode shapes are more or less what would be expected from conventional beams or columns. Furthermore, there might be other mode shapes of a more local nature. If the core is very weak, or if there is no continuous support for the faceplates (as in all-steel or honeycomb-cored sandwiches), local buckling of the faceplates can occur (see figure 3.5.1.2-2).

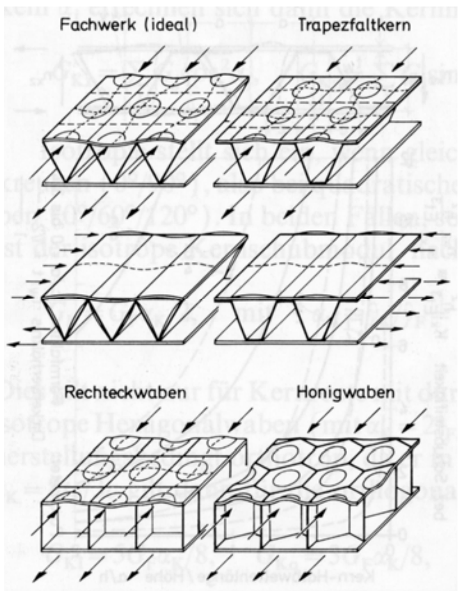


Figure 3.1.2.2-2 - local buckling deformation of sandwich faceplates (from: Wiedemann 1986).

3.1.3.2b. Element Types

If the buckling load corresponds to a global mode shape, it is usually sufficient to perform the modelling with shell elements representing the entire sandwich section. The choice of shell element will depend upon the nature of the sandwich (see section 3.1.1.2a).

In those cases where local buckling might occur, the faceplates and core (or stiffeners) must be modelled individually. This can be done with either solid elements (as in figure 3.1.3.2-1), or with shell elements as shown in figure 3.1.3.2-3.

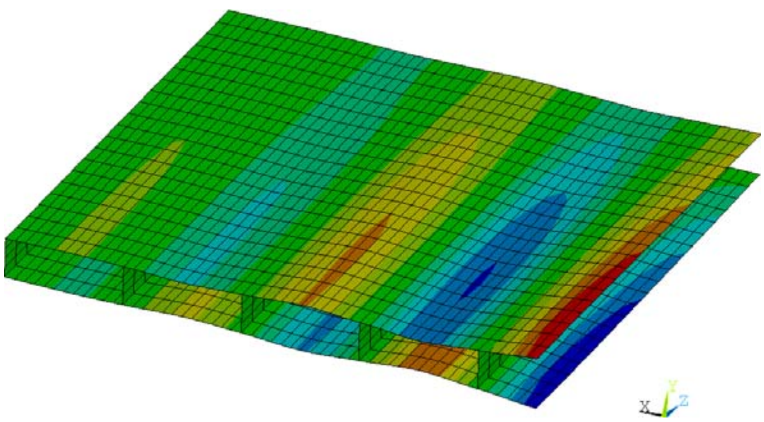


Figure 3.1.3.2-3 - FEA local buckling model of a sandwich panel constructed with shell elements.

3.1.3.2c. Effect of Plasticity

Due to the support of the faceplates by the core, the buckling load of a sandwich panel is often beyond the yield limit of the faceplates. In these cases, the ultimate buckling load can be significantly overestimated by eigenbuckling analyses and, therefore, non-linear buckling analysis should be used. As an example, the axial load versus elongation of a sandwich column (both sides clamped) is shown in Figure 3.1.3.2-4a. The blue and the red lines represent the results from an eigenbuckling analysis and a geometrically non-linear (but materially linear) analysis respectively. They yield almost the same buckling load. The green line represents a non-linear analysis in which the effect of plasticity has been included. In figure 3.1.3.2-4b it can be seen that the plasticity results in some local buckling (wrinkling) of the upper faceplate. The actual buckling load is less than 70% of the linear result.

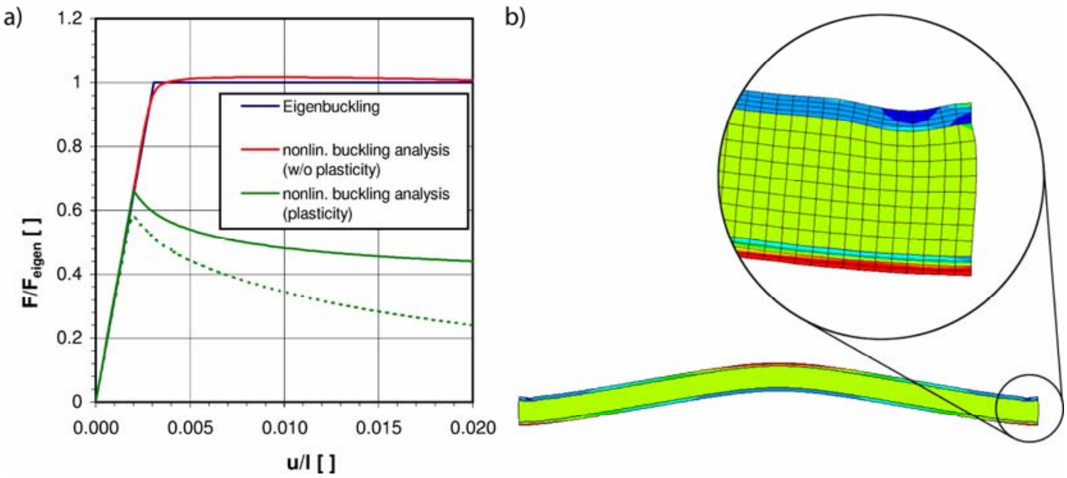


Figure 3.1.3.2-4 - a) plot of axial load vs. elongation of a sandwich column, b) deformation plot showing local faceplate buckling (wrinkling).

3.1.3.2d. Imperfections, Lateral Loads and Failure

Imperfections and/or lateral loads prevent most real-world structures from achieving their theoretical buckling strength. Non-linear buckling analyses can account for these effects. Often imperfections are assumed to be of the same shape as the first mode achieved from an eigenbuckling analysis. The "amplitude" of the imperfection should be chosen according to manufacturing standards.

The continuous and the dotted green lines in Figure 3.1.3.2-4a show the load-deflection curves for two sandwich columns with imperfection amplitudes of approximately 1/100th and 1/25th of the thickness respectively.

Bond failures between cores and faceplates, or rupture of the core, can also reduce the buckling strength of a sandwich. These effects are not discussed in this section. The reader is referred to the section 3.1.2.2a – “numerical methods for strength prediction”.

3.1.3.2e. Guidelines on the Numerical Buckling Analysis of Sandwich Structures

- An appropriate modelling approach should be chosen such that it covers all the relevant mode shapes of the structure. Very weak core materials or discontinuous cores often result in local buckling (wrinkling) of the faceplates. In these cases, the faceplates and the core should be modelled individually.

- If shell elements are used to represent the whole sandwich section, the analyst should be certain that the element formulation accommodates any bending and shear deflections (see section 3.1.1.2a).

- Sometimes buckling loads are beyond the yield limit of the faceplates. Non-linear buckling approaches should therefore be used to account for plasticity effects. Eigenbuckling analyses may overestimate the ultimate load significantly.

- Initial imperfections and lateral loads may also reduce the buckling load significantly. These effects can only be accounted for by using non-linear analyses.

3.1.3.3. Buckling of Sandwich Structures: Test Data

This section describes **in-plane compression tests** of large **all-metal** and **hybrid metal** sandwich panels. The panels have areal dimensions of 3000 mm x 500 mm. Two panel types, **I-Core** and **V-Core**, are reported with the following variations in parameters:

I-Core (i.e. stiffeners perpendicular to the facings):

- Faceplate thickness = 1 mm and 3 mm.

- Stiffener height = 20 mm and 60 mm.

- Core filling = empty and filled with a high density balsa wood.

V-core (i.e. corrugated stiffeners):

- Faceplate thickness = 1 mm and 2 mm.
- Stiffener height = 20 mm and 60 mm.
- Core filling -= empty and filled with a low density polyurethane foam.

For further information on the panel configurations, please refer to section 3.1.1.3b.

Figures 3.1.3.3-1 – 3.1.3.3-4 below show some typical test results. The data shows the relationship between the nominal stresses created by in-plane loading (calculated as load per area of the compressed section) and the longitudinal displacement between the ends of the specimen in the direction of the applied loading. The test specimen nomenclature used is the same as that employed for other panel test data in this guide, i.e:

stiffener height (mm) x facing thickness (mm) x
[E (empty) or L (low density filling) or H (high density filling)]

So, for example, a panel designated 20x1xH had a stiffener height of 20 mm, a facing thickness of 1 mm, and the core had a high density (balsa wood) filling.

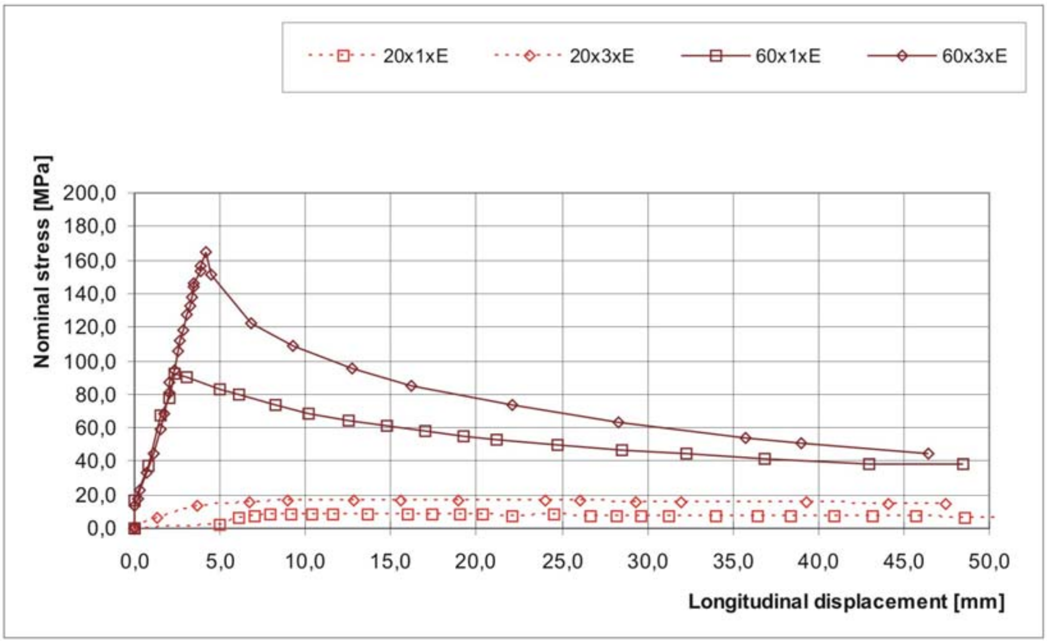


Figure 3.1.3.3–1 – all-metal I-Core panels under in-plane compression.

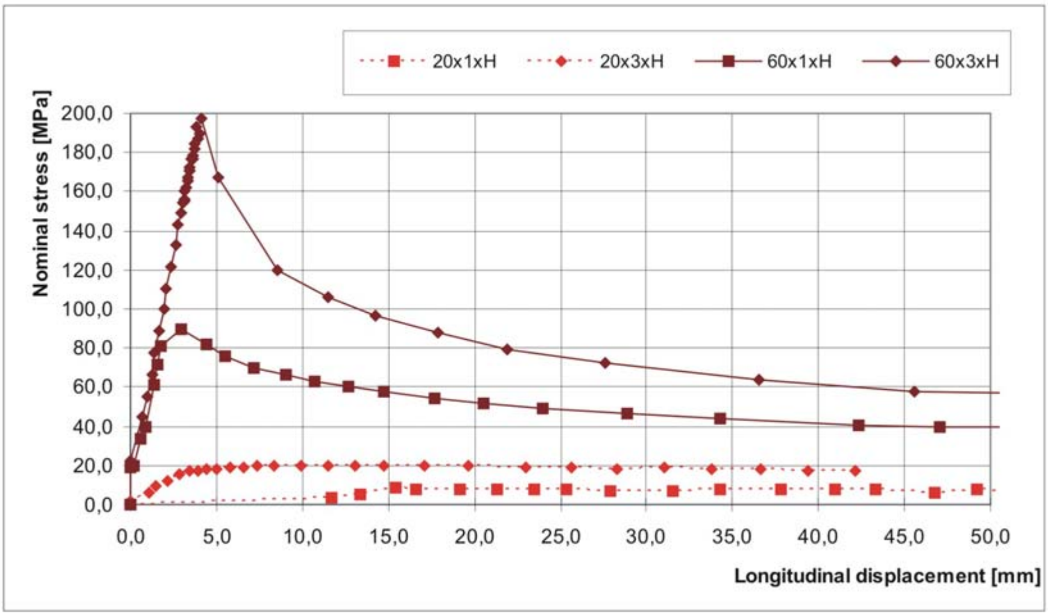


Figure 3.1.3.3–2 – hybrid metal I-Core panels under in-plane compression.

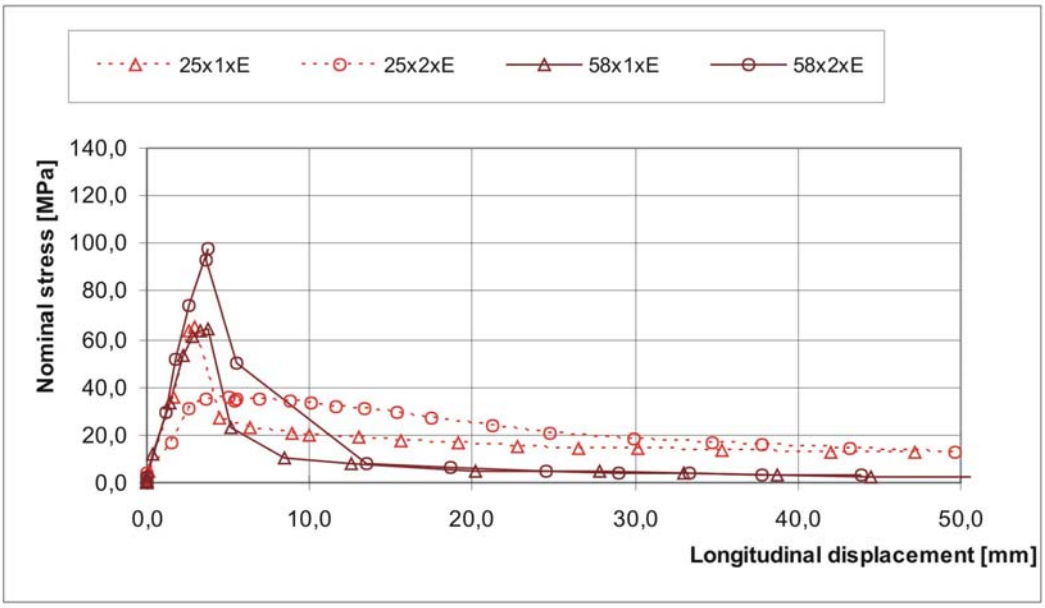


Figure 3.1.3.3–3 – all-metal V-Core panels under in-plane compression.

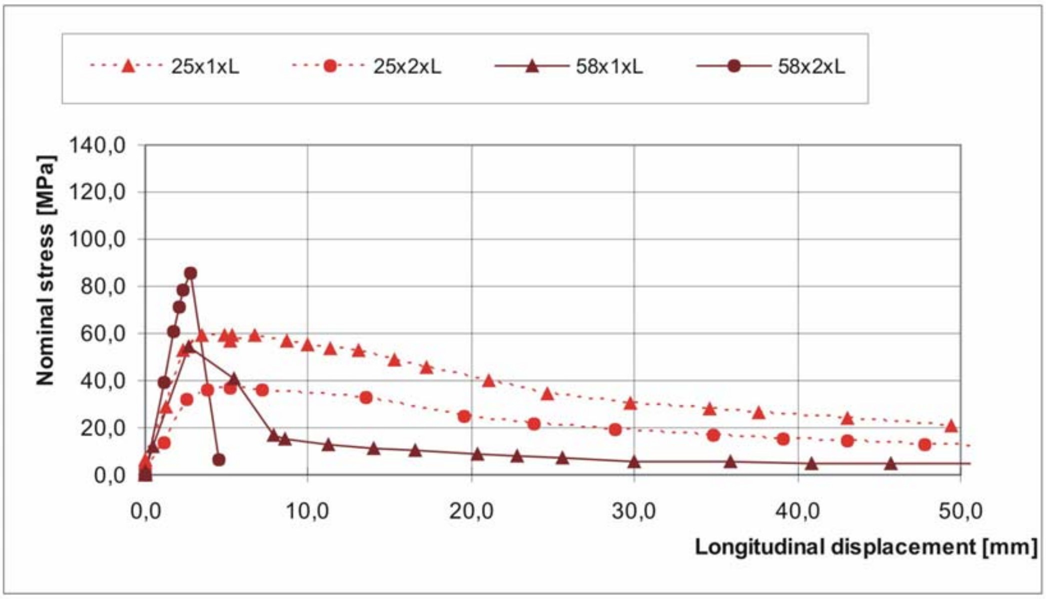


Figure 3.1.3.3–4 – hybrid metal V-Core panels under in-plane compression.

It was observed during the testing that the panels' failure mechanisms were strongly influenced by their initial deformation. Three deformation modes were observed:

- Stable bending of the whole panel (figure 3.1.3.3-5).
- Local buckling deformation over an entire faceplate (figure 3.1.3.3-6).
- Global loss of stability across the middle of the panel (figure 3.1.3.3-7).

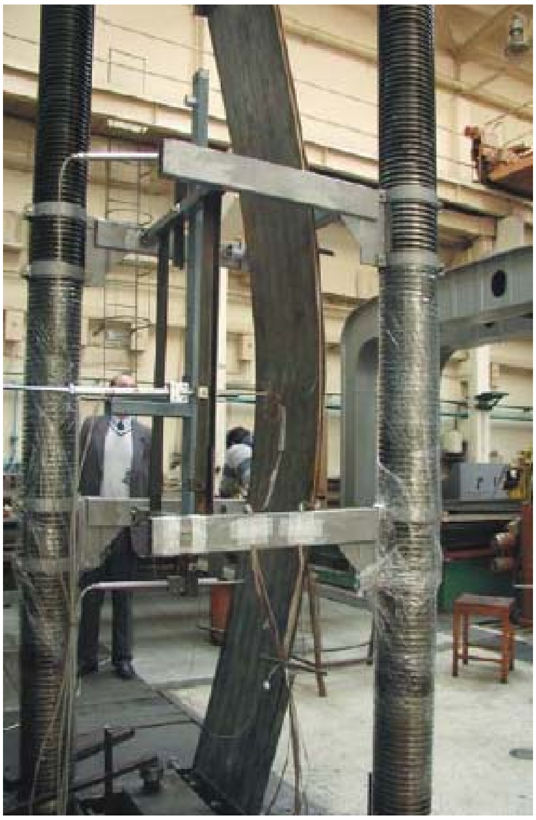


Figure 3.1.3.3-5 – stable bending.

Figure 3.1.3.3-6 – local buckling deformation over an entire faceplate.

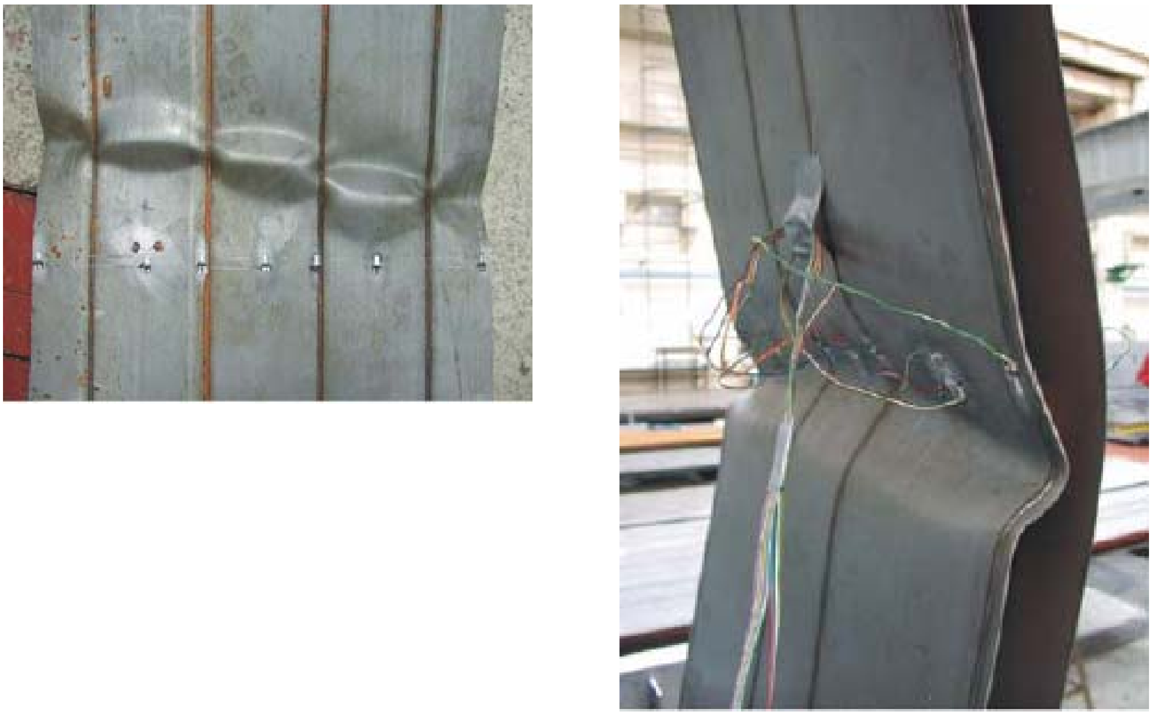


Figure 3.1.3.3-7 – global loss of stability across the middle of a panel.

Other observations from the testing:

- The failure modes can be correlated to the stress-displacement plots. For a **global buckling** failure, there is a linear rise of load with displacement up to a critical load level, followed by a rapid load drop upon buckling. For a **local buckling** (faceplate wrinkling) failure, there is a smooth rise of the load which remains more or less constant (peaking at a much lower level than for the case of global buckling) for a significant amount of the applied displacement.

- Qualitative comparisons between I-Core and V-Core panels indicate a superior performance from the I-Core system with respect to in-plane load response.

- Manufacturing deformations can have a significant influence on the in-plane load-displacement characteristics of a panel. This is one of most important parameters influencing the buckling characteristics of steel sandwich. Establishing proper tolerances for accuracy of manufacturing, as well as ensuring that the final product is within assumed values, is critical for attaining a buckling strength which is reproducible and closer to the predicted theoretical values.

3.2. Crash / Impact Response

3.2.1. Crash / Impact Response of Sandwich Structures – General Overview

Sandwich structures generally have good energy absorption properties, leading to favourable **crash / impact** characteristics. Compared to single skin constructions, the relatively thick core materials or stiffening elements of sandwich structures provide an additional energy absorption capability. Figure 3.2.1-1 shows a typical force-penetration curve for a sandwich panel subjected to a localised impact. From such data, important information such as the impact energies required to perforate the inner and outer facings of, for example, a sandwich hull can be determined.

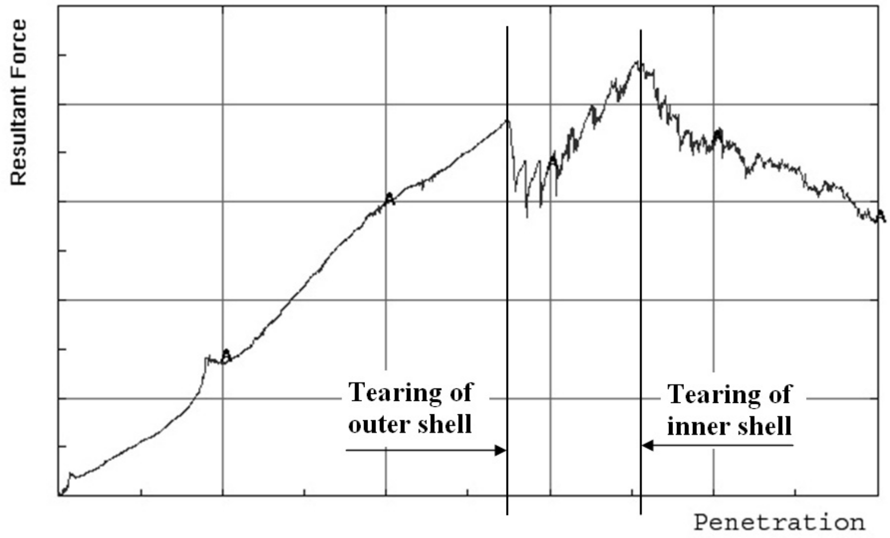


Figure 3.2.1-1 – typical force penetration curve for a sandwich panel subjected to a localised impact.

When designing or evaluating sandwich structures for their crash or impact characteristics, analytical approaches are generally not feasible. This is because of the complex, non-linear nature of most crash events. In comparison to static analyses, the following is a list of some of the additional important factors that generally need to be accommodated in a dynamic crash / impact analysis:

- Large strains / deformations of structural elements.
- Non-linear material behaviour (e.g. plastic deformation or brittle fracture).
- Transient behaviour – how a structure behaves over the duration of a crash / impact event.
- Elevated strain rates and their effect on material properties (some materials behave differently at high strain rates in comparison to quasi-static conditions).
- Contact algorithms (e.g. for modelling an impactor, or regions where deformed structural elements come into contact with one another).

In light of the above, non-linear, explicit finite element codes such as LS-DYNA, PAM-CRASH and ABAQUS Explicit are currently the most commonly used approach for performing crash or impact analyses. Sections 3.2.2 and 3.2.3 that follow provide guidelines on modelling metal and composite sandwich structures respectively.

Experimental testing is also an important component of crash / impact analysis, both for material property data generation to support numerical modelling, and for the validation of numerical results. However, experimental crashworthiness testing is, by its very nature, destructive. As such, even if testing could be conducted on a reduced scale or on a selected component basis, it is likely that a wholly experimental approach to the design and validation of a crashworthy structure would be prohibitively expensive. This is why predictive finite element techniques have such an important role to play.

Experimental methodologies for crash / impact testing and material property determination at elevated strain rates is a specialist field, particularly with respect to instrumentation and the associated the capture and processing of the test data. Furthermore, for large "real world" structures, bespoke testing arrangements are often necessary. For these reasons, it is recommended that appropriate expert organisations are consulted for experimental crash or impact test programmes.

3.2.2. Crash / Impact Response of Metal Sandwich Structures

If a **steel** structure experiences **impact loading**, the impact energy is absorbed through the deformation of structural members. The main energy absorbing mechanisms are membrane stretching, bending and folding. Unless the impact is minor, the deformations exceed the elastic region and the material deforms plastically. This plastic deformation can be coupled with strain rate effects if the deformation velocity is sufficiently high.

Such non-linearities cannot feasibly be studied using analytical methods. Therefore, direct calculations using numerical simulations must be performed. As impact / crash scenarios are dynamic problems with non-linear characteristics, **explicit finite element codes** (e.g. LS-DYNA or ABAQUS Explicit) provide the best approach. When performing the analyses, geometrical and material non-linearities must be considered when selecting material models, element types and mesh densities. The following sections present some guidelines for the **finite element modelling** of **steel sandwich structures** under **crash and impact loading**.

3.2.2.1. Element Types, Meshing of the Model and Boundary Conditions

For a collision analysis, **shell elements** will be mainly used to model structural members such as plating, web-frames, frames, stiffeners, etc. Under-integrated Belytschko-Tsay elements ("Type 2" in LS-DYNA) are one possible option for such modelling. However, in these elements the strains are only evaluated at the element centre. This means that zero energy modes can occur (so-called “hour-glassing”). Therefore, the level of hour-glassing energy should be monitored, and this level should be small compared to the overall energy level of the model. Another possible option is to use fully integrated elements (“Type 16” in LS-DYNA), although these are more computationally expensive.

The **mesh density** of the model should be defined according to the expected outcome. Some preliminary calculation runs might be necessary to determine an appropriate mesh density. As mentioned previously, for under-integrated Belytschko-Tsay elements, the stresses and strains are only evaluated at the element centre. Therefore, these elements only describe precisely a *linear* deformation field. Consequently, in areas where the stresses and strains are linear, the mesh can be coarser. Similarly, areas with a non-linear stress / strain distribution must use a higher density mesh. Additionally, element types can vary throughout a model, with linear-elastic elements in areas away from the impact location, and non-linear elements in the impact zone. When a structural element is subjected to buckling, folding or bending, then in order to accurately capture such physical phenomena, at least 4-6 elements must be used for each fold. If fracturing of the material needs to be predicted, then this also has to be considered in the element size - see section 3.2.2.3 on “failure criteria”.

When a metallic material is bent or stretched in-plane, deformations in the through-thickness direction occur. For the proper inclusion of these deformations in finite element calculations, the number of integration points in the through-thickness direction should preferably be five (or more). As the number of through thickness integration points increases, so does the calculation time. It may therefore be necessary to reduce the number of points in large calculations. In any event, the number of points should not be less than three.

Zhang et al. 2004 provide guidelines on the extent of finite element models and their corresponding boundary conditions. Principally, a finite element model should at least capture all of the plastic deformations induced in an impact. Therefore, in terms of ship collisions, a finite element model should extend from one hard point (e.g. a bulkhead or other strong supportive member) to another. So, for example, with cargo ships it is recommended that at least the whole length of a cargo hold is modelled. For a symmetrical collision, it is sufficient to model just one half of the hold. Generally, at both hard points all 3 translatory degrees of freedom should be restricted. After completing the finite element model, a test collision calculation should be performed to ensure that there is no occurrence of plastic deformation near the constraint boundaries.

3.2.2.2. Material Properties and Material Models

Finite element codes work with true stresses and strains. True stress-strain is obtained from a tensile test by considering the changes in the cross-sectional area of the test specimen. It is generally recommended to use a true stress-strain relationship, which can be obtained from a tensile test as follows (Zhang et al. 2004):

$$\sigma = C \cdot \varepsilon^n \qquad \textit{(equation 3.2.2-1)}$$

where:

$$n = \ln(1 + A_g)$$

$$C = R_m \cdot \left(\frac{e}{n}\right)^n$$

A_g is the maximal uniform strain relating to the ultimate tensile stress R_m. Both values can be measured from a specimen tensile test. e is the natural logarithmic constant. For a typical shipbuilding steel, if only the ultimate stress R_m is available, equation 3.2.2-2 can be used to estimate a value for A_g (R_m in MPa):

$$A_g = \frac{1}{0.24 + 0.01395 \cdot R_m} \qquad \textit{(equation 3.2.2-2)}$$

Engineering and true stress-strain curves for a typical ship building steel are shown in Figure 3.3.2-1.

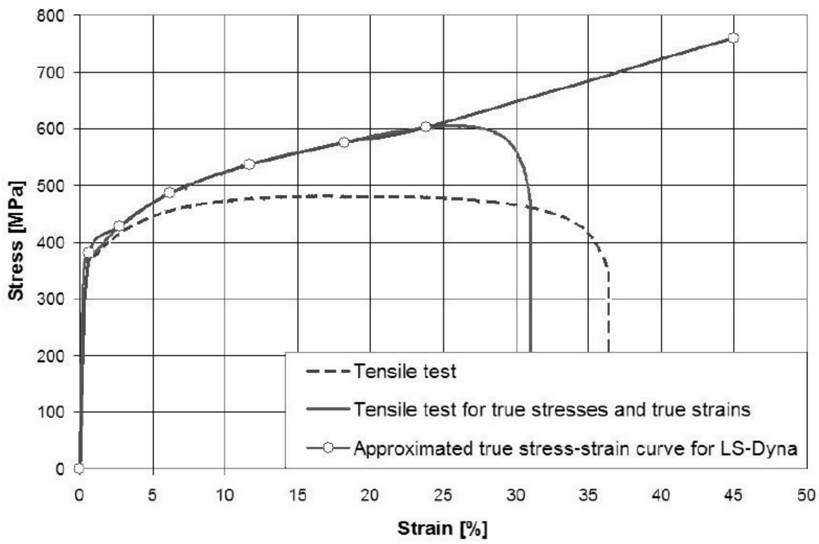


Figure 3.2.2-1 – engineering and true stress-strain curves for a typical shipbuilding steel.

In numerical calculations, the strain rate dependency of a material can be included by inputting separate stress-strain curves for different strain rates, or by using a built-in Cowper-Symonds constitutive equation (Jones 1989). The Cowper-Symonds model simply scales the static yield stress value σ_Y by considering strain rate $\dot{\varepsilon}$ and constants q and D for a particular material:

$$\sigma_Y^* = \sigma_Y \left[1 + \left(\frac{\dot{\varepsilon}}{D} \right)^{\frac{1}{q}} \right] \qquad \textit{(equation 3.2.2-3)}$$

For some materials these constants are given in the following table (Jones 1989):

Material	D **(s^-1)**	q
Mild steel	40.4	5
Aluminium alloy	6500	4
α-titanium (Ti 50A)	120	9
Stainless steel 304	100	10

In LS-DYNA, material model 24 (“Piecewise Linear Isotropic Plasticity”) is generally considered suitable as it has built-in options to model impact / crash processes. More precise representations can be implemented through user-defined material models.

3.2.2.3. Failure Criteria

The rupture of an element in a finite element analysis will typically be defined with a failure strain value, which is a function of the element’s dimensions. The following definition for failure strain is recommended (Scharre et al. 2002 and Zhang 2004):

$$\varepsilon_f(l_e) = \varepsilon_g + \varepsilon_e \cdot \frac{t}{l_e} \qquad \textit{(equation 3.2.2-4)}$$

where ε_g is the uniform strain and ε_e is the necking strain, and t and l_e are the plate thickness and the individual element length respectively. It is generally recommended that the ratio l_e/t should not be less than 5 for a shell element. The values of uniform strain and necking strain determined from thickness measurements are related to the calculated stress states as follows:

Stress State:	1-D	2-D
ε_g	0.079	0.056
ε_e	0.76	0.54
Element type:	Beam, truss	Shell, plate

Much more realistic ε_g and ε_e values can be obtained if additional thickness measurements from prototype damage cases and experiments are evaluated.

It should be noted that equivalent failure strain is not the best approach for the prediction of ductile failure. Ductile failure is a strong function of the hydrostatic tension and this is not captured using equivalent failure strain. A more precise approach, but one that is currently not implemented in commercial finite element codes, takes into account the stress triaxiality and the element size (Törnqvis et al. 2004).

Mesh density in the areas where the fracturing might occur must be high enough to capture the phenomenon. From experience of modelling ship collisions, the maximum element length should not be more than 200 mm in impact / crash areas, whilst a suggested value is around 50-100 mm.

3.2.3. Crash / Impact Response of Composite Sandwich Structures

The controlled brittle failure of thermosetting **fibre reinforced polymers** is a very efficient energy absorption mechanism. Indeed, it has been demonstrated that composites can be designed to exhibit higher specific energy absorption capabilities than metals (see, for example, Thornton 1979, Farley 1983, Schmueser & Wickliffe 1987 and Carruthers et al. 1998). In other words, a properly designed composite vessel ought to be capable of absorbing more collision energy than a steel or aluminium equivalent.

As a result of the above, the application of composite materials in crashworthy structures has been a subject of considerable research and development interest. Perhaps the most visible demonstration of progress in recent years has been in Formula 1 racing cars. However, the crushing behaviour of composite sandwich structures is very complex due to the interactions between the facing fibres, facing matrix and core material. This means that numerical approaches to simulating the crash response of composite structures are considerably less well developed than their metallic counterparts. The most robust approach to the development of crashworthy composite structures remains experimental testing (i.e. “make it and break it”).

This section provides an overview of numerical approaches to simulating the crashworthiness behaviour of composite sandwich structures, as well as presenting some more practical guidelines on exploiting the energy absorption potential of composites.

3.2.3.1. Numerical Methods

If a finite element model is to accurately predict the crashworthiness behaviour of a composite sandwich structure, then it must be capable of accommodating its unique failure characteristics. For example, in LS-DYNA, Material Models 54 and 55, "Enhanced Composite Damage", have been developed for modelling damage progression in fibre reinforced polymers. These material models have the following features:

- Arbitrary orthotropic properties can be defined by the specification of appropriate constitutive constants and local material axes.

- Laminates can be represented by assigning one element through-thickness integration point to each ply. A unique orientation angle can then be attached to each ply to generate different lay-ups.

- A local reduction in the failure strength of those elements in a crush zone can be specified so as to generate a characteristic progressive crushing mode of failure.

- Failed elements can be removed to simulate brittle fracture.

The failure criteria employed by Material Model 54 are based on those due to Chang & Chang 1987. These criteria accommodate four in-plane failure mechanisms: matrix cracking, matrix compression, fibre-matrix shearing and fibre breakage. Material Model 55 differs only in the criteria used to predict matrix failure – it uses an expression based on the theory of Tsai & Wu 1971.

In both Material Models 54 and 55, brittle fracture is simulated through the deletion of failed elements. This process can be controlled in two ways:

- By setting critical values for matrix cracking, matrix compression, fibre matrix shearing and fibre breakage

- By the element *timesteps*. Each element in LS-DYNA has an associated timestep. This timestep defines an upper limit on the rate at which a transient analysis may proceed without the onset of numerical instability. Consequently, the overall speed of a transient analysis is controlled by the element with the smallest timestep in any particular calculation cycle. Now, the timestep of an element is a function of both its geometry and its material properties. Therefore, as an element deforms and its geometry changes, its timestep will generally fall. One way in which the brittle fracture facility of Material Models 54 and 55 works is by deleting those elements whose timesteps fall below a certain (user specified) fraction of their initial value.

LS-DYNA also includes material models for core materials such as polymer foams and honeycombs. Two examples are Material Model 53, "Closed Cell Foam", and Material Model 63, "Crushable Foam". Material Model 53 is based on a linear stress-strain response, whilst Material Model 63 utilises a non-linear stress-strain characteristic.

Overall, the ability of commercial finite element codes to model the crash response of composite structures is continuing to evolve. However, at present they are not sufficiently well developed to be used in isolation. They generally need to be supported with a complimentary programme of experimental testing (see the "guidelines" in section 3.2.3.3 below).

3.2.3.2. Experimental Characterisation

Typical crushing responses for a composite sandwich structure (in this case, the axial compression of a hollow rectangular tube) are shown in figures 3.2.3-1 and 3.2.3-2 below. If stable, progressive crushing occurs then (after an initial peak force) there will be a near-uniform constant stress failure. From a structural crashworthiness perspective, this is an excellent response as it results in substantial levels of energy absorption. However, for a composite structure to collapse in this way, it is usually necessary to employ some sort of triggering device (see the "guidelines" in section 3.2.2.3 below). In the absence of a trigger, unstable, catastrophic, low energy failure can occur, which is undesirable from a crashworthiness perspective.

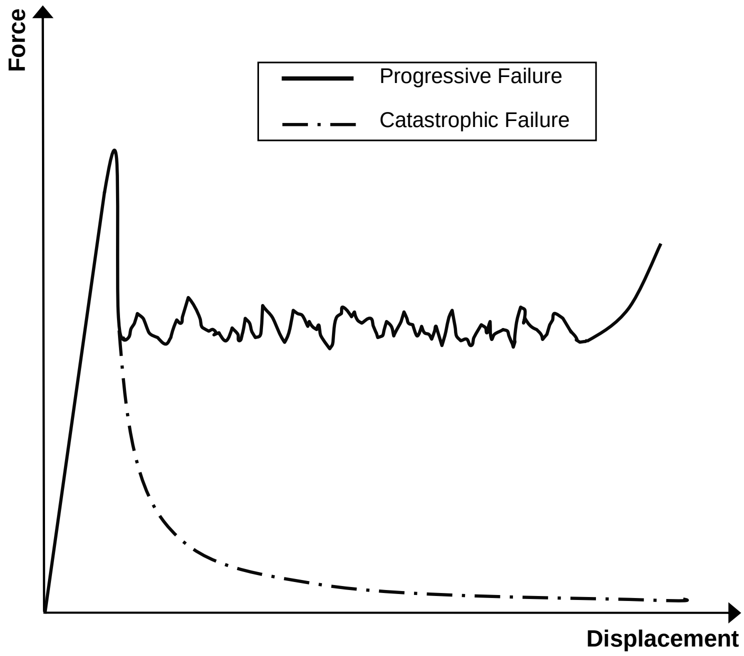


Figure 3.2.3-1 - typical collapse behaviours for the axial compression of a hollow rectangular sandwich tube (from Pitarresi et al. 2006).

Figure 3.2.3-2 - a hollow rectangular composite sandwich tube following progressive crushing (from Pitarresi et al. 2006).

For a composite sandwich structure based on glass reinforced polymer facings and a polymer foam core, a typical specific energy absorption capability (assuming stable progressive crushing) would be around 20 kJ/kg (see, for example, Pitarresi et al. 2006). Sandwich structures with more costly carbon fibre reinforced polymer facings would yield even higher values. However, it is difficult to be more precise as there are many aspects that influence the energy absorption capability of a composite structure. These include the specific fibre and matrix materials employed, the fibre orientation and lay-up with respect to the loading direction, the overall geometry of the energy absorbing component, and the loading rate. Carruthers et al. 1998 provide an overview of such issues.

3.2.3.3. Guidelines

- As mentioned above, composite sandwich structures generally require a collapse trigger mechanism to promote stable progressive crushing. Otherwise, sudden catastrophic failure can occur. Generally, collapse trigger mechanisms create a region of locally elevated stress at one end of the tube from which failure than propagates. Examples of collapse trigger mechanisms include chamfers and tulip geometries (Pitarresi et al. 2006).

- Caution should be exercised when extrapolating quasi-static crush performance to dynamic scenarios. There is a general lack of consensus regarding the influence of strain rate on composite crush performance. Some researchers have reported up to 30% increases in energy absorption capability with strain rate. Others have reported similar decreases. What does seem clear is that the failure modes of composite structures can be different under quasi-static and dynamic conditions, and that thermosetting matrix resins seem to be influential in this behaviour. From a design perspective, in the absence of any dynamic experimental data, it is probably best to adopt a conservative approach and assume that dynamic energy absorption might be up to 30% lower than quasi-static values.

- One aspect of composite sandwich structures that can compromise their crush performance is the often relatively weak core-to facing-bond. This is particularly the case for foam-cored sandwich structures. If the facing and the core separate under impact, then the sandwich will lose its load bearing capability and catastrophic unstable failure will occur. The tied-core composite sandwich designs described by Pitarresi et al. 2006 were specifically designed to overcome this limitation.

- Numerical approaches to simulating the crashworthiness of composite material sandwich structures are considerably less well-developed than their metallic counterparts. As such, it would be unwise to rely on them too strongly for design purposes. They often require very extensive (and sometimes obscure) material property data that is difficult to obtain. They also tend to be very computationally intensive (much more so than metals), so that solutions take a long time to obtain. Furthermore, they often don’t capture all the critical failure modes (delamination being one of the most difficult to simulate). And finally, the simulation of brittle fracture through element deletion (see above) is a rather crude approach unless a very refined mesh is employed. Overall, numerical analysis is a valid approach that can be used as one component of a crashworthy composite development programme. However, it is recommended that it is supported by a comprehensive programme of experimental data generation and validation.

3.3. Fatigue Analysis

3.3.1. Fatigue of Sandwich Structures: Analytical and Numerical Methods

The development of **fatigue** damage in sandwich structures is extremely complex. Therefore, in order to achieve reasonable predictions of fatigue failure in real structures, a combination of **analytical** and **numerical** techniques is required.

Fatigue life can be assessed using:

- *S-N* curves in a stress-based approach.
- Fracture mechanics.
- Local strain methods.

The use of *S-N* curves obtained through laboratory testing (see section 3.3.2) is the most common approach. The International Institute of Welding distinguishes between three types of *S-N* curve-based fatigue analysis (figure 3.3.1-1):

- Nominal stress.
- Hot spot (structural) stress.
- Notch stress (alternatively a “notch strain” approach can be used - Niemi 1995).

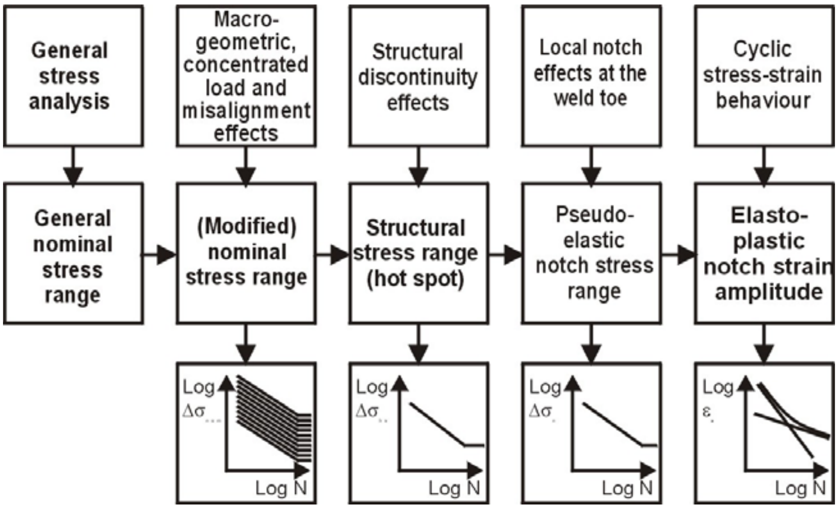


Figure 3.3.1-1 – approaches to fatigue life calculations (Niemi 1995).

3.3.1.1. Nominal Stress Approach

Nominal stresses are those derived from beam models or from coarse-mesh finite element analyses. These stresses should then be combined with the appropriate *S-N* curve for the class of structural detail concerned. Design *S-N* curves for different classes of welded joints can be found in Fricke 1997. Differences between the fatigue lives of real components and those obtained from *S-N* curves are normally due to stress concentrations arising from variations in the quality of materials / welds and geometrical details. Fricke 1997 provides an example of these differences for the fatigue life prediction of a laser-welded butt joint.

3.3.1.2. Hot Spot Stress Approach

Hot spot stresses include nominal stresses and stresses due to structural discontinuities, but exclude stresses due to the presence of welds. The hot spot stress approach removes any uncertainties relating to the local stresses attributed to the actual weld properties, because notch stress effects are embedded within the *S-N* data. Therefore, a single *S-N* curve is required for each weld method or weld type.

Usually, a coarse finite model or an analytical method is used to establish the nominal stress just outside the weld, and then a fine mesh sub-model of the weld detail is created to obtain stresses at the region close to the weld toe. Since the structural discontinuity at the weld toe leads to a singularity of solution (i.e. infinite stress), the stress is normally determined at a small distance away from the weld toe and then extrapolated to the weld toe. Different extrapolation standards are presented in figure 3.3.1-2 below.

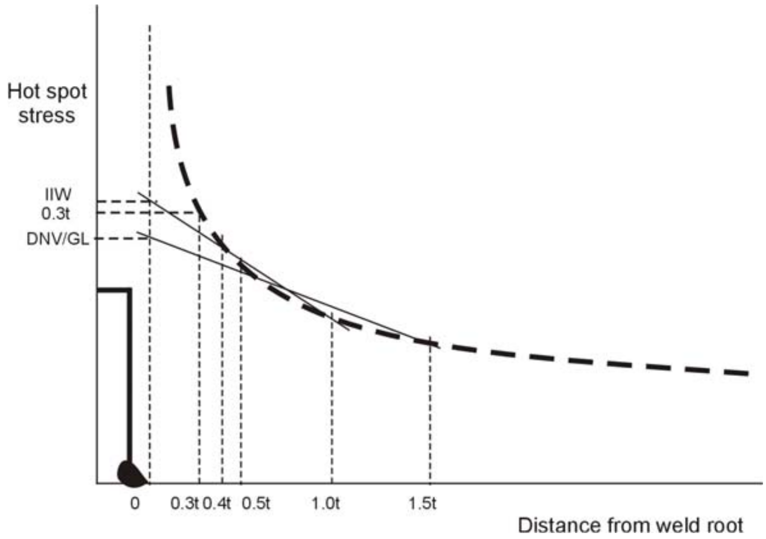


Figure 3.3.1-2 - different methods of hot spot stress estimation (Madox 2001).

3.3.1.3. Notch Stress Approach

Notch stresses are the total stresses at the weld toe including both hot spot (geometric) stresses and the stresses due to the presence of the weld. These stresses should be combined with the basic *S-N* curves given in, for example, Det Norske Veritas 2003. Four different basic *S-N* curves may be distinguished through combinations of either a welded joint or the base material, and a corrosive or non-corrosive environment.

Notch stresses may be determined in two ways:

- Stress concentration factors are determined using analytical methods or finite element analysis to predict the stress at the notch due to a particular imperfection. Within a finite element analysis, this can be done for a number of geometrical variations and then a regression analysis can be carried out to determine an appropriate formula. It should be noted that the profiles of real welds will differ from an assumed shape (figure 3.3.1-3). Thus, depending on the sensitivity of the detail, significant errors may be introduced. Notch stresses should therefore be determined by finite element models of the notch with a radius of 1 mm.

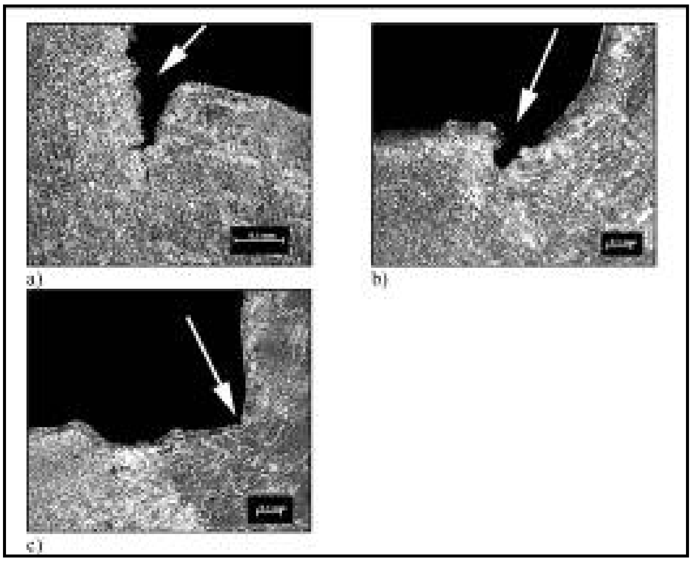


Figure 3.3.1–3 - notches in welds: a) typical, b) undercut, c) sharp (Martinsson 2005).

- Under the DNV approach, the basic *S-N* curves used in notch stress analysis are based on smooth test samples in which the notch stress is equal to the nominal stress. Thus the notch stress range to be used with the appropriate *S-N* curve is:

  $\sigma_{notch} = K\sigma_{nominal}$ *(equation 3.3.1-1)*

  The final stress concentration factor, K, is the product of a number of other K factors reflecting different geometric imperfections:

  $K = K_g K_w K_{te} K_{ta} K_n$ *(equation 3.3.1-2)*

  where K_g, K_w, K_{te}, K_{ta} and K_n are stress concentration factors due to the geometry of the detail, the weld geometry, eccentricity tolerance, angular mismatch, and non-symmetrical stiffeners on laterally loaded panels respectively (Det Norske Veritas 2003).

  Alternatively, a hot spot stress may be used and the resulting notch stress is described by:

  $\sigma_{notch} = K_w\sigma_{hot\ spot}$ *(equation 3.3.1-3)*

3.3.1.4. Calculation of Stresses

For the calculation of notch stresses, a detailed stress analysis may be performed using a linear or non-linear finite element model in a standard package (e.g. ABAQUS, ANSYS, NASTRAN, or SESAM). Since fatigue damage is highly sensitive and directly related to the critical stress value, a very fine mesh may be required to estimate the notch stress in, for example, the weld root or the weld toe.

Both 2D and 3D finite elements may be used in direct, sub-model or super-element analyses (SESAM Users Manual 2003). In addition, if the analysis is related to structural details in ship structures, a full spectral analysis may be performed (Rudan et al. 2002).

3.3.1.5. Fatigue Damage Accumulation

The majority of real structures, including ships, are subjected to variable amplitude cyclic loading as opposed to the constant amplitude cyclic loading that is normally used for the construction of *S-N* curves. For the fatigue life determination of real structures, hypotheses of fatigue damage accumulation are therefore required. The most commonly used is the Miner-Palmgren law which states that the amount of fatigue damage accumulated during each load cycle is proportional to the stress during that cycle:

$$D_F = \sum_i^k \frac{n_i}{N_i} = 1 \qquad \text{(equation 3.3.1-4)}$$

where D_F is the accumulated fatigue damage, n_i is the number of stress cycles at a stress amplitude of σ_{ai}, and N_i is the number of load cycles to fatigue failure as a result of the application of stress σ_{ai}.

In the above approach the accumulated fatigue damage is a linear function of the number of cycles only. Depending on the form of the load history, different formulae based upon Miner-Palmgren are proposed. For ship structures with a long-term stress range defined by applying a Weibull distribution, and for a one-slope *S-N* curve, **high-cycle fatigue** damage, D_{HCF}, can be calculated from:

$$D_{HCF} = \frac{\nu_0 T_d}{\bar{a}} \sum_{n=1}^{N_{load}} p_n q_n^m \Gamma\left(1 + \frac{m}{h_n}\right) \leq \eta \qquad \text{(equation 3.3.1-5)}$$

where N_{load} is the total number of loading conditions considered, p_n is the fraction of the design life in load condition n, T_d is the design life of the ship in seconds, h_n and q_n are the

Weibull stress distribution parameters for load condition *n*, ν_0 is the long-term average response zero-crossing frequency, and Γ is a gamma function (from Det Norske Veritas 2003).

Should local (notch) stresses approach or exceed yielding stress leading to **low-cycle fatigue**, a local strain approach should be applied using the Neuber rule, Ramberg-Osgood equation and Morrow equation (Sherratt), amongst other methods.

Alternatively, a recently proposed method of pseudoelastic stress (Urm et al. 2004) may be conveniently applied with the DNV high-cycle *S-N* curve extended to a low-cycle regime. The combined high-cycle and low-cycle fatigue damage is then:

$$D_F = D_{HCF}\left(1-\frac{\nu_{LCF}}{\nu_0}\right)+\nu_{LCF}\left\{\left(\frac{D_{LCF}}{\nu_{LCF}}\right)^{1/m}+\left(\frac{D_{HCF}}{\nu_0}\right)^{1/m}\right\}^m \leq \eta \qquad \textit{(equation 3.3.1-6)}$$

where:

$$D_{LCF} = \sum_{i=1}^{k}\frac{n_i}{N_i}$$

ν_{LCF} = mean zero-crossing frequency for the low cycle fatigue response.

3.3.1.6. Guidelines on the Fatigue Analysis of Sandwich Structures

- Only a few *S-N* curves for laser welded steel joints are published (Kozak 2005). The alternative approach is to use *S-N* curves recommended for steel (Fricke 1997).

- Due to the high stress gradients in steel sandwich structures, it is crucial to select the appropriate reference stresses in relation to the *S-N* curve used.

- Sources of information on the fatigue response of composite materials include Kaminski 2002 and Burman & Zenkert 1997.

- Different crack propagation criteria may be evaluated using standard finite element analysis software (Chen et al. 2001).

- Mackerle 2002 presents an exhaustive review of the finite element analysis of sandwich structures, including fracture mechanics, fatigue and damage.

3.3.2. Fatigue of Sandwich Structures: Test Data

The implementation of new structural designs requires the availability of simple, reliable and accurate design tools that can be used easily by engineers. For the **fatigue analysis** of **steel** sandwich panels, although progress has been made (see section 3.3.1), precise design tools are still not available. It is therefore necessary to have information on the behaviour of real sandwich structures. One source of such data is **laboratory fatigue testing**. In this section the methodology, results and observations of fatigue tests on large sandwich steel panels is presented. Fatigue results for three types of sandwich are reported:

- Specimen A – **hybrid metal** sandwich (I-Core filled with polyurethane foam), clamped around its edges.
- Specimen B **– all-metal** sandwich (I-Core), simply supported along its longer edges.
- Specimen C **– hybrid metal** sandwich (I-Core filled with polyurethane foam), with a region of variable thickness to facilitate joining with an adjacent structure.

3.3.2.1. Clamped Hybrid-Metal Sandwich

Specimen A was a laser welded steel (I-Core) sandwich panel with areal dimensions of 3000 mm × 1500 mm. The faceplate thickness was 2 mm and the stiffener height was 40 mm. The cavities of the panel were filled with a polyurethane foam. Further details of the sandwich geometry are provided in section 3.1.1.3b.

The test set-up is shown in figure 3.3.2-1. The load was applied as a point force at the centre of the panel and all four edges of the panel were clamped. The cyclic load frequency was 4 Hz, with a load ratio (minimum force to maximum force) of 0.1.

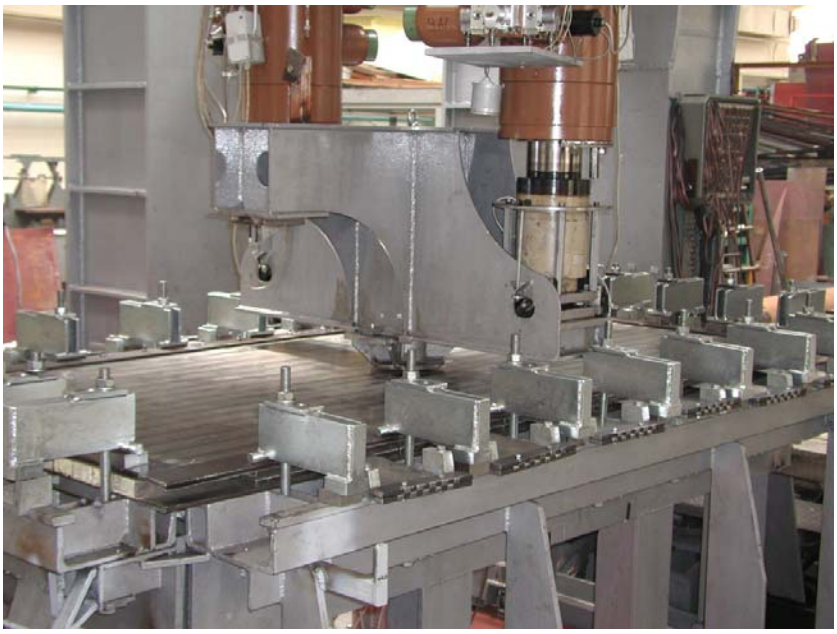


Figure 3.3.2–1 – test set-up for the clamped hybrid metal sandwich (specimen A).

Fatigue cracks developed in the weld toe zone, in the middle of the specimen, on the tensile faceplate, and propagated parallel to the stiffener direction. Specifically, a crack designated "*1-2-3*" developed in the region of the central stiffener in the middle of the panel (figure 3.3.2-2). Furthermore, a crack designated "*A-A*" developed in the same region but at the third stiffener from the centre of the panel (figure 3.3.2-2).

The fracture pattern of the fatigue crack (figure 3.3.2-3) shows the existence of a chain of fatigue crack initiation sites propagating in the through-thickness direction of the faceplate and into the weld toe. These initiation sites develop into semi-elliptical fatigue cracks in the early stages of fatigue crack growth, and then join up into a single long crack. This is marked in figure 3.3.2-3 as "*face of crack in later propagation phase*".

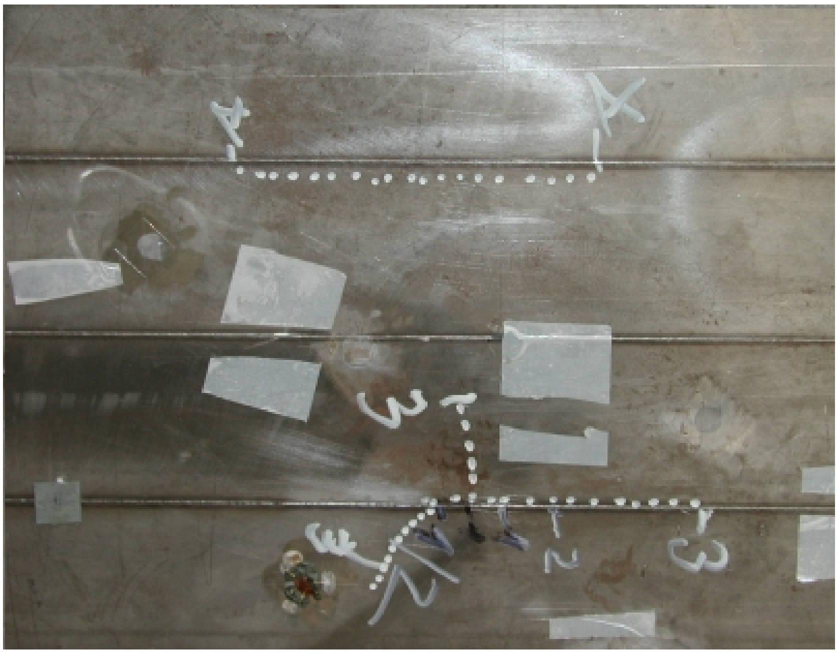


Figure 3.3.2-2 – specimen A: fatigue crack propagation paths.

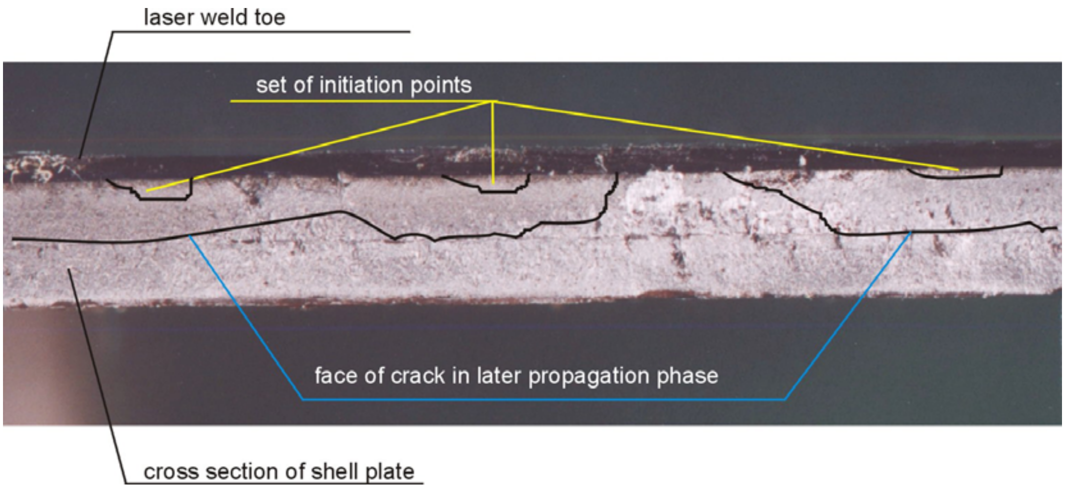


Figure 3.3.2-3 – specimen A: fatigue crack fracture.

The *S-N* curve constructed from the fatigue tests on specimen A are shown in figure 3.3.2-4. The slope of the curve has a magnitude of approximately 4.7. Comparing this value with the slopes of fatigue *S-N* curves provided by classification societies, it can be seen that it falls between the values of 3 for welded joints, and 5 for notches at free plate edges for classical welded steel structures.

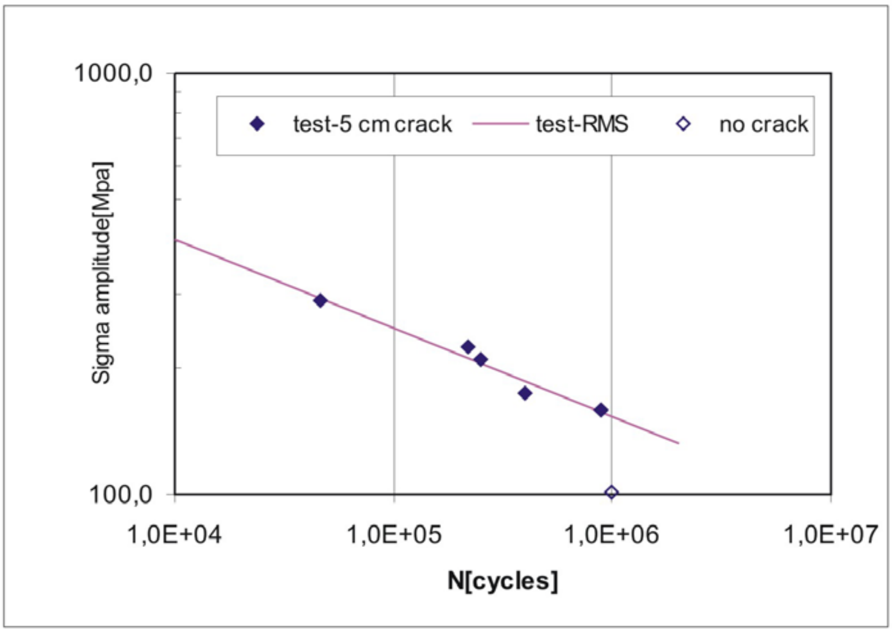


Figure 3.3.2–4 – specimen A: S-N curve from tests.

3.3.2.2. Simply Supported All-Metal Sandwich

Specimen B was a laser welded steel (I-Core) sandwich panel with areal dimensions 1000 mm × 500 mm. The thickness of the faceplates was 3 mm, the stiffener height 40 mm, and the distance between stiffeners was 80 mm. The load was applied as a point force at the centre of panel. The sandwich was simply supported on stiffeners along its longer edges. The cyclic load frequency was 4 Hz, with a load ratio of 0.1.

Fatigue cracks initiated in the laser welds in the edge stiffeners close to the open ends of the panel, and then propagated along the stiffeners, as shown in figure 3.3.2-5.

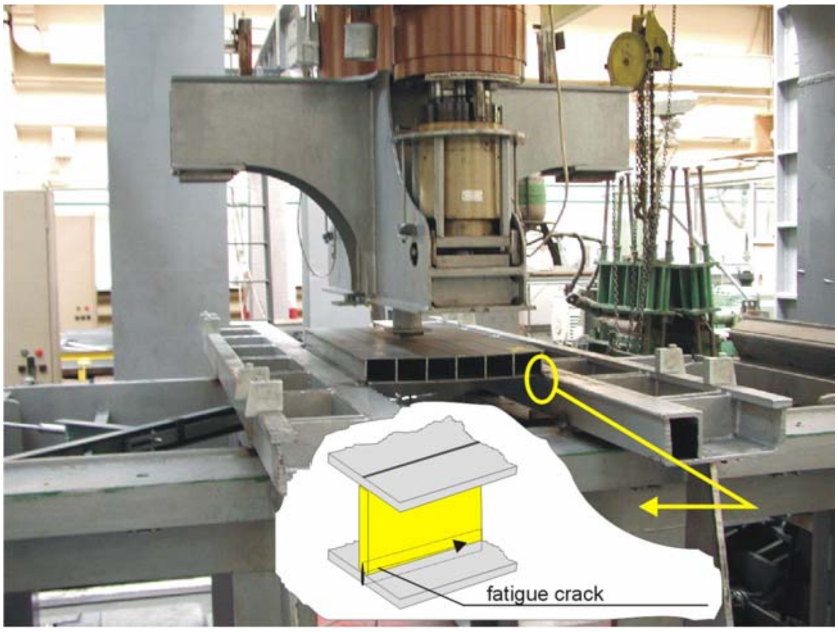


Figure 3.3.2-5 – specimen B: test set up and failure mode.

3.3.2.3. Clamped Hybrid-Metal Sandwich with Variable Thickness

Specimen C was the same as specimen A apart from two important differences.

- The faceplate thickness was 3 mm (rather than 2 mm).
- The panel included a region of variable thickness that would be typical for facilitating joints with adjacent structures (figure 3.3.2.6).

Fatigue cracks were found to initiate in the weld toe on the tensile faceplate, and then propagate in a direction perpendicular to the weld direction into the material of the faceplate.

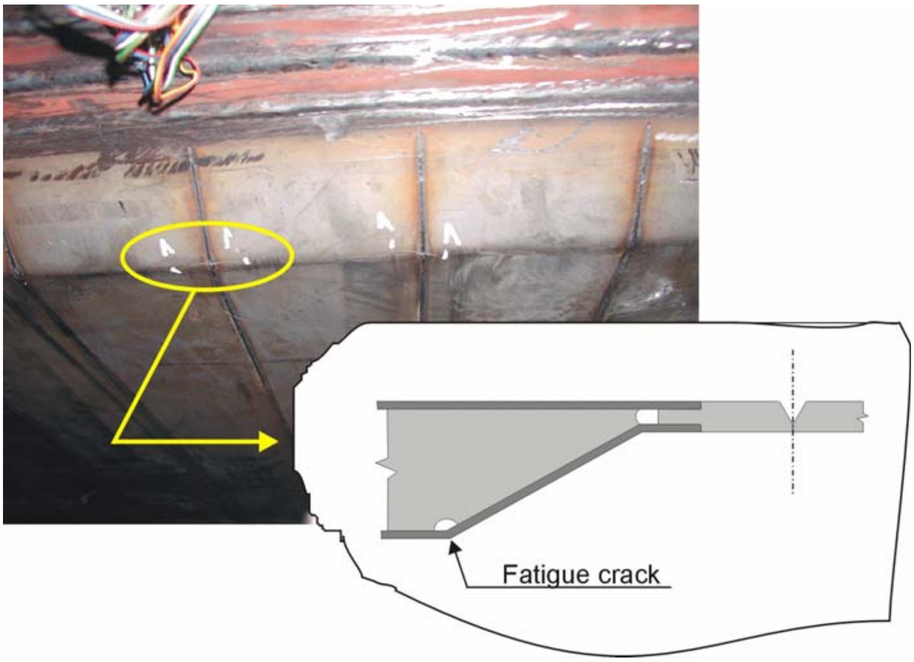


Figure 3.3.2–6 – specimen C: failure mode.

3.3.2.4. Conclusions from Fatigue Testing

For the steel sandwich panels tested, fatigue cracks have been observed in the following locations and directions (figure 3.3.2-7):

- Type 1: in a laser weld toe or heat affected zone in the tensile faceplate, in a direction parallel to the stiffeners, as a result of tensile stresses caused by global bending.
- Type 2: in a laser weld toe in the tensile faceplate, in a direction transverse to the stiffeners, as a result of tensile stresses caused by global bending.
- Type 3: in a faceplate due to the effect of tensile and bending stresses due to local bending or buckling.
- Type 4: in a laser weld as a result of rotation between a stiffener and a faceplate.
- Type 5: in a laser weld in the compressed faceplate as a result of shear stresses caused by global bending.

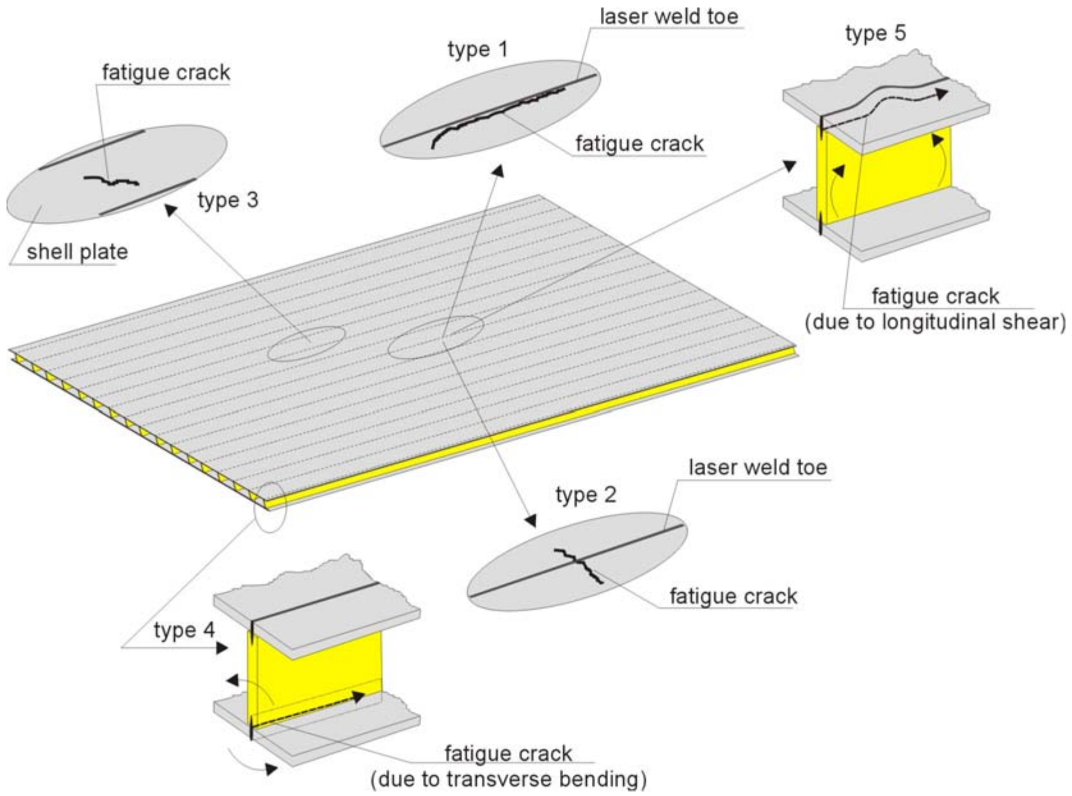


Figure 3.3.2–7 - steel sandwich panels: types of fatigue damage.

3.3.2.5. Guidelines on Sandwich Fatigue

- The introduction of loads into the faceplate, *between stiffeners*, should be avoided to prevent fatigue failure type 3. For properly designed constructions, type 3 failure should not occur.

- Fatigue failure type 4 does not depend on the level of the applied stress but is a result of the deformation pattern generated by the applied load. Clamping of the sandwich edges will prevent against type 4 fatigue failure.

- The risk of occurrence of fatigue failure type 5 rises with increasing stiffener height.

- For properly designed steel sandwich structures, the dominant modes of fatigue failure will be types 1 and 2.

- Design curves can be determined from systematic laboratory tests. The design curve data should be obtained via specimens that reflect as closely as possible the materials and manufacturing processes of the real structure. The number of tests performed should be in accordance with proper statistical representation (e.g. 5 levels of load, 5 specimens for each load level).

- It should be ensured that the reference stresses used for the calculation process are the same as those used for determining the design curve.

- Scale effects (i.e. size of a laboratory specimen with respect to the size of a real structure) have not been assessed and warrant further investigation.

3.4. Vibration Analysis

3.4.1. Vibration of Sandwich Structures: Analytical Methods

Vibration analyses of sandwich structures can include **free, forced and torsional vibrations** of both clamped and simply-supported sandwich beams and panels. Vibration due to **shock loading** can also be examined. Due to the complexity of the problem, 3D finite element analysis is normally employed for vibration studies. However, analytical methods are also available and are described here.

3.4.1.1. Recommended Analytical Approach to Vibration Analysis

Sandwich beams and sandwich panels with different types of sandwich core cross section (e.g. corrugated, I-Core, Z-Core, etc.) may be transformed into equivalent homogeneous orthotropic thick plate continuums. Lok & Cheng 2000 and 2001 formulated closed-form solutions for the free and forced vibration response of orthotropic sandwich panels. An overview of this method is presented here.

The governing differential equations are based on the small deflection theory of Libove 1948. These have been extended for vibration analysis by including the mass and moment of inertia of the plate. In order to perform the transformation of the sandwich to an equivalent orthotropic plate, seven elastic constants are required: D_x and D_y are bending stiffnesses, D_{xy} is torsional stiffness, D_{Qx} and D_{Qy} are transverse shear stiffnesses, and ν_x and ν_y are Poisson's ratios.

3.4.1.1a. Natural Frequencies of a Clamped Beam

The differential equations and boundary conditions may be simplified for the free vibration of a clamped beam. When a beam is vibrating in its m^{th} order natural frequency, the ω_m mode shape functions are (from Lok & Cheng 2000):

$$\begin{aligned} W_{xm} &= A_1 \cosh(s_1 x) + A_2 \sinh(s_1 x) + A_3 \cos(s_0 x) + A_4 \sin(s_0 x) \\ \Psi_{xm} &= B_1 \cosh(s_1 x) + B_2 \sinh(s_1 x) + B_3 \cos(s_0 x) + B_4 \sin(s_0 x) \end{aligned}$$ *(equations 3.4.1-1)*

where s_0 and s_1 are obtained from:

$$\frac{s_1}{s_0} = \frac{\omega_m}{\sqrt{2}} \sqrt{\mp\left(\frac{\rho h}{D_{Qx}} + \frac{gJ_x}{D_x}\right) + \sqrt{\left(\frac{\rho h}{D_{Qx}} + \frac{gJ_x}{D_x}\right)^2 + \frac{4g\rho h}{\omega_m^2 D_x}}}$$ *(equation 3.4.1-2)*

And, $g = 1-\nu_x \nu_y$, ρ is the material density, h is the orthotropic plate thickness, and J_x is the moment of inertia per unit area of the plate. The frequency ω_m and the coefficients A_i and B_i, (i = 1, 4) are determined from the clamped boundary conditions and then the coefficients are normalised to A_1.

3.4.1.1b. Natural Frequencies of a Clamped Orthotropic Plate

According to Hamilton's principle for free vibration, the total strain energy, U, and kinetic energy, T, of a plate satisfy the equation:

$$\xi \int_{t_1}^{t_2} (T - U) dt = 0$$ *(equation 3.4.1-3)*

where ξ is a variational operator. After the transformations and simplifications described by Lok & Cheng 2000, the following set of matrix equations are obtained

$$\left[K_{mn}^{mn}\right] \begin{Bmatrix} a_{mn} \\ b_{mn} \\ c_{mn} \end{Bmatrix} = 0$$ *(equation 3.4.1-4)*

where $\{a\}$ is a vector of unknowns and $[K]$ are sub-matrices. The non-trivial solution of equation 3.4.1-4 gives the (m, n) order frequencies $\omega_{mn}^{(r)}$ (r = 1, 2, 3). The lowest frequency (r = 1) is the flexural mode, whilst the two higher frequencies are related to transverse shear deformations in the x and y directions respectively.

3.4.1.1c. Forced Vibration Analysis of a Clamped Orthotropic Plate

The forced vibration of an orthotropic plate subjected to dynamic loading $p = p(x,y,t)$ may be expressed by the modal superposition method described by Lok & Cheng 2001:

$$w(x,y,t) = \sum_m \sum_n \sum_r A_{mn}^{(r)}(t) W_{mn}^{(r)}$$
$$\theta_x(x,y,t) = \sum_m \sum_n \sum_r A_{mn}^{(r)}(t) \Phi_{xmn}^{(r)} \qquad \textit{(equations 3.4.1-5)}$$
$$\theta_y(x,y,t) = \sum_m \sum_n \sum_r A_{mn}^{(r)}(t) \Phi_{ymn}^{(r)}$$

where w, θ_x and θ_y are the displacements and rotations of the plate, and $A_{mn}^{(r)}(t)$ are the unknown vibration functions to be derived. The forced response is then determined using Duhamel's integral.

The forced vibration of a *simply supported* orthotropic sandwich panel is described by Lok & Cheng 2001.

3.4.1.1d. Shock Loading

The response of clamped sandwich beams subjected to air and underwater shock loading may be determined by the analytical model developed by Fleck & Deshpande 2004. The maximum transverse deflection of the inner face of a sandwich beam at its mid-span, and the time required to achieve this deflection, may be calculated as described by Qiu et al. 2003.

3.4.1.2. Applying the Analytical Approach

Mastering the closed-form solutions requires:

- The elastic constants to be known (from open literature or derived).
- The basics of matrix calculus and differential equations.

Closed-form solution analysis is applicable to many types of sandwich beams and panels once the equivalent orthotropic plate parameters have been determined.

3.4.2. Vibration Analysis of Sandwich Structures – Numerical Methods

This section describes methodologies for determining the dynamic characteristics of sandwich structures, and consequently their **vibration** behaviour, using **finite element analysis**.

3.4.2.1. Numerical Vibration Analysis of Elastic Sandwich Structures

The numerical vibration analysis of **elastic** sandwich structures is relatively straightforward. It can be performed using any universal finite element code, using standard elements in the frequency and time domains. Analysis types include:

- Modal analysis (reduced, subspace, non-symmetric, damped methods, etc.).
- Harmonic analysis (full, reduced, mode superposition methods, etc.).
- Transient dynamic analysis (full, reduced, mode superposition methods, etc.).
- Spectrum analysis (response spectrum, dynamic design analysis method, power spectral density, etc.).

The results of such analyses provide eigenfrequencies, corresponding eigenmodes, frequency responses and time responses.

The main issue relating to the numerical elastic vibration analysis of sandwich structures is the size of the resulting models. In the case of 3-D finite element models, the size of the problem becomes very large for dynamic analyses. For this reason, the building of 3-D finite element models of hybrid-metal and composite sandwich constructions using standard finite elements is not a realistic proposition. A much more usable approach is to use 2-D finite element models with equivalent material properties for the sandwich core, or to transform the sandwich into an equivalent orthotropic panel. For such purposes, two widely known approaches can be applied (see Lok & Cheng 1999 or Barkanov et al.):

- The rule of mixtures.
- Calculation of equivalent stiffness.

Both of these approaches give sufficient accuracy and approximately the same values of orthotropic material parameters, apart from the case where determination of the in-plane shear modulus is required. In this instance, the values obtained by the rule of mixtures are considerably lower than those obtained by the calculation of equivalent stiffness.

3.4.2.2. Numerical Vibration Analysis of Viscoelastic Sandwich Structures

The vibration analysis of **viscoelastic** sandwich structures cannot be performed by standard finite element codes. Non-commercial, specialist finite element codes must be employed. These codes are strongly dependent upon the hypotheses that describe the rheological properties of the viscoelastic materials in the sandwich construction. Among these hypotheses, the complex modulus model (Nashif et al. 1985) is the most widely applied for the solution of different engineering problems associated with damping analysis. It provides the possibility to preserve the frequency dependence for the storage and loss moduli of viscoelastic materials, and to use the same hypothesis in the free vibration, frequency and transient response analyses. Moreover, the storage and loss moduli are defined directly in the frequency domain by an experimental technique for each material. These can be used after a curve fitting procedure in the numerical analysis.

For the vibration analysis of viscoelastic sandwich structures (hybrid-metal and composite), additional dynamic characteristics (modal loss factor η_n, logarithmic decrement, δ) describing their damping properties should be determined. These parameters can be evaluated by applying a complex modulus model according to the following approaches (Barkanov et al. 2005):

- The energy method:

$$\eta_n = \frac{\overline{\mathbf{X}}_n^T \mathbf{K}'' \overline{\mathbf{X}}_n}{\overline{\mathbf{X}}_n^T \mathbf{K} \overline{\mathbf{X}}_n} \qquad \textit{(equation 3.4.2-1)}$$

where $\mathbf{K}^* = \mathbf{K} + i\mathbf{K}''$ is the complex stiffness matrix of the sandwich structure, and $\overline{\mathbf{X}}_n$ are the eigenvectors of the corresponding elastic sandwich structure.

- The method of complex eigenvalues:

$$\eta_n = \frac{\lambda_n''}{\lambda_n} \qquad \textit{(equation 3.4.2-2)}$$

where $\lambda_n^* = \lambda_n + i\lambda_n''$ are the complex eigenvalues.

- From the resonant peaks of the frequency response function (figure 3.4.2-1):

$$\eta_n = \frac{1-\left(f_b / f_a\right)^2}{1+\left(f_b / f_a\right)^2}$$ *(equation 3.4.2-3)*

where f_a and f_b are the resonant peaks for a particular mode.

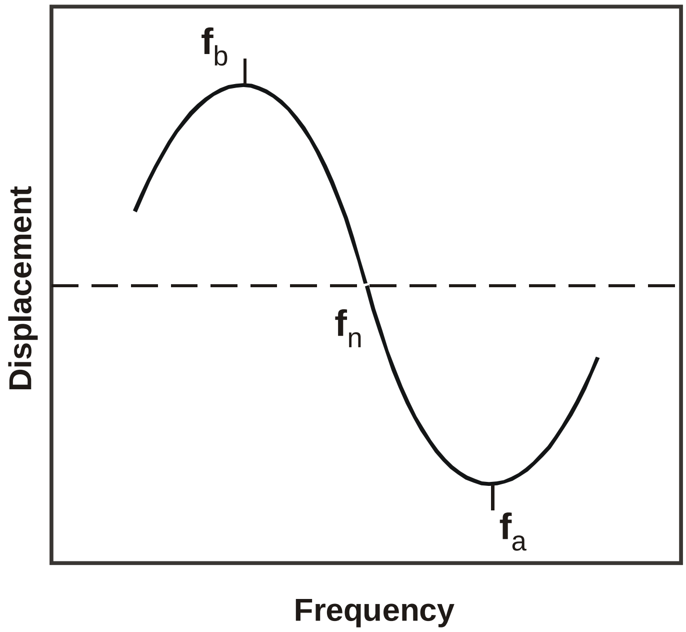


Figure 3.4.2-1 - frequency response.

- Using the steady state vibrations (figure 3.4.2-2):

$$\delta = \frac{1}{N} \ln \frac{X_n}{X_{n+N}}$$ *(equation 3.4.2-4)*

where X_n and X_{n+N} are the amplitudes of n and $n+N$ cycles respectively, and N is an arbitrary integer.

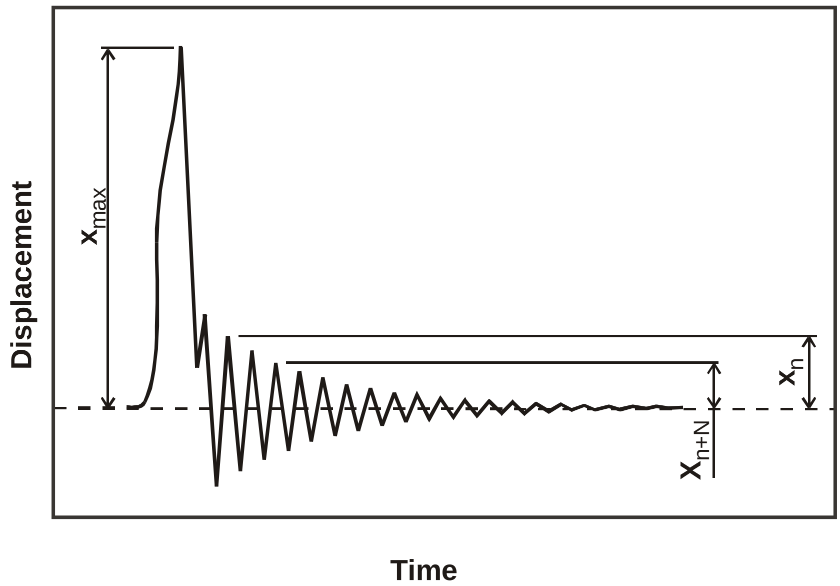


Figure 3.4.2-2 - transient response.

3.4.3. Vibration Analysis of Sandwich Structures – Test Data

Here, example test data is provided for the **vibration response** of different types of **all-metal** and **hybrid metal** sandwich panels. Furthermore, experimental results are compared with numerical predictions obtained using the methods described in section 3.4.2. As with the other test data sections in this guide, the data presented is intended to be illustrative only, and caution should be exercised when applying it or extrapolating it more widely.

3.4.3.1. Experimental Set-up and Data Analysis

An **experimental set-up** for the determination of the **dynamic characteristics**, **eigenfrequencies** and corresponding **loss factors** of laser-welded sandwich panels is presented in figure 3.4.3-1. To perform measurements, each sandwich specimen is suspended by two long lightweight strings for the achievement of free-free boundary conditions. An accelerometer is attached to one end of each sandwich specimen, and an impulse hammer is used for to excite the other end.

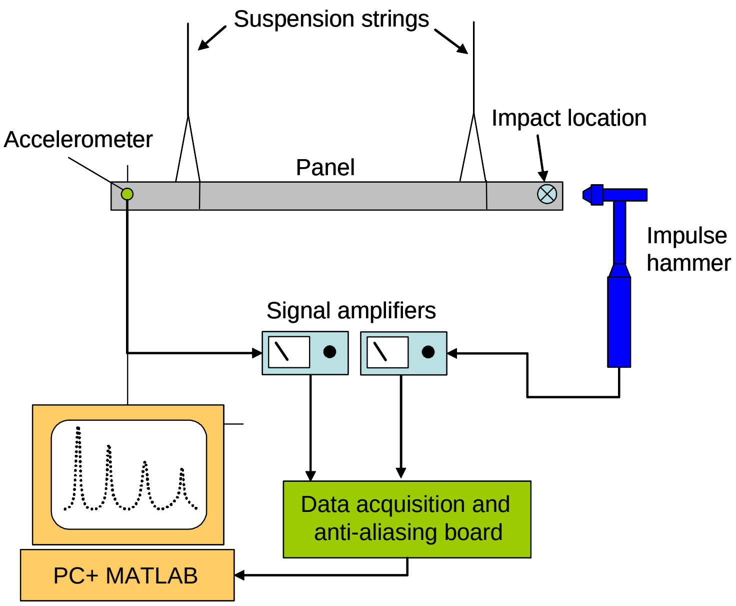


Figure 3.4.3-1 - experimental set-up for vibration measurements.

For the specimens discussed here, the time histories of the accelerometer and the force transducer incorporated in the hammer's head were recorded for ten seconds following impact. After a process of signal conditioning and data reduction, a Fourier transformation of the data was performed. Using visual inspection of both time histories and the frequency response, repeat tests were carried out on each specimen until ten good measurements were obtained.

To determine the resonance frequencies and corresponding loss factors from the frequency response plot, a short programme was written in the MATLAB code to produce a Nyquist plot (see, for example, Ewins 1984). In order to capture resonance frequencies of up to 1000 Hz and to obtain a frequency resolution of about 0.125 Hz, the sampling frequency of the data acquisition board was set to 12,800 Hz and a low-pass filter with a cut-off frequency of 3,200 Hz was used.

3.4.3.2. Results

The eigenfrequencies (in Hz) were obtained experimentally for five types of laser-welded sandwich panel:

- Type I - all-metal: I-Core, longitudinal webs.
- Type II - all-metal: I-Core, transverse webs.

- Type III - hybrid metal: I-Core, longitudinal webs, filled with 145 kg/m^3 rigid polyurethane foam.

- Type IV - hybrid metal: I-Core, transverse webs, filled with 80 kg/m^3 rigid polyurethane foam.

- Type V - hybrid metal: I-Core, transverse webs, filled with balsa wood.

Each sandwich panel was 2 m in length (Type I = 1 m), with a width of 0.18 m and a height of 0.044 m (figure 3.4.3-2). The facing thickness was 2 mm (2.5 mm for Type I), the stiffener height was 40 mm, the stiffener thickness was 4 mm, and the distance between stiffeners was 120 mm.

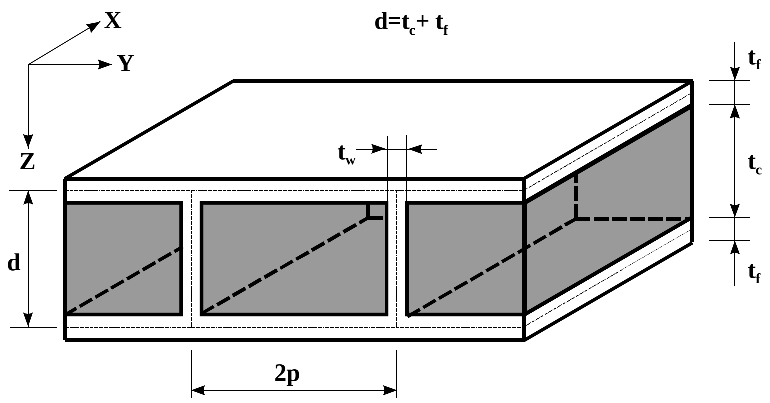


Figure 3.4.3-2 – general geometry of the sandwich test specimens.

In addition to the experimental measurements, the sandwich panels were modelled using 8 broken line sandwich beam finite elements (Barkanov et al. 2004 and 2005) to obtain convergence for the first ten eigenfrequencies. The material properties used for the sandwich constituents were as follows:

Material	Density (kg / m^3)	Young' Modulus (GPa)	Shear Modulus (GPa)	Poisson's Ratio
Steel	7800	210	-	0.3
Polyurethane foam PU145	145	48	10	0.3
Polyurethane foam PU80	80	26	5	0.3
Balsa wood	100	14	9	0.3

For the hybrid metal sandwich panels, the transverse and longitudinal core moduli were assumed to be equivalent because of the stiffening provided by the filler materials.

It should be noted that the large number of local modes posed considerable experimental difficulties. For this reason, some experimental eigenmodes were lost, but some local modes could be present in the spectrum. The absence of some theoretical eigenfrequencies is related to the impossibility of obtaining the torsional modes (figure 3.4.3–3) using sandwich beam finite elements.

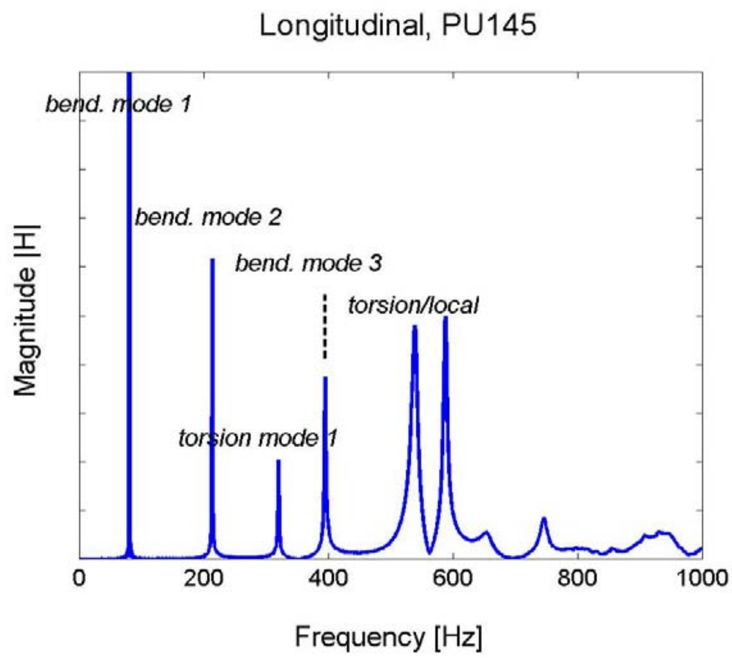


Figure 3.4.3-3 - experimental frequency response of a type III sandwich showing the different mode types.

Unfortunately, it was not possible to obtain a good correlation between theoretical and experimental modal loss factors since additional mechanisms of energy dissipation were involved in the experiment. The theoretical model only includes the dissipation mechanism associated with the viscoelastic properties of the core filler material.

The experimental results and their correlation to the numerical and analytical predictions are presented in the tables that follow:

Experimental	ANSYS	Theoretical			
		Free Vibration Analysis		Frequency Response Analysis	
		By Equivalent Stiffness*	By Rule of Mixtures*	By Equivalent Stiffness*	By Rule of Mixtures*
331.9	332.7	340.9	341.6	340.9	341.6
378.8	396.9	-	-	-	-
527.2	541.1	-	-	-	-
592.6	613.5	-	-	-	-
693.0	720.9	-	-	-	-
757.6	823.8	-	-	-	-
789.0	826.9	-	-	-	-

** See section 3.4.2.*

Eigenfrequencies (Hz) of a Type I panel (all metal: I-Core, longitudinal webs).

Experimental	ANSYS	Theoretical	
		Free Vibration Analysis	Frequency Response Analysis
		By Equivalent Stiffness*	By Equivalent Stiffness*
31.7	33.8	32.0	31.6
-	45.2	-	-
47.9	51.6	48.7	47.6
67.6	72.5	69.1	66.9
84.4	90.5	87.0	83.2
103.8	110.4	108.0	101.6
121.3	118.6	-	-

** See section 3.4.2.*

Eigenfrequencies (Hz) of a Type II panel (all metal: I-Core, transverse webs).

Experimental	Theoretical			
	Free Vibration Analysis		Frequency Response Analysis	
	By Equivalent Stiffness*	By Rule of Mixtures*	By Equivalent Stiffness*	By Rule of Mixtures*
79.9	81.5	81.5	81.5	81.5
213.1	219.2	219.7	219.2	219.7
319.9	-	-	-	-
394.6	414.4	416.2	414.4	416.2
587.9	-	-	-	-
-	656.5	661.1	656.6	661.2
746.4	-	-	-	-
913.0	931.3	940.3	931.6	940.5

** See section 3.4.2.*

Eigenfrequencies (Hz) of a Type III panel (hybrid metal: I-Core, longitudinal webs, filled with a 145 kg/m^3 rigid polyurethane foam).

Experimental	Theoretical	
	Free Vibration Analysis	Frequency Response Analysis
	By Average Stiffness	By Average Stiffness
43.9	40.0	40.0
58.5	63.1	63.1
74.1	89.5	89.6
103.9	113.0	113.1
137.0	139.2	139.3
156.2	164.0	164.2
-	191.1	191.3
-	219.1	219.3
258.7	249.7	249.9

Eigenfrequencies (Hz) of a Type IV panel (hybrid metal: I-Core, transverse webs, filled with an 80 kg/m^3 rigid polyurethane foam).

Experimental	Theoretical	
	Free Vibration Analysis	Frequency Response Analysis
	By Average Stiffness	By Average Stiffness
53.9	44.5	44.1
-	72.3	71.3
95.5	102.7	100.9
138.9	130.1	127.1
-	159.9	155.2
179.7	188.4	181.5
215.6	218.8	208.9
255.0	250.3	236.6
298.1	284.0	265.2

Eigenfrequencies (Hz) of a Type V panel (hybrid metal: I-Core, transverse webs, filled balsa wood).

3.5. Joint Design and Analysis

3.5.1. Joint Design

3.5.1.1. Joint Design for Sandwich Structures – General Overview

The relative overall thickness of sandwich panels, together with their relatively thin faceplates, means that it is *not* generally possible to join a sandwich directly to its surrounding structure. Therefore, some sort of intermediate joining element is normally employed. Figure 3.5.1.1-1 shows a typical joint for an all-metal sandwich. Figure 3.5.1.1-2 shows some examples of joints for hybrid metal SPS panels.

a) b)

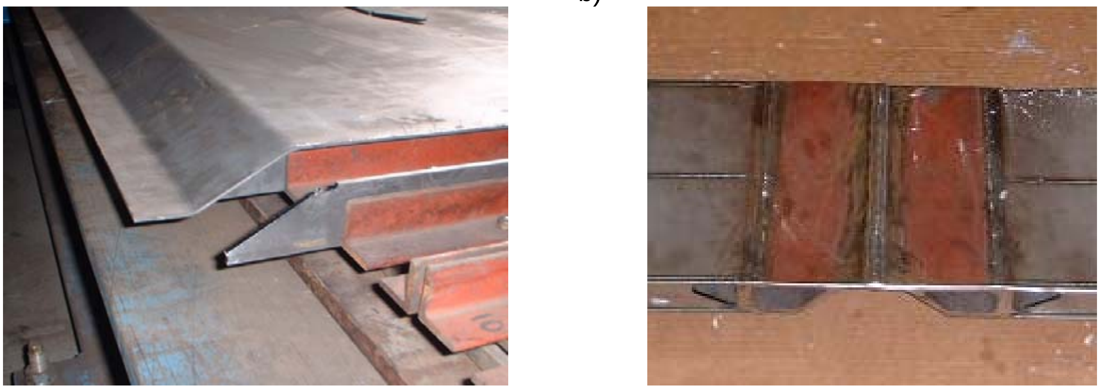
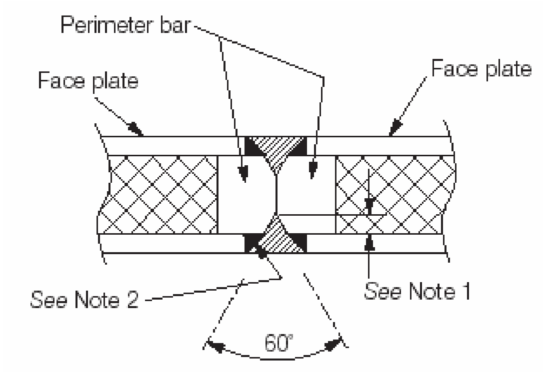
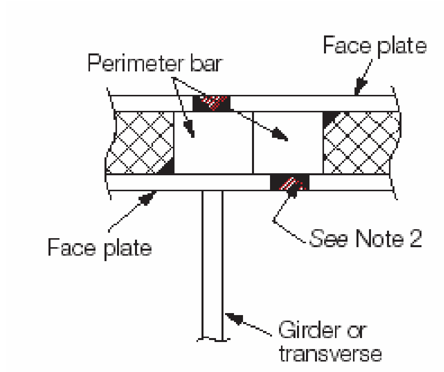


Figure 3.5.1.1-1 - a) all-metal panel joint in production, b) asymmetric joint panel.

a) Panel - panel



b) Panel - girder or traverse



c) Panel – girder – panel

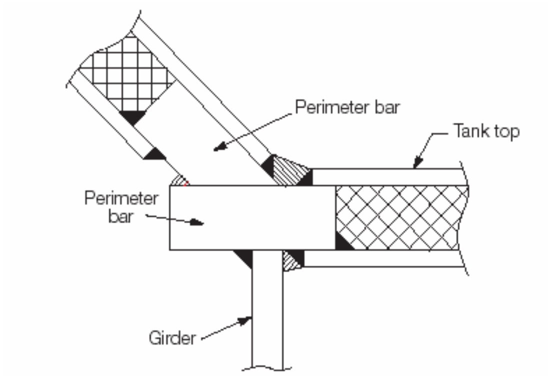


Figure 3.5.1.1–2 – hybrid metal (SPS) sandwich panel joints (Lloyds Register 2006).

When designing a joint, careful consideration should be given to:

- The loading condition of the structure.
- The geometric constraints of the joint.

The following joining methods can be considered for all-metal and hybrid metal sandwich panels:

- Welded joints.
- Mechanically fastened joints.
- Adhesively bonded joints.
- Combined joints.

Welded connections are the most typical sandwich joints within the marine industry. Mechanically fastened and adhesively bonded connections are being researched and are available for a limited number of applications.

In addition to a joint's performance under static loading conditions, fatigue is another important consideration, particularly with fusion welded joints (figure 3.5.1.1-3). Investigations have shown that the fatigue strength of all-metal and hybrid metal sandwich panel joints is critical, which makes their application for structural decks demanding (Ehlers 2006). Good fatigue performance for joints can, in principle, be assured by a smooth flow of the applied stress - in other words, avoidance of sharp corners or rapid changes of slope.

A joint's geometry is additionally influenced by the type of connection, i.e. whether it is a panel-to-panel connection or a panel-to-single skin connection. Further consideration should also be given to the use of symmetric or asymmetric joints. Asymmetric joints are more likely to generate high stress concentrations than symmetric ones. Designers should adopt symmetric joints if possible when considering highly loaded structures.

Figure 3.5.1.1-3 - fatigue failure of a sandwich joint.

3.5.1.2. Joint Design for All-Metal and Hybrid Metal Sandwich Structures

The design of **joints** for **all-metal** and **hybrid metal** sandwich panels can be neatly outlined using the flow chart presented in figure 3.5.1.2-1.

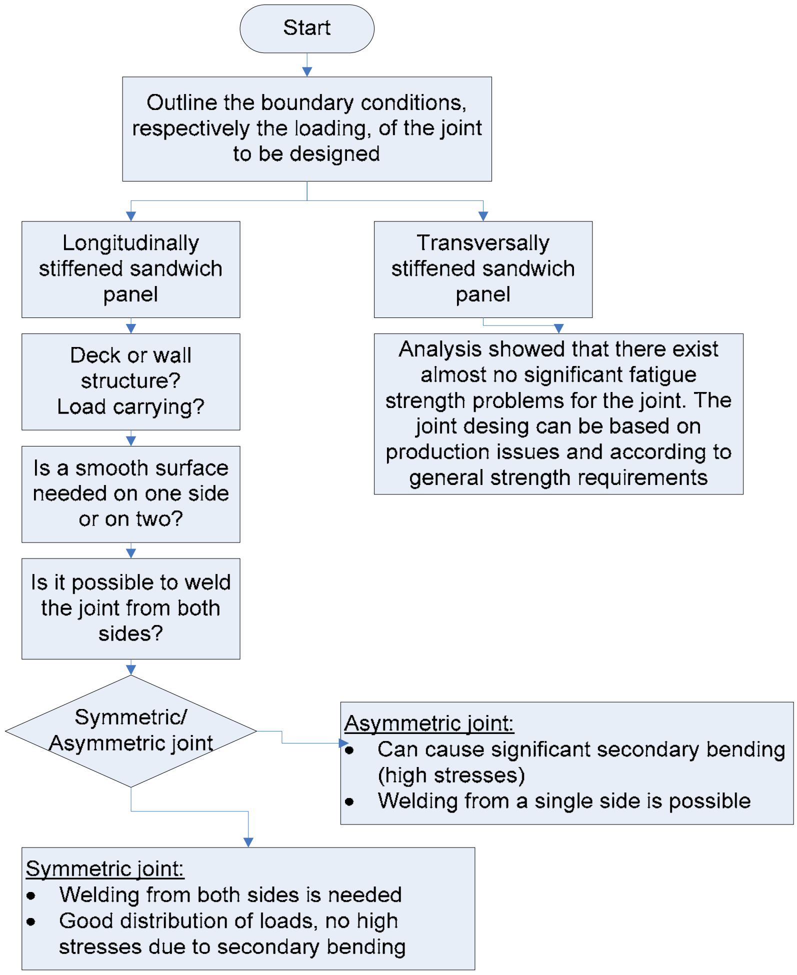


Figure 3.5.1.2–1 - design flow chart for all-metal and hybrid metal sandwich panel joints.

When designing joints for connecting all-metal and hybrid metal sandwich panels, the designer has to define precisely the boundary conditions of the structure that will include the joint. This is important with respect to core orientation, as transversally-stiffened panels exhibit less critical stresses than longitudinally-stiffened panels.

Depending on the application, the assembly determines whether sandwich panel joints can be welded from both sides and whether one side demands a smooth surface finish.

In the case of panel-to-panel connections, it has been found that symmetric joints are a favourable solution due to a more even distribution of stress. However, these joints require welding from both sides. Asymmetric joints on the other hand, whilst tending to be less favourable from a fatigue perspective, can be welded from a single side.

Figure 3.5.1.2-2 shows a set of typical joints that can be used for all-metal and hybrid metal sandwich panels. The critical stress locations within the joints are highlighted by a red mark. The position of the critical stress depends mainly upon a joint's geometry. Critical stresses are usually found in welds. Examples of mechanical joints are given in figures 3.5.1.2-3 and 3.5.1.2-4.

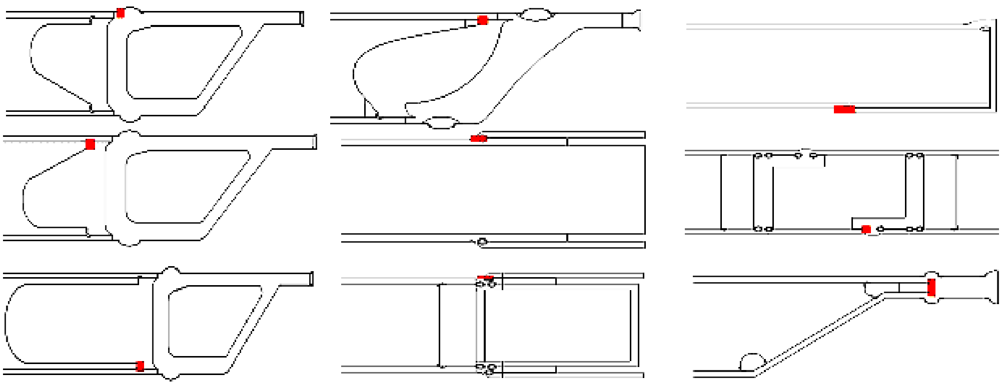


Figure 3.5.1.2-2 - Various joint geometries for laser welded sandwich panels.

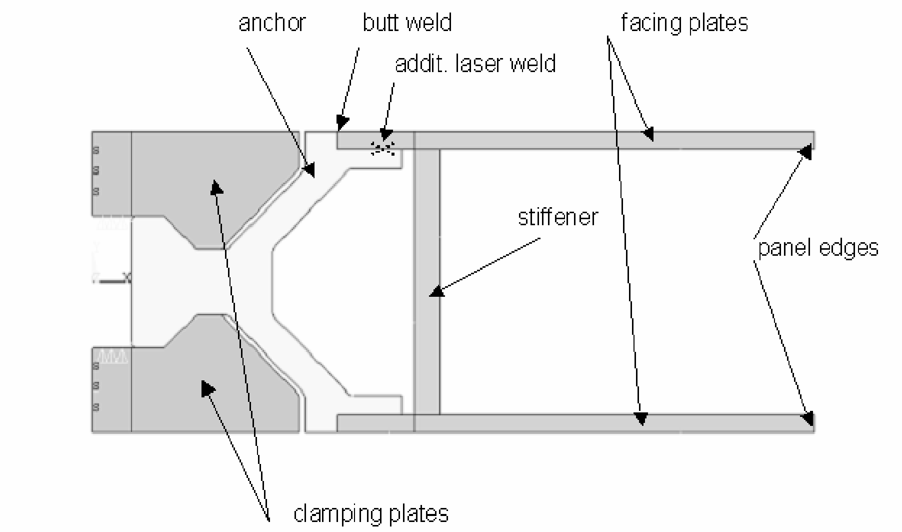


Figure 3.5.1.2-3 - mechanical joint with damping plates.

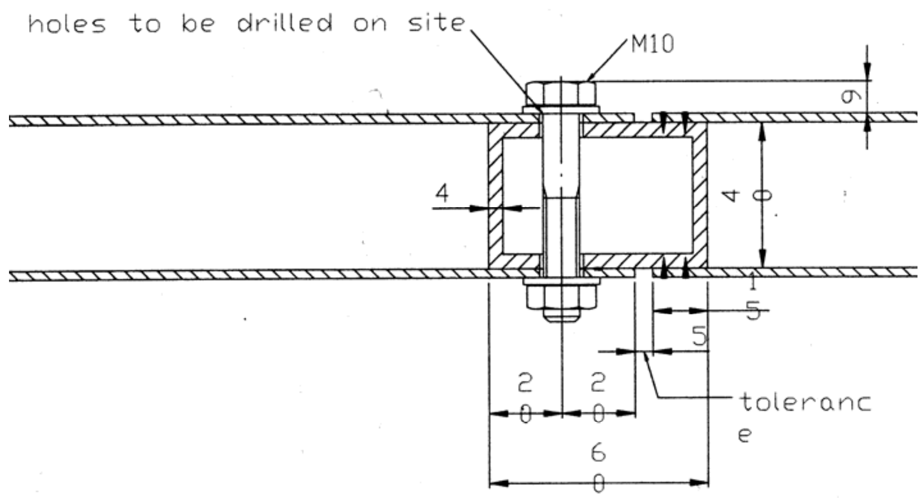


Figure 3.5.1.2-4 - mechanical joint example.

3.5.1.2a. Design of Joints for Production

Structural joints should be primarily designed to withstand the loads of a particular application. However, joint designs also need to take into consideration the production sequence and equipment in the particular assembly yard. Recommendations regarding joint design for easy assembly are as follows:

- Although the pre-manufacturing accuracy of all-metal sandwich panels is usually high, there may be some global distortions in the case of large panels (local distortions rarely appear before assembly). Such distortions can complicate the joining of panels. In order to assist the easy fitting of adjacent panel edges, it is recommended, where possible, to **place panel joints on supporting longitudinal girders or transverse beams**. Common mechanical devices can then be used to press the panels down to the girders and fit them.

- A general design principal is to try and **prevent the transfer of global loads to sandwich structures**. This can be easily achieved for applications such as sun decks or moveable ramps, and makes the sandwich joints more straightforward and less costly to assemble.

- **Tolerance friendly joints** (e.g. tongue and groove) help to accommodate the dimensional tolerances of sandwich panels and, more importantly, the surrounding ship structure, thereby minimising costly fitting work.

- In order to avoid global distortions due to welding during panel fabrication and assembly, a **minimum moment of inertia** is recommended for sandwich panels. This is most readily achieved by ensuring that the overall thickness of a sandwich panel is sufficiently high. For example, based on the experience of using I-Core sandwich panels in the decks of inland waterway cruise ships, Meyer Werft recommends a minimum stiffener height of 40 mm.

3.5.1.3. Joint Design for Composite Sandwich Structures

In this section the most common types of **composite sandwich panel joint designs** are presented along with the parameters that define these designs. Two classes of joint are discussed **– in-plane joints** and **tee joints**.

3.5.1.3a. Types of Composite Sandwich Joint

In-plane joints

The different types of (bonded) **in-plane joints** for composite sandwich structures are shown in figure 3.5.1.3-1.

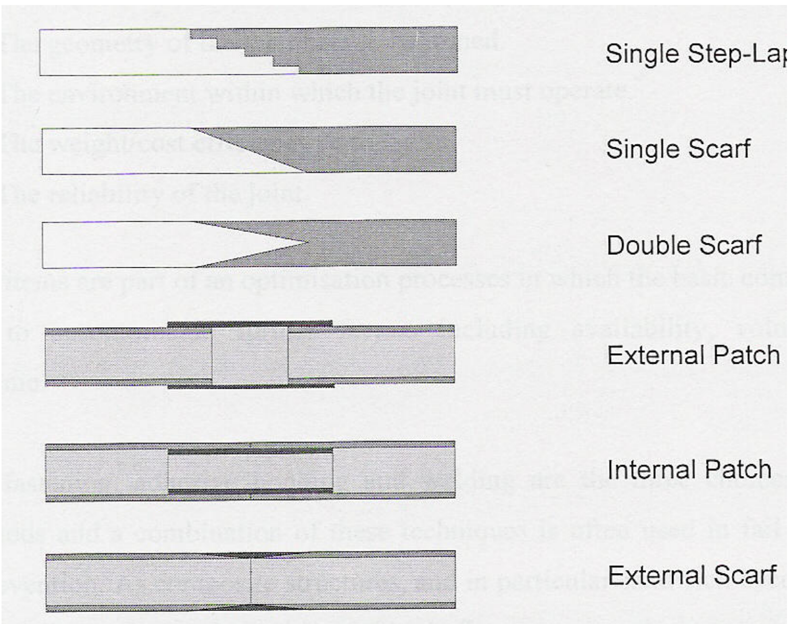


Figure 3.5.1.3-1 - in-plane joints for composite sandwich structures (Cossich 2000).

The **stepped lap** and the **single / double lap** joints involve precise shaping of the panels prior to bonding. This will increase production times. Performing the bond itself is then relatively quick provided that appropriate quality controls are implemented. The converse is, to some extent, true for the **internal and external patch** joints. With these, the base panels are relatively easy to manufacture and shape. The actual joining though is more labour intensive. The practical choice, in most cases, is between the stepped lap and patch joints, with the decision being based on load carrying ability and production / maintenance issues.

Tee joints

The different types of tee joints for composite sandwich structures are shown in figure 3.5.1.3-2.

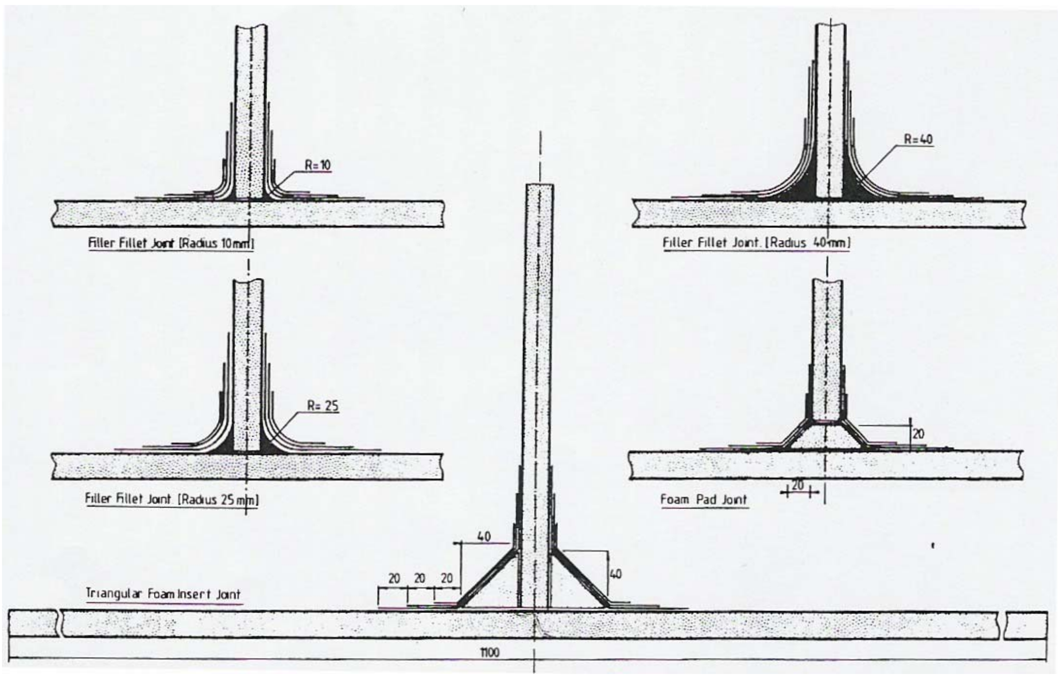


Figure 3.5.1.3-2 - tee joints for composite sandwich structures (Violette and Shenoi 1990).

A general guideline for the adoption of the types of tee joint presented above is that when no local hotspot stresses are expected, or when the transverse shear force is low, a filler fillet joint with as high a fillet radius as possible should be used. On the other hand, when the local transverse shear force is deemed to be high, a foam pad joint should be used to spread the load over a wider area on the base (flange) panel.

3.5.1.3b. Design Variables

In-plane joints (see figure 3.5.1.3-1)

Joint Type	Material Parameters	Topological Parameters
Single step lap	Adhesive type.	Step length and step depth.
Single scarf	Adhesive type.	Scarf angle and scarf length.
Double scarf	Adhesive type.	Scarf angle and scarf length.
External patch	Fibre reinforcement type. Reinforcement architecture. Resin type. Lamination scheme. Core filler type. Adhesive type.	Filler core width. Patch overlap length. Patch thickness.
Internal patch	Fibre reinforcement type. Reinforcement architecture. Resin type. Lamination scheme. Filler core type. Adhesive type.	Filler core width. Patch overlap length. Patch thickness.
External scarf	Fibre reinforcement type. Reinforcement architecture. Resin type. Lamination scheme. Adhesive type.	Patch / scarf length. Scarf angle.

Tee joints (see figure 3.5.1.3-2)

Joint Type	Material Parameters	Topological Parameters
Filler fillet type	Filleting resin. Fibre reinforcement type. Reinforcement architecture. Laminating resin type. Lamination scheme.	Fillet radius. Overlap length – web and flange. Overlaminate thickness.
Triangular foam insert type	Foam type. Fibre reinforcement type. Reinforcement architecture. Laminating resin type. Lamination scheme.	Foam dimensions. Overlap length – web and flange. Overlaminate thickness.
Foam pad type	Foam type. Fibre reinforcement type. Reinforcement architecture. Laminating resin type. Lamination scheme.	Foam dimensions. Overlap length – web and flange. Overlaminate thickness.

3.5.1.3c. Design Criteria

In-plane joints (see figure 3.5.1.3-1)

Joint Type	Criteria
Single step lap	Peel stress in adhesive. Axial stress in facing connection.
Single scarf	Peel stress in adhesive. Axial stress in facing connection.
Double scarf	Peel stress in adhesive. Axial stress in facing connection.
External patch	Match of stiffness between joint and parent facing. Peel stress of adhesive. Axial stress in adhesive patch. Axial stress in parent facing. Shear stress across core connection.
Internal patch	Match of stiffness between joint and parent facing. Peel stress of adhesive. Axial stress in adhesive patch. Axial stress in parent facing. Shear stress across core connection.
External scarf	Match of stiffness between joint and parent facing. Peel stress of adhesive. Axial stress in adhesive patch. Axial stress in parent facing. Shear stress across core connection.

Tee joints (see figure 3.5.1.3-2)

Joint Type	Criteria
Filler fillet type	Match of stiffness between joint and parent facings. Through-thickness stress in overlaminate. Principal stress in fillet. In-plane stress in overlaminate. Peel stress at overlaminate to web/flange facing interface.
Triangular foam insert type	Match of stiffness between joint and parent facings. Through-thickness stress in overlaminate. In-plane stress in overlaminate. Peel stress at overlaminate to web/flange facing interface.
Foam pad type	Match of stiffness between joint and parent facings. Through-thickness stress in overlaminate. In-plane stress in overlaminate. Peel stress at overlaminate to web/flange facing interface.

3.5.1.3d. Choice of Joint Production Process

It should be noted that the choice of joint production process influences the material properties. Therefore the design criteria must be tailored according to the chosen process. Broadly, the joints can be made through an adhesive bond using prepreg (for example) as the patch or overlaminate material, or through co-cured lamination of the bonding patch or overlaminate. The single step lap, single scarf and double scarf can only be produced by the adhesive bonding technique, while the rest can be fabricated using either process.

3.5.1.3e. Final Selection Criteria

The overall approval of a joint will rely on characterising its performance under the static, dynamic, fatigue and creep load conditions that are likely to be experienced by the structure in service. It is preferable that an experimental evaluation is carried out to provide this information on joint performance.

Note that there is increasing interest in the use of composite sandwich structural panels for the superstructure of steel-hulled vessels (see, for example, section 8.1). The joining between a steel hull and a composite superstructure needs to be addressed with care. Although there is progress still to be made, current knowledge favours the use of either a bonded solution, or an approach in which the composite sandwich panels are co-cured by resin infusion with steelwork upstanding from the main deck.

Finally, and importantly, the designer should also ensure that the joint design is producible and that the maintenance / operational issues underpinning the joint are also considered, especially in terms of the associated costs.

3.5.2. Joint Analysis

3.5.2.1. Joint Analysis for Sandwich Structures – General Overview

In general, 3-D finite element models should be developed for the analysis of joints for sandwich structures. However, such models are large and the computational demand very high. For this reason, the design problem can be converted to a 2-D finite element analysis. It is recommended that a 2-D structural solid finite element analysis is used, with higher order elements to provide more accurate results for mixed (quadrilateral - triangular) automatic meshes and to accommodate irregular shapes without significant loss of accuracy. Such finite elements have compatible displacement shapes and are well suited to the modelling of curved boundaries.

For the two different types of joint-to-stiffener connections - parallel and perpendicular (see Figure 3.5.2.1-1) - different finite element analyses should be developed: plane strain for parallel connections and plane stress for perpendicular connections. Plane strain state is applicable for the modelling of solids that are continuous in one direction. Plane stress models can be built with or without thickness. Some finite elements combine these behaviours and only the choice of key option is required. The finite element mesh should be more precise near the sites of possible stress concentrations such as welds. Symmetrical boundary conditions can be exploited to decrease considerably the magnitude of the finite element analysis and consequently the time required to perform the calculations.

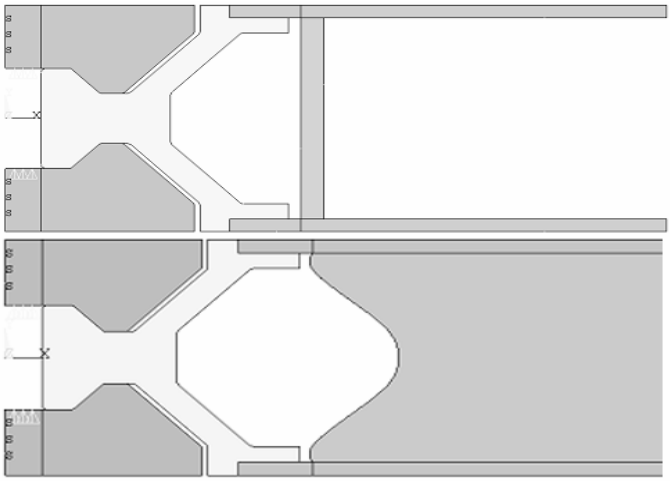


Figure 3.5.2.1-1 - two different joint-to-stiffener connections – parallel (top) and perpendicular (bottom).

For modelling contact surfaces (i.e. the interaction between different parts of a joint), 2-D line contact pairs representing target segment elements and contact elements should be used. The contact elements describe the boundary of a deformable body that can potentially come into contact with a target surface. Contact occurs when an element surface penetrates one of the target segment elements on a specified target surface. Coulomb and shear stress friction can be accommodated. A standard unilateral contact option should be used to define the contact behaviour.

Having developed a finite element representation of a particular joint design, the model can then be used to investigate a wide range of aspects such as:

- Stress concentrations and stress concentration factors.

- Displacements and plastic deformations in the case of material plasticity.

- Design optimisation to save weight or eliminate undesired stress concentrations (Ozoliņš 2003).

It should be noted that only the numerical analysis of joining technologies for metallic structures is well established. Areas that require further investigation include the analysis of joints under complex loading configurations, multi-material joints, durability aspects (fatigue, creep and environmental resistance), and joints for composite material sandwich structures.

3.5.2.2. Joint Analysis for All-Metal and Hybrid Metal Sandwich Structures

The general recommendations provided in section 3.5.2.1 are also applicable to the **finite element analysis** of **joints** for **all-metal** and **hybrid metal** sandwich structures.

For all-metal and hybrid metal sandwich structures, all the parts of a joint are made normally from steel, apart from the rubber inserts used for improvement of a joint's damping properties. Usually, for the modelling of rubber parts, quadrilateral 2-D hyperelastic solid elements are used. The Mooney-Rivlin material model (figure 3.5.2.2-1) is often used to represent the behaviour of rubber materials because of its simplicity. Example finite element meshes of sandwich joints are shown in figure 3.5.2.2-2. Most models are usually loaded using a force applied to the sandwich panel edge. However, exceptions to this approach include models with rubber materials – these should be loaded by an applied displacement due to solution convergence problems.

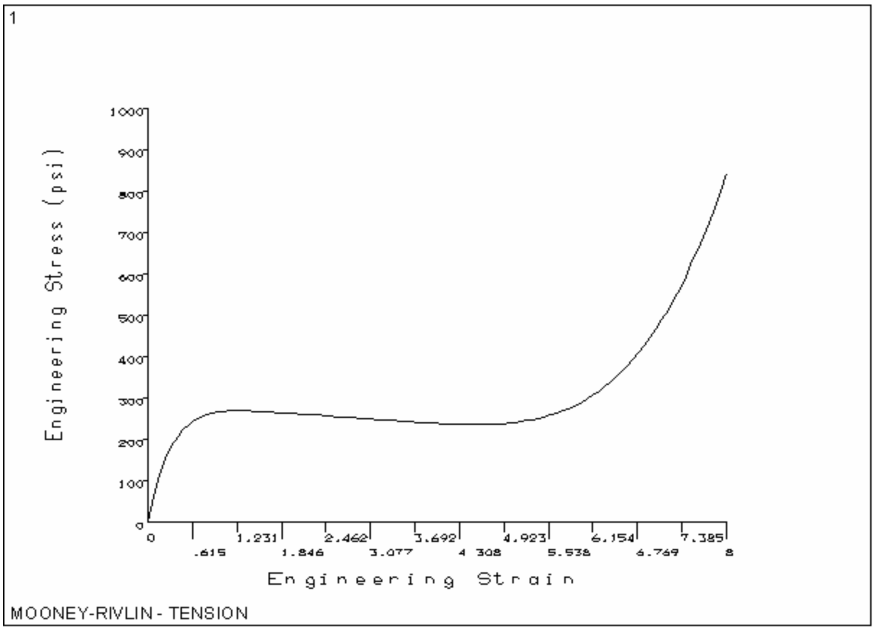


Figure 3.5.2.2-1 - Stress-strain curve for the Mooney-Rivlin material model.

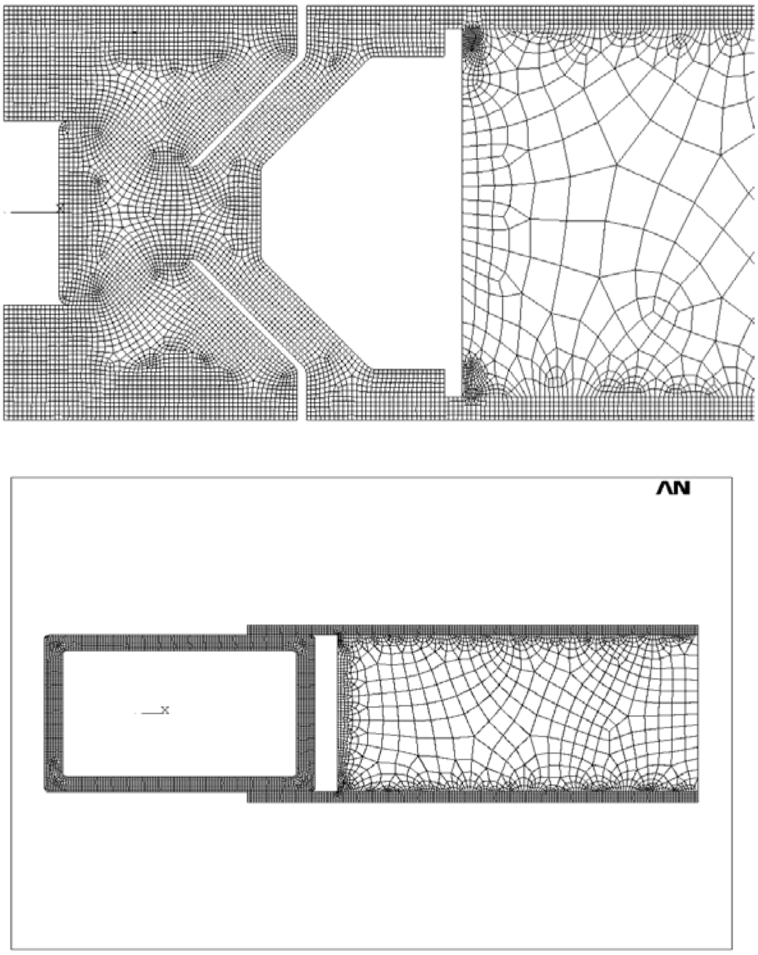


Figure 3.5.2.2-2 – finite element models of sandwich joints.

It should be noted that the joint performance of foam-filled hybrid metal sandwich panels can be better than that of all-metal sandwich panels. This is because the foam filling tends to improve the overall transverse stability of a panel, thereby reducing stress concentrations at welds.

Figure 3.5.2.2-3 shows the results of sandwich joint finite element analyses that highlight regions of stress concentration

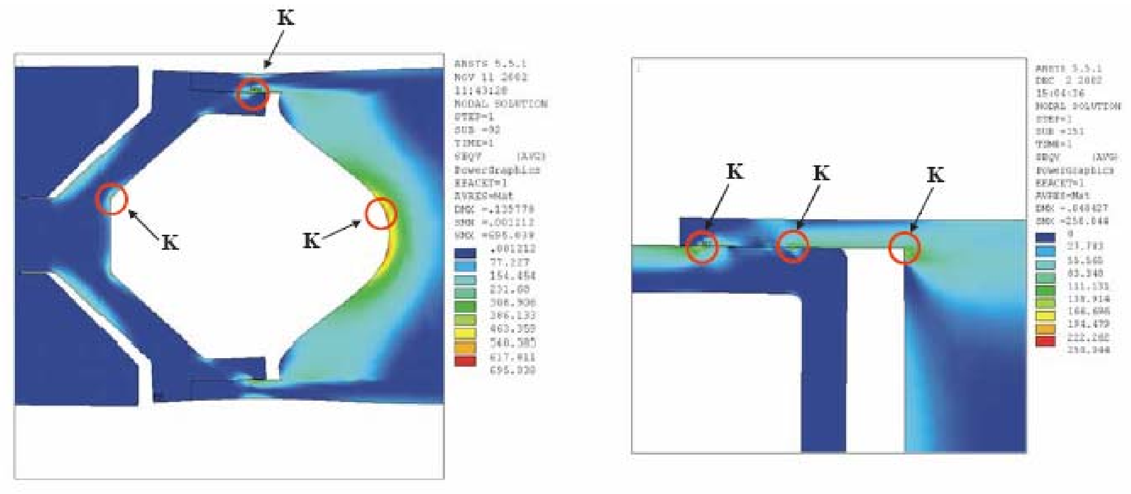


Figure 3.5.2.2-3 – finite element analyses showing regions of stress concentration (K) in sandwich joints.

3.5.2.3. Joint Analysis for Composite Sandwich Structures

3.5.2.3a. Joint Analysis for Composite Sandwich Structures: Analytical Approaches

The **composite sandwich joint** types shown in figures 3.5.1.3-1 and 3.5.1.3-2 in section 3.5.1.3 can be analysed, as a first approximation, by considering the shear and direct stresses in the adhesive interface and in the overlaminate. In this first approximation, the configuration is taken as being planar with one adherent (e.g. the patch or overlaminate) over the other (e.g. the base skin of the panel or web/flange). The analysis can then be carried out using a variety of closed form solutions such as the ones below:

- Shear lag model that neglects the effects of joint eccentricity and considers only adhesive shear deformation and adherent elongation (Volkerson 1938).
- A modified shear lag model that accounts for load eccentricities and resulting bending moments and consequential joint rotations (Goland & Reissner 1944).
- An approach based on elasticity theory and stress functions which satisfies the stress free boundary condition for a symmetrical lap joint; the solution for non-symmetrical adherents becomes unnecessarily complex and hence numerical solutions are preferred (Allman 1977).

In such approaches, the effects of the core material and the “unaffected” skin (i.e. the one away from the patch or overlaminate) are neglected since it is argued that the joint assessment is a localised phenomenon. Material properties are derived from either testing or from appropriate rule-of-mixtures formulations; such properties are smeared over the entire laminate and distinctions between laminae are not included.

As a most basic step, it would be advisable to check the shear stress in the adhesive layer by dividing the shear load by joint area.

3.5.2.3b. Joint Analysis for Composite Sandwich Structures: Numerical Approaches

For a more refined analysis after preliminary sizing of a joint, it is recommended that finite element analysis techniques should be employed to derive the limiting stress and other behavioural parameters.

In-Plane Joints

For in-plane joints, Cossich 2000 provides examples of how to conduct detailed assessments. He considered various scarf joints between two sandwich panels connected in-plane. The analysis mainly considered variations in the scarf angle, from about 60° to the in-plane direction to 90° to the in-plane direction. The finite element analysis was conducted using ANSYS. The following were some of the modelling issues:

- The sandwich panels being joined were modelled using isoparametric brick elements, with a coarse mesh away from the joint. The mesh became progressively more dense and detailed near the joint. The properties of the core were taken from manufacturers' data sheets. The properties of the skins of the sandwich were derived from in-house testing.
- The adhesive layer was modelled using isoparametric elements with isotropic properties; the adhesive properties were deduced from coupon level tests.
- The analysis type was linear elastic on the flexural load.
- Checks were made on element compatibility. Result convergence was benchmarked against gross load-deflection data derived from experiments on a few baseline joints.
- Once the FEA model was validated, results were extracted in terms of stresses in the skins and core and, importantly, in the adhesive joint. The adhesive stresses pertained to the tensile and shear modes respectively, with the former being the decisive value for determining limit state.

A typical plot of the stress patterns that can be obtained through detailed meshing is provided in figure 3.5.2.3-1.

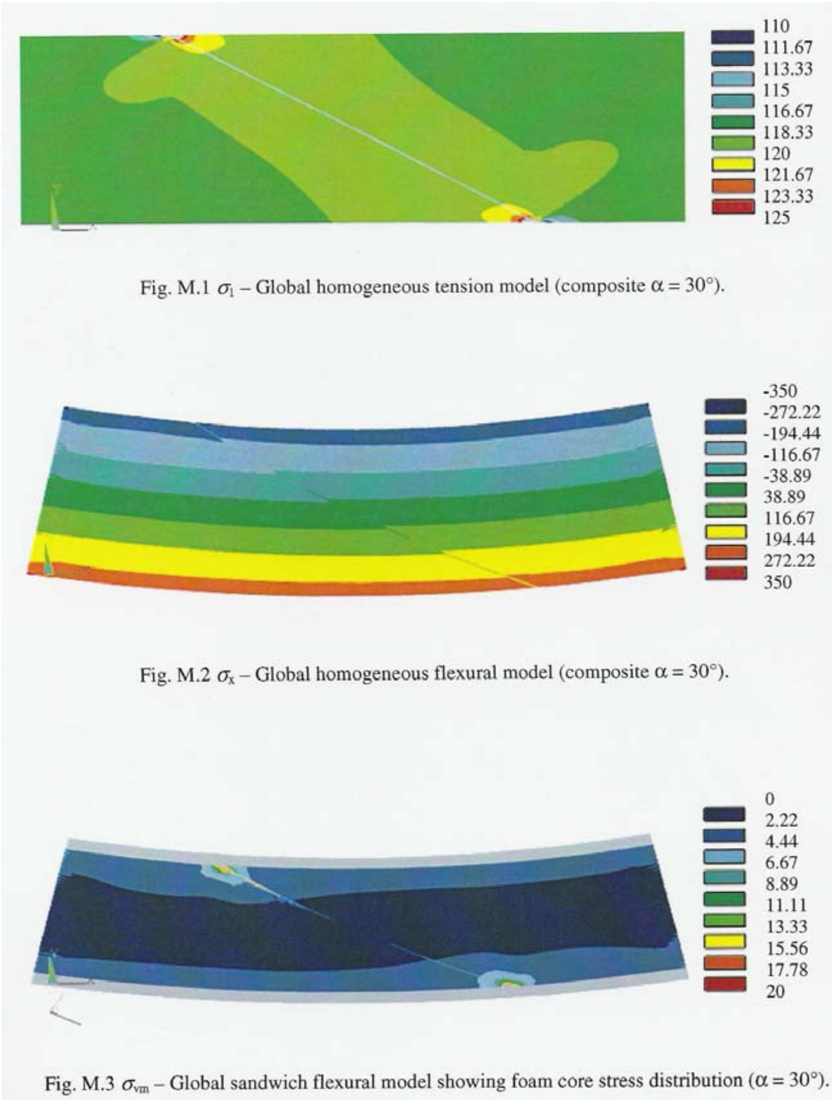


Fig. M.1 σ_1 – Global homogeneous tension model (composite $\alpha = 30°$).

Fig. M.2 σ_x – Global homogeneous flexural model (composite $\alpha = 30°$).

Fig. M.3 σ_{vm} – Global sandwich flexural model showing foam core stress distribution ($\alpha = 30°$).

Figure 3.5.2.3-1 - Example stress distributions for a composite sandwich scarf joint under tensile (M.1) and flexural (M.2, M.3) loads.

Tee Joints

When performing detailed analyses of tee joints, it is important that the modelling is carried out with due care given to the material properties pertinent for this depth of assessment. Section 3.1.1.2d addresses the generic modelling issues concerning polymer composite sandwich structures in more depth. Figure 3.5.2.3-2 shows an example of the meshing required to achieve a detailed assessment of load transfer, failure load estimation and failure mode determination – see Dulieu-Barton et al. (2001) for more details.

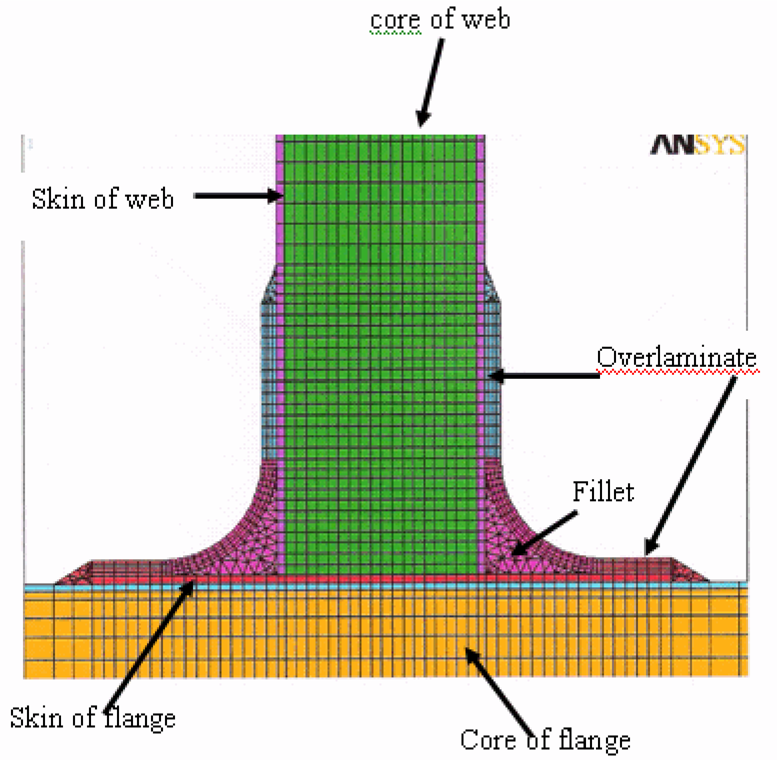


Figure 3.5.2.3-2 - meshing in the region of interest, namely in the curved overlaminate.

Some of the modelling issues relating to the composite sandwich tee-joint shown in Figure 3.5.2.3-2 were as follows:

- The sandwich panels forming the web and flange base plates in the joint were modelled using layered shell elements. Element properties, layer-wise, were derived from manufacturer's data sheets.

- The core properties used for the model were derived from supplier's leaflets. The skin properties were derived from the manufacturer's data base.

- The overlaminate joint was modelled using layered shells. Properties for the overlaminate were introduced on a layer-by-layer basis with data derived from the manufacturer.

- The fillet insert beneath the overlaminate was modelled using a plane strain isoparametric element with isotropic properties, consistent with the shell element used for the overlaminate and the skin of the flange.

- The analysis type was linear elastic. This was deduced from examination of the test results.

- The model was validated at a global level by considering load-deflection results.

- Stresses and strains were derived for the overlaminate region. Care had to be taken to ensure that stresses were derived in the principal axes of the materials in the local coordinate system; this necessitated transformation from the global axis system.

- Initial checks were done using the strain field to ensure that compatibility was maintained during the analysis. Only after this confirmation were the stress fields used against failure criteria of fillet limiting stress and through-thickness interlaminar stress for the overlaminate.

4. Sandwich Manufacturing

The "**manufacturing**" of sandwich materials is understood by this guide to refer to the processes and techniques employed to produce sandwich structures as pre-fabricated components. This primarily involves the joining of the facings to the core. It also includes the joining of connecting or edge profiles to the panel.

In most practical cases, the manufacturing of sandwich structures as components is performed by specialist suppliers. This is because sandwich manufacturing requires particular knowledge, equipment and processes that are not generally available within shipyards. However, as the target audience of this guide is potential users of sandwich structures, this section has been included by way of background to facilitate discussions with potential suppliers, customers and classification societies. It is the user who will normally select the type of sandwich structure to be employed based on the functional requirements of the application, cost constraints, and the availability / reliability of suppliers.

Sections 4.1 - 4.3 below refer to the sandwich panel types defined in sections 2.2 – 2.4, namely **all-metal**, **hybrid metal** and **composite**. The joining of sandwiches to other sandwiches, or to conventional structures, is addressed in section 5.1 – "Joining and Assembly". The implementation of penetrations, attachments, cut-outs, etc. is covered in section 5.2 – "Outfitting".

4.1. Manufacturing of All-Metal Sandwich Structures

With the exception of extruded aluminium profiles (which are not considered in this guide – for further information see, for example, www.corusgroup-koblenz.com/english/products/index.htm or www.aluminium-structures.com), the **manufacturing** of **all-metal** sandwich structures primarily involves the joining of purchased raw materials such as sheet metals (for the facings) and metal stiffening profiles or metallic foam blocks (for the core).

Three principal joining techniques are generally used to manufacture all-metal sandwich structures – **thermal joining** (e.g. arc welding, laser welding, or brazing), **adhesive bonding**, and **mechanical joining** (e.g. riveting or the DAVEX® process – www.davex.de). Whilst the first technique can only be used for all-metal sandwich structures, the latter two can also be used for hybrid metal or composite sandwich structures.

4.1.1. Requirements of the Base Materials

The **base materials** (i.e. the facing sheets and core elements) for all-metal sandwich structures are usually purchased by the panel manufacturer. Therefore, the production of these base components is not considered here. However, it is important to ensure that the base materials fulfil certain minimum requirements:

- The chemical composition of any base materials to be joined by welding should comply with minimum weldability requirements. In particular, steels to be laser welded should have a low carbon content, low sulphur and phosphor contents, and a fine grain structure. Special laser-weldable steels (e.g. RAEX) and some thermo-mechanically treated steels have been shown to be easily weldable in sandwich structures.

- The surfaces to be joined need to be clean and free of contamination. “Pickled” facings provide the best results.

- If flat bars are used as the core stiffening elements, their edges need to be rectangular or slightly bulbous to prevent gaps with the facings during welding.

- More complex stiffening elements (e.g. corrugations, L-profiles or Z-profiles) need to be dimensionally accurate and stable in order to minimise gaps during welding or bonding.

4.1.2. Laser Welding of All-Metal Sandwich Structures

With **laser welding**, the high energy density of the laser beam causes a rapid vaporisation of the work piece material. This results in a key hole and the characteristic long, thin shape of laser welds. This technique allows welding of sandwiches that are too thin (narrow) to allow conventional arc welding. The facings can be joined to core stiffeners by welding from outside of the panel through the facings (so-called “stake welds”). This is illustrated in figure 4.1-1 below. A second major advantage of laser welding is that it offers significantly higher welding speeds than arc welding. For these reasons, laser welding is (along with aluminium extrusions) by far the most widely used technique to produce all-metal sandwich structures for the maritime sector.

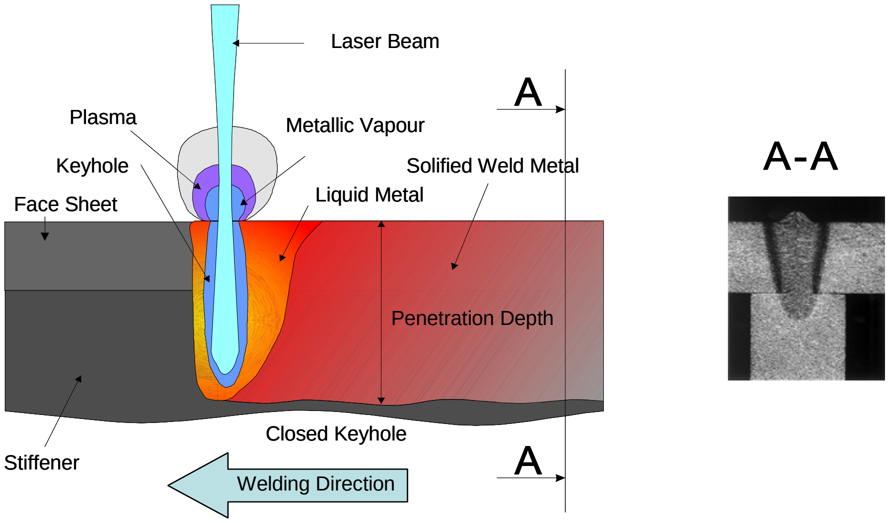


Figure 4.1-1 - laser welding of all-metal sandwich structures (from Roland et al. 1998).

Typical laser welding installations for sandwich structures are based on gantry systems that guide the laser beam to the work piece (see figures 4.1-2 and 4.1.3 below). The laser beam is normally focused using copper mirrors (for CO_2 lasers) or lenses (for solid state lasers) to a spot with a diameter of less than 0.5 mm diameter on top of the work piece.

Figure 4.1-2 - gantry and sliding table (from www.i-core.com)

Figure 4.1-3 - laser welding head (from www.schulergroup.com/en/30products/ 80laser_technology/20PEDILAS/index.php)

Key considerations relating to the laser welding sandwich structures can be summarised as follows:

- It is important to determine the correct focal parameters for the laser beam. By adjusting the focal length and diameter of the laser, the geometry of the welds, as well as other weld properties, can be modified.

- It is also important to accurately guide the laser beam along the internal stiffeners over the entire length of a panel (which might be up to 17 m for current installations). Mechanical guides can be used to help achieve this.

- The clamping system used for the internal stiffeners must be sufficiently accurate and flexible to accommodate different core geometries and scantlings.

- Pressure rollers attached to the welding head can be used to minimise the gap between the facing sheets and the core stiffener being welded.

- Edge profiles and outfitting components can also be integrated into sandwich structures using laser welding. Structures should, as far as is possible, be prefabricated to include edge profiles and outfitting elements such as penetrations and attachments. This is to prevent damage or quality problems during assembly and outfitting at the end-user.

- “Open” core geometries, such as corrugations, L-profiles, or Z-profiles, can be welded without panel turning. This results in one absolutely flat panel surface. “Closed” core geometries, such as flat bars or square tubes, require the panel to be turned for welding on both sides. This means that both facings will have visible laser welds at the surface.

- Air pressure testing is often used to check the integrity of laser welded sandwich structures. It should be noted that the high quality and reproducibility of the core-to-facing joints produced by laser welding is another of its key benefits.

Laser welding techniques are also used for all-aluminium sandwich structure. This includes CORALDEC™ developed by Corus, in which thin corrugated stiffening elements are laser welded to facing sheets

4.1.3. Alternative Manufacturing Techniques for All-Metal Sandwich Structures

Conventional arc welding using a special device is applied for the COREX™ all-metal sandwich structures by MacGregor (www.macgregor-group.com). Conventional arc welding is also used for some relatively "thick" sandwich structures such as the Schelde collision resistant Y-frame stiffened shells.

Adhesive bonding and **mechanical joining** can also be applied to all-metal sandwich structures. An example of bonding for all-metal sandwich structures is the patented Metawell® design (www.metawell.com). This panel has a corrugated core bonded to one or two thin cover sheets with a hot-melt glue. The resulting panel is extremely rigid and very light, particularly when used in big formats. It allows significant savings in weight. Another example is aluminium honeycomb panels in which the core is bonded (or brazed) to the facings

Sandwich structures with flat bars as core stiffeners can be manufactured by welding or mechanical fastening (e.g. using the DAVEX® process). Sandwich structures with corrugated or Z-profile cores can by manufactured by welding, adhesive bonding, or riveting.

4.2. Manufacturing of Hybrid Metal Sandwich Structures

As described in section 2.3, this guide considers three types of **hybrid metal** sandwich:

- Panels with **filled metallic core stiffeners**. The stiffeners are usually joined to metallic facings by welding (see section 4.1) or mechanical joining (e.g. using the DAVEX® process - see section 4.2.2). The filling material can be inserted by in-situ foaming (section 4.2.1.1) or adhesive bonding (section 4.2.1.2).

- Panels with **non-metallic core stiffeners**. Non-metallic core stiffeners can be joined to metallic facings by adhesive bonding or mechanical joining. These techniques are described in more detail in section 4.2.2 below.

- Panels with a **non-metallic solid core layer**. The solid core layer can be inserted by in-situ injecting, foaming, or adhesive bonding. Section 4.2.3 describes the manufacturing of these types of panel in more detail.

4.2.1. Insertion of Filling Materials into All-Metal Sandwich Panels

Depending on the type of core filling material, two principle techniques are used – **in-situ foaming/filling** and the **adhesive bonding of block materials**. Each technique is discussed separately in sections 4.2.1.1 and 4.2.1.2 below.

4.2.1.1. In-Situ Foaming/Filling

4.2.1.1a. In-Situ Foaming/Filling Techniques

Two component polyurethane foams of different densities were inserted under pressure into prefabricated all-metal sandwich panels as part of the SANDWICH European project (figure 4.2-1). Originally liquid, the foams solidified inside the prefabricated steel structures. Although the foams made good contact with the faceplates and the core stiffeners, their low density did not provide significant improvements to the strength of the panels. However, it was found that the damping and insulative properties of all-metal sandwich panels could be significantly improved by this method.

Figure 4.2-1 - in-situ foaming of an all-metal sandwich panel.

Light concrete can also be used as a material for filling all-metal sandwich panels (figure 4.2-2). Concrete is relatively cheap, easy to implement, and special grades are available that provide low densities and low shrinkage after drying. Tests conducted within the SANDWICH project demonstrated that concrete core fillings can significantly improve the local strength and fire insulation properties of all-metal sandwich panels (in conjunction with thin core stiffeners). Furthermore, whilst uni-directionally stiffened panels usually exhibit strongly orthotropic properties, light concrete can be used to significantly enhance panel properties in the transverse direction.

Figure 4.2-2 – all-metal sandwich panels filled with light concrete.

An A60 fire classed all-metal sandwich panel was developed within the framework of a Finnish research project (figure 4.2-3). In order to reduce the overall thermal conductivity of the panel, a large number of long holes were cut into the 0.7 mm thick core stiffeners, and the voids of the panel were filled with mineral wool.

Figure 4.2-3 – an all-metal sandwich panel filled with mineral wool.

4.2.1.1b. Advantages and Disadvantages of In-Situ Foaming/Filling

- In situ foaming/filling of all-metal sandwich panels is a less complicated and cheaper process than the adhesive bonding of block materials (section 4.2.1.2).

- Some filler materials (light concrete, mineral wool) can provide significant improvements to the performance of all-metal sandwich panels (in terms of load-bearing capacity and insulation respectively). The risk of internal corrosion can also be reduced.

- Such improvements in performance can often justify (technically and economically) the use of a core filler.

- To realise significant improvements in mechanical performance, the filling material must be well adhered to the faceplates and core stiffeners of the panel.

- The use of combustible core filling materials is likely to compromise further welding operations on a panel.

4.2.1.2. Adhesive Bonding of Block Materials

4.2.1.2a. Adhesive Bonding Techniques

Feasibility studies on the insertion of blocks of solid filling materials into all-metal sandwich panels have been carried out within two European projects – SANDWICH and BONDSHIP (figure 4.2-4). Materials investigated include balsa wood, PVC foam, polyurethane foam, ceramic foams and metallic foams

Figure 4.2-4 – all-metal sandwich panels filled with adhesively-bonded solid block materials.

As welding the second faceplate of a steel sandwich *after* bonding-in core filler materials has proven to be difficult without damaging the adhesive or any combustible materials employed, the following strategy for bonding solid blocks of material into an all-metal sandwich has been developed:

- Both facings of the sandwich are welded to provide a closed panel.

- Blocks of the filling material are cut to size allowing for a small gap between the blocks and the metallic structure to accommodate a “glue line”. Channels are also cut into the blocks to provide adhesive flow channels.

- The prefabricated sandwich panel is placed upright, closed on the lower side, and filled with an appropriate amount of liquid adhesive.

- The solid material blocks are then inserted into the cavities of the sandwich from the top of the panel. In doing so, the adhesive at the bottom of the panel is squeezed up through the gaps between the blocks and the metallic structure, as well as up through the channels cut into the blocks.

- Excess glue is removed from the top of the panel.

Although this approach does not guarantee a constant bond-line thickness, panels filled in this way have realised demonstrable performance enhancements, particularly with respect to increases in local indentation resistance.

4.2.1.2b. Advantages and Disadvantages of Adhesively-Bonded Block Materials

- The insertion of solid block materials into all-metal sandwich panels can improve a panel’s strength, particularly with respect to local indentation resistance.

- The properties of the adhesive can be exploited to improve a panel’s damping properties, reduce internal corrosion and accommodate differences in thermal expansion between the panel and the filler material.

- Welding on top of adhesives and combustible material blocks can result in adhesive damage, poor quality laser welds and toxic emissions.

- Bonding solid blocks into prefabricated “closed” panels appears to be feasible, albeit time consuming and relatively complicated. The technology requires further improvement for wide scale industrial application.

- The selection of the proper adhesive, insufficient experience in the design, dimensioning, performance and production of bonded joints, and a lack of relevant skills and experience are typical obstacles to the wider use of adhesive bonding in shipyards. It is therefore recommended to carry out the adhesive bonding of core filling material blocks at the prefabrication stage (i.e. at the panel supplier) or in consultation with bonding experts from research institutes, adhesive suppliers or classification societies.

4.2.2. Mechanical Joining to Produce Hybrid Metal Sandwich Panels

Recent German projects have investigated the fabrication and application of tailor made girders and lightweight components produced using the so-called DAVEX technique. With this technique, grooves are rolled into the facing sheets whilst a specific contour is embossed simultaneously in the edges of the web. The web is then put into the groove and closing grooves are rolled into the face sheets on both sides of the web. Rolling the closing grooves plasticises the sheet material, which then flows into the embossed contour of the web. The principle of DAVEX for beams is illustrated figure 4.2-5.

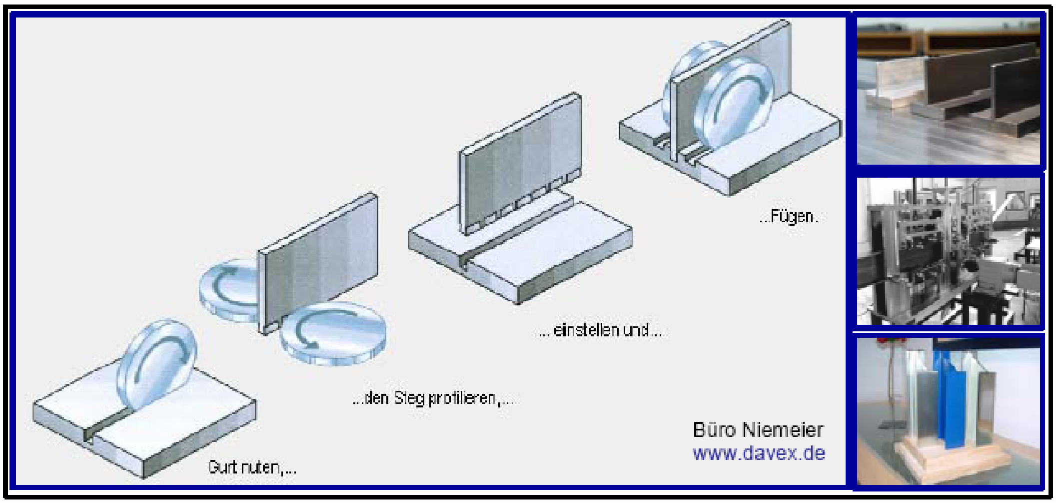


Figure 4.2-5 – overview of the DAVEX technique.

Whilst applications of the technique are currently limited to areas outside shipbuilding and are for single web profiles only (I-beams), the potential to use it for hybrid sandwich structures is worthy of further investigation. Its main advantages are its ability to combine metallic and non-metallic materials, and its suitability for mass production. On the downside, the technique is currently only suitable for linear joints. Furthermore, it requires complicated tools that are not yet available for panel production.

4.2.3. Manufacturing of Hybrid Metal Sandwiches with Non-Metallic Solid Cores

4.2.3.1. SPS

"SPS" (figure 4.2-6) uses a special elastomer as a core material that is injected into preformed air-tight cavities between two faceplates, either in pre-manufacturing or in-situ at a shipyard. After solidification of the liquid filling material, a rigid sandwich structure is formed.

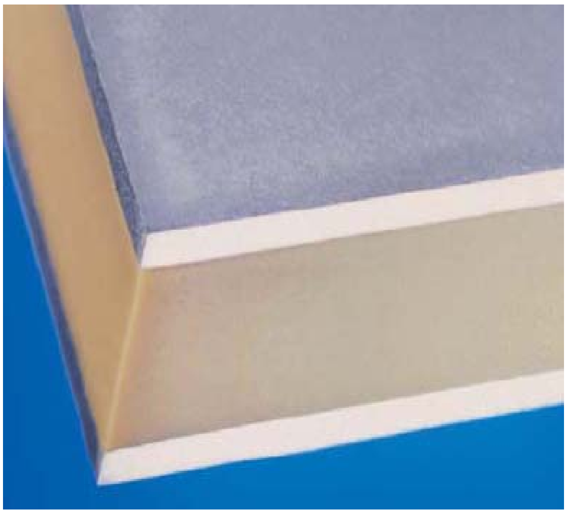


Figure 4.2-6 – SPS sandwich construction.

4.2.3.1a. Manufacturing of SPS Panels

The production process for SPS panels is as follows:

- Lay down the bottom face plate.
- Apply perimeter bars and internal spacers by welding or bonding.
- Clean internal parts.
- Install any outfitting items that need to be connected to the lower plate (see also section 5.2).
- Add the upper face (again including any outfitting items).
- Weld or bond the upper faceplate to the close the cavities.

- Install filling and air vent holes.
- Install restraint bars.
- Perform pressure test to check the cavities for leakage
- Inject the elastomer.

SPS has found substantial applications in ship repair (e.g. of RoRo decks and ramps) using the "overlay" technique. This technique uses the existing stiffened plating of the structure as the lower faceplate of the SPS sandwich. New-build applications at present are more limited. One example is funnel casings in which SPS panels provide a reduction in structural space and the necessary A60 fire performance. Another application has been a small inland barge. However, an application for an entire inland waterway chemical tanker mid-ship section is currently being prepared. According to Intelligent Engineering, more than 35,000 m^2 of SPS panels are currently in operation in the marine and construction sectors.

4.2.3.1b. Advantages and Disadvantages of SPS

- High weight (compared to all-metal or composite sandwich panels).
- In all currently known application cases, SPS panels have been produced at a shipyard, which requires specific skills and equipment. However, pre-manufacturing by external suppliers is planned according to the developer.
- Fabrication of SPS panels is a simple process and can be done under ordinary shipyard conditions. It is very easy to optimise in industrial production.
- Weld volume is reduced by up to 60% compared to stiffened plates.
- SPS is a robust design that reduces repair costs. Welding on top of SPS panels in assembly has been shown to be possible. However, repair requires, as is common with most types of sandwich, specialist skills and experience.
- Good heat insulation, vibration damping and crash resistance are other benefits of SPS panels.

4.2.3.2. INCA

INCA is a joint development between Det Norske Veritas and Aker Yards that uses light concrete to produce crashworthy side and bottom structures for ships. As is the case with SPS, the core filling material is introduced to cavities that have been produced by conventional welding. The low density concrete core has inherently good insulation and fire properties. Additionally, the properties of the concrete can be customised for different application cases. The density of the concrete core would typically be between 350 kg/m^3 and 1,200 kg/m^3. However, there is little information on this development currently available in the public domain.

4.3. Manufacturing of Composite Sandwich Structures

In comparison to all-metal and hybrid metal sandwich structures, a significant difference with the production of **composite** sandwich materials is that the fibre reinforced polymer facings are normally produced at the same time as the overall sandwich in a single manufacturing step. The lack of rigid facings prior to manufacturing means that complex shapes can be readily achieved through moulding processes. Indeed, the ability of composite sandwich structures to produce complex profiles or geometries is one of their main advantages compared to metal sandwich structures.

There is an extremely wide variety of generic and proprietary composite moulding techniques available. Here, four generic processes are described that cover a broad range of production volumes and structural capabilities. The interested reader is referred to www.netcomposites. com/education.asp?sequence=53 for a more detailed overview of composite manufacturing technologies, including diagrams of the various processes.

4.3.1. Hand Lay-Up

With hand lay-up, the dry fibre reinforcement is normally placed in a female mould and the thermosetting liquid resin is then applied, by hand, using a brush and/or roller to “wet-out” the fibres. Core materials (normally polyurethane foam or balsa) are positioned as required. Curing usually takes place at room temperature. Hand lay-up requires little capital equipment, but is labour intensive and product quality is very dependent upon the skill of the operator. It is well suited to the production of large non- or semi-structural parts in low volumes (less than 100 parts per year).

4.3.2. Vacuum Infusion

As with hand lay-up, the dry fibres and foams are placed in a mould. However, rather than applying the resin by hand, a vacuum is used to draw the resin through the fibres. A flexible cover, often referred to as a “vacuum bag”, is placed over the top of the mould to form a vacuum-tight seal. Compared to hand lay-up, parts produced by vacuum infusion are generally more consistent and have better mechanical properties (due to higher fibre volume fractions of up to 35%). Vacuum infusion is well suited to large parts (greater than 1 m) in low-medium production volumes (less than 500 parts per year).

4.3.3. Resin Transfer Moulding

Both hand lay-up and vacuum infusion use one-sided moulds. This means that it is only possible to control the geometry and surface finish of one face of the part. With resin transfer moulding (RTM) a two-sided mould is used. The dry fibre/foam preform is placed in the mould, which is then closed and resin is injected into the cavity. The two-sided closed mould permits the production of complex shapes with good surface finish and relatively high fibre contents (30 – 55% by volume). Furthermore, the use of catalysed resins results in short cycle times. This means that RTM is suitable for higher production volumes of up to around 30,000 parts per year. The main disadvantage of RTM is the cost of the two-sided tooling. This normally prohibits its use with small production volumes and/or parts that are larger than 2 m.

4.3.4. Prepreg Consolidation

Hand lay-up, vacuum infusion and RTM are all liquid resin moulding processes. Prepregs are different in that the fibre reinforcements have already been impregnated with partially cured "solid" resin. Prepreg materials normally come in rolls or sheets that can be easily stacked (along with the core materials) within a mould. Consolidation is then achieved by the application of pressure and heat using either a vacuum bag in an oven, or an autoclave. The advantages of prepreg consolidation over liquid resin moulding processes are that it is possible to achieved very high fibre volume fractions (up to 70%) and that it is easy to control the orientation of the fibres within the facing layers. This leads to very high performance, optimised, structural parts. However, prepreg materials are considerably more expensive than those based on liquid moulding technologies and the relatively long lay-up and curing times normally restrict their use to lower volume applications. Performance yacht hulls would be a typical marine application for sandwich materials with prepreg facings.

4.3.5. Guidelines on the Manufacturing of Composite Sandwich Materials

- Composite material manufacturing is not an exact science and there is no substitute for experience. It is generally recommended that such work is undertaken by a specialist subcontractor, particularly for structural parts.

- The choice of production technique will normally be influenced by application-specific factors such as production volume, tooling cost, and the required structural performance. Some rules of thumb with respect to these aspects would be:

	Increasing →			
Production Volume	Hand Lay-Up	Prepreg Consolidation	Vacuum Infusion	RTM
Tooling Cost	Hand Lay-up	Prepreg Consolidation / Vacuum Infusion		RTM
Structural Performance	Hand Lay-up	Vacuum Infusion	RTM	Prepreg Consolidation

- Prior to lay-up, moulds should be treated with a **release agent** to prevent the composite component sticking to the mould.

- For a good surface finish, apply a **gel-coat** to the surface of the mould prior to lay-up. Alternatively, a **surface veil** can be used to obtain a good quality resin-rich surface.

- There are a wide variety of formats available for the **reinforcement fibres** – chopped strand mats, woven fabrics, braids, stitched fibres, etc. The choice of reinforcement type is very important as it will influence the performance of the part, its surface finish, its processing characteristics, and the cost/time of lay-up.

- Similarly there are many options for the **core materials**. Cost-effective polymer foams such as polyurethane and PVC are compromised by their relatively poor fire, smoke and toxicity performance. Other foams such as PEI and PMI have better fire properties but are more costly. Balsa wood is still widely used for marine applications as a good compromise between performance and cost.

- Open cell foams and honeycombs are generally not well suited to use with liquid resin moulding processes. This is because the resin has a tendency to fill up the cavities in the core leading to a significant weight penalty. Closed cell core materials should be used with liquid moulding processes. Both honeycombs and open cell foams are compatible with prepregs.

- A key consideration when manufacturing composite parts is the viscosity and working time of resin. For example, if the resin is too viscous, it will be difficult to wet-out all the fibres. Similarly, if the working time of the resin is too short, it will begin to cure before the wetting-out processes have been completed.

- Particularly with thermosetting resin systems that cure at room temperature, it may be necessary to **post-cure** a composite structure after processing to complete the cross-linking of the polymer resin and achieve the best mechanical properties. This can be achieved using heaters, an oven or a warm room.

- **Fire performance** is likely to be an important consideration for composite sandwich structures in marine applications. This is because the thermosetting resin systems that form the basis of most composite sandwich structures are organic and hence burn. Phenolic resin systems have the best unmodified fire performance because, when burnt, they tend to produce a thick char that protects the underlying material. However, it is also possible to improve the fire performance of other resin systems (e.g. polyester) through the use of additives. One such additive is alumina trihydrate (ATH), $Al(OH)_3$, which decomposes upon heating to give aluminium oxide and water. The release of the water dilutes combustible gases, hinders the access of oxygen to the polymer surface and has a smoke suppressing effect. However, whilst fire performance improves with increasing ATH content, processing generally becomes more difficult due to the increased viscosity of the resin. There is also obviously a weight penalty in using fillers such as ATH.

- Because they are moulded, composite sandwich structures lend themselves to **design integration**. Significant reductions in part count can be achieved by “moulding-in” secondary parts and stiffeners as part of the primary manufacturing operations.

5. Joining, Assembly and Outfitting

5.1. Joining and Assembly

Whilst pre-fabricated sandwich structures are in many cases available from specialised suppliers, the **integration of sandwich components into conventional ship structures**, as well as the implementation of various outfitting components (pipes, cables, air conditioning, etc.), usually presents a challenge for most assembly yards. This is primarily due to a lack of sandwich experience amongst shipyard personnel, and a lack of "design for production".

This section aims to give potential users of sandwich panels an overview of the common problems and possible solutions associated with the assembly of all-metal, hybrid metal and composite sandwich panels within ships.

5.1.1. Joining and Assembly of All-Metal Sandwich Structures

5.1.1.1. Transportation, Handling and Fitting

Most types of **all-metal** sandwich panel have thin face sheets (as opposed to thicker conventional stiffened plates). Moreover, sandwich panels are usually stiffer than orthotropic plate structures. This makes the usual straightening and fitting operations more complicated and labour intensive.

Special care should be taken during the transportation and fitting of sandwich panels in the assembly shipyard. In order to avoid damage to panel edges, it is strongly recommended that they are supported by stiff and robust edge profiles (figure 5.1.1-1). These can be attached to panels at the pre-assembly stage (e.g. by the panel supplier), reducing the number of joining operations during on-board assembly. For cases in which edge profiles are not required to join sandwich panels, the use of temporary edge supports is recommended (e.g. profiles that can be removed before joining, or wooden supports) to protect the panel during transit.

Sandwich panels can be handled in a shipyard by using vacuum or magnetic devices applied to the top faceplate, or by mechanical clamps that are attached to robust edge profiles. Special temporary lifting supports can be welded to the edge profiles to support handling (see figure 5.1.1-1b). **Avoid using mechanical clamping devices on unprotected edges**.

(a) (b)

Figure 5.1.1-1 - a) all-metal sandwich panels with edge profiles, b) panel transportation via lifting supports attached to the edge profiles.

The weight of all-metal sandwich panels can lead to global distortions if they are improperly handled and transported. Due to the high stiffness and the thin faceplates, adjusting these distortions by thermal straightening or mechanical devices is not straightforward and can lead to further damage. It is therefore recommended that a sufficient number of clamping points or vacuum (magnetic) traverses are used for handling. On the other hand, the high stiffness of all-metal sandwiches does provide some handling advantages compared to conventional panels.

Furthermore, it is important that transportation companies and shipyard personnel are provided with adequate training on the handling of sandwich panels.

5.1.1.2. Joints Between Panels and Conventional Structures

The joining of sandwich panels to one other and to conventional ship structures (e.g. girders, bulkheads, etc.) represents the bulk of sandwich assembly operations. A selection of typical joints used to connect all-metal sandwich panels is shown in figure 5.1.1–2. The figure shows the preferred fitting direction, which should be considered in the design of the joints and in the planning of the assembly processes and sequence. The figure also shows that the type of joint employed largely defines the complexity and expense of assembly. For example the joint type at the top of the figure allows for welding from one side only, whereas the two other require welding from above and below (which is more difficult to carry out in a shipyard environment). On the other hand, the joint at the top is more costly. Close interaction between design and production personnel is therefore required when planning a sandwich application. Recommendations on joint design for easy assembly are provided in section 3.5.1.2 (“design of joints for production”).

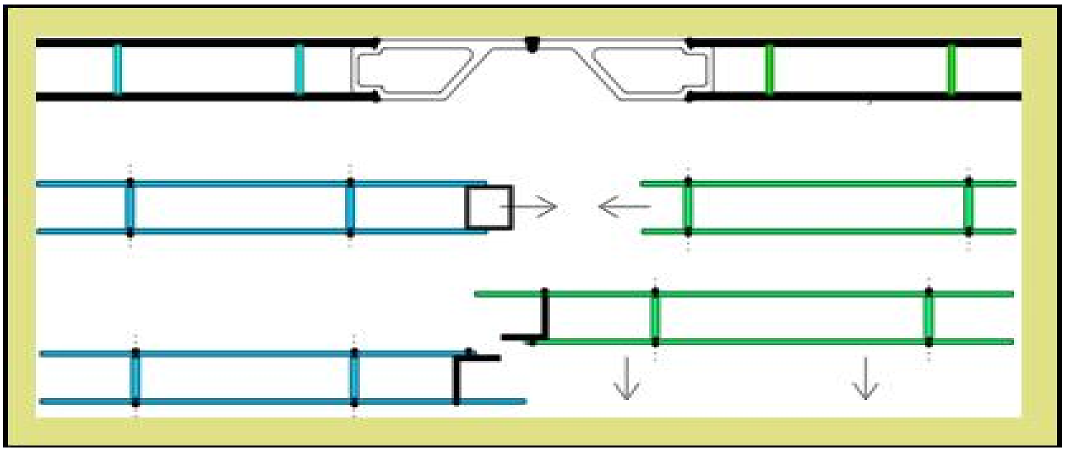


Figure 5.1.1-2 - typical joints between all-metal sandwich panels.

5.1.1.2a. Welded Joints

Welding is the most widely used technique for joining all-metal sandwich panels. Special care needs to be taken when making connections with the thin face sheets of sandwich panels. Some recommendations on the welding of all-metal sandwich joints are as follows:

- Whenever possible, **avoid welding directly on top of the face sheets**. Welds should be primarily placed on the more robust edge profiles of the sandwich panels.
- **Low heat input welding techniques** (e.g. gas metal arc welding rather than submerged arc welding) are strongly recommended for welded joints in order to prevent damage to the panels and to reduce distortions.
- Where available, **mobile laser welding equipment** is an excellent means of producing high quality joints with a drastically reduced heat input. Both equipment and the corresponding procedures have been developed by the DockLaser project (www.docklaser.com). Special task forces with mobile laser equipment may soon be available to conduct critical welds in assembly shipyards.
- **Special guidance** is required for the **welders** with respect to sandwich panel joints. Welding procedures and assembly guidelines are available from some sandwich suppliers (see, for example, www.i-core.com).
- **Automatic or mechanised welding equipment** (e.g. tractors) should be used to achieve a consistent weld quality and to reduce human error.

- As the stiffeners of all-metal sandwich panels are usually difficult to join, welds of the face sheets are normally used for load transfer. **Edge profiles can provide a backing for butt welds**, making them easier to produce.

- When sandwich panel connections are placed **on top of supporting girders**, the flanges of the girders can be welded to the face sheets with fillet welds. In less critical load cases, this solution can be used to join the lower face sheets of adjacent panels.

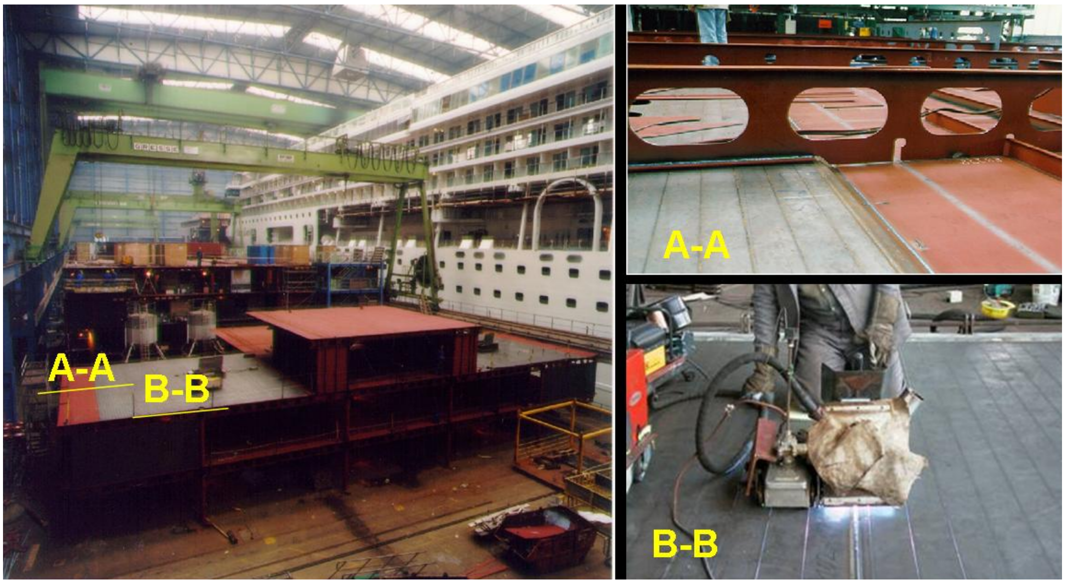


Figure 5.1.1-3 - typical joints between all-metal sandwich panels, and to conventional deck platings (source: Meyer Werft).

5.1.1.2b. Adhesively-Bonded Joints

Adhesive bonding can provide an alternative to welding for the joints of all-metal and hybrid metal sandwich panels. The most convenient joint for adhesive bonding is an overlap connection. Specialist expertise is required to design and produce adhesive joints. Adhesive bonding was addressed by the European BONDSHIP project (figure 5.1.1-4). The interested reader is directed to Roland et al. 2004 and Weitzenböck & MacGeorge 2005.

Figure 5.1.1-4 – example of an adhesive joint, taken from the BONDSHIP project.

5.1.1.3. Robustness in Assembly and Operation

The thin face sheets of all-metal sandwich panels require special care in design (section 3.5.1.2), assembly and operation to avoid damage and related problems. Typical examples of production damage and its associated issues include:

- Faceplate buckling arising from thermal distortions.
- Local puncture of the faceplates.
- Misfit due to pre-manufacturing inaccuracies or transport damage.

There are two principal approaches to the avoidance of such damage:

- The installation of sandwich panels by specialist groups of workers.
- A robust sandwich design.

The first option requires a certain critical mass to justify the investment in special equipment and training. The second option needs to be considered by the sandwich supplier in cooperation with the designers.

Furthermore, **welding sequences** need to be carefully planned to minimise distortions during assembly. Low heat input joining techniques, such as laser welding, adhesive bonding or mechanical joining should be applied as much as possible.

5.1.1.4. Last Minute Changes During Assembly

As for any kind of modular solution, any benefits due to economies of scale are marginalised by last minute changes. Sandwich panels are therefore most effectively applied in areas where the risk of such changes is low.

5.1.2. Joining and Assembly of Hybrid Metal Sandwich Structures

As described in section 2.3, **hybrid metal** sandwiches encompass:

- Metal sandwiches in which the core cavities have been filled with a non-metallic material (e.g. polymer foam or balsa wood).

- Sandwiches with metal facings and non-metallic core stiffeners.

- Sandwiches with metal facings and solid non-metallic core materials (e.g. elastomers, polymer foams, or lightweight concrete).

Normally, pre-fabricated panels will include **edge stiffeners** of various types. As a result, the joining of hybrid metal sandwich panels is in many respects similar to the all-metal sandwiches described in section 5.1.1. Reference is made to that section for additional information.

The combination of a sandwich panel with edge stiffeners results in a component that is quite stiff. This makes for easy handling during assembly, although some care must be taken not to damage (dent, or even perforate) the relatively thin faceplates. Obviously, care must also be taken not to deform the overall panel through mishandling. Sandwiches are less easy to repair on-site than conventional stiffened panels.

Similarly to all-metal sandwiches, edge stiffeners may comprise standard profiles (e.g. angle bars or rectangular tubes), or dedicated profiles (e.g. to facilitate special joint designs). When applying the joining welds, care must be taken not to damage (too much) any core filling materials.

The edge stiffeners may also be *solid* pieces of material. These may be provided with edge preparations to facilitate easy welding. Figure 5.1.2-1 shows a typical example for an SPS panel with a solid elastomer core. It should be noted that in this case the solid edge stiffener, apart from other considerations, also acts as a heat sink for the high temperatures induced by welding, thereby protecting the elastomer core material from burning or otherwise deteriorating as a result of the joining process.

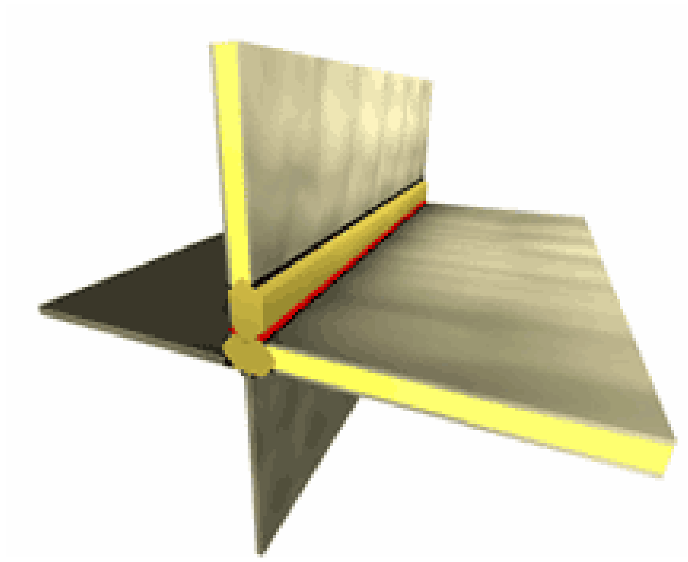


Figure 5.1.2-1 - edge stiffening of SPS panels (Intelligent Engineering).

Other examples of solid edge stiffeners are given in the provisional hybrid sandwich rules of Lloyd's Register 2006. Figure 5.1.2-2 shows two typical examples from this reference. Note that many of the panel joint welds are not full-penetration welds. Furthermore, the weld quality may be affected by the amount of solid steel in the edge stiffeners, and by the limited opportunity for pre-heating due to the presence of the elastomer core material. Consideration should also be given to the fatigue loading of joints, including the possibility of fatigue loading through vibrations.

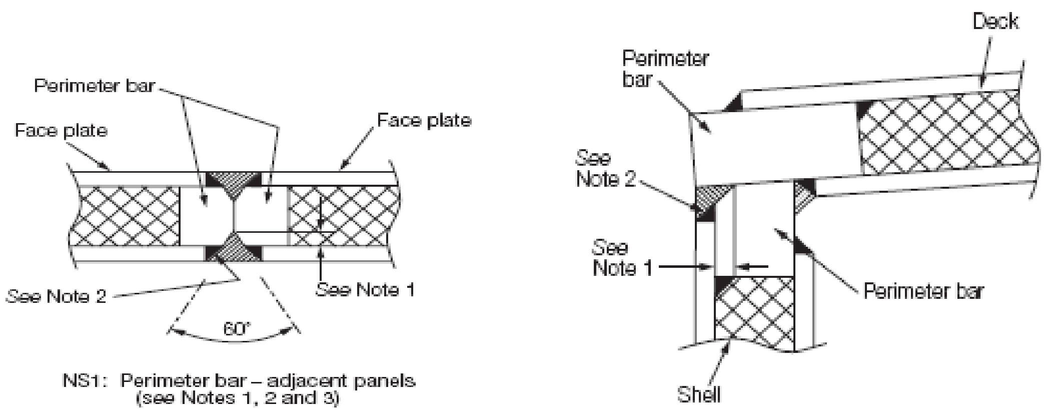


Figure 5.1.2-2 - examples of panel joints for hybrid sandwiches (Lloyd's Register 2006)

A special joining case is presented for **in-situ fabrication** of hybrid metal sandwich panels. At present, this is mainly confined to repairs, strengthening and modifications. The only sandwich system currently used is the *SPS-Overlay* system of Intelligent Engineering.

Briefly, this operation consists of first welding or gluing perimeter bars to the existing structure (which acts as the lower faceplate of the sandwich). A top faceplate is then attached to these perimeter bars, and the elastomer is injected. The process is described more fully in section 4.2, as well as in the appropriate sections of the Intelligent Engineering website (www.ie-sps.com). The Lloyd's Register provisional hybrid sandwich rules also give good examples for the application of the overlay technique, such as the one shown in figure 5.1.2–3.

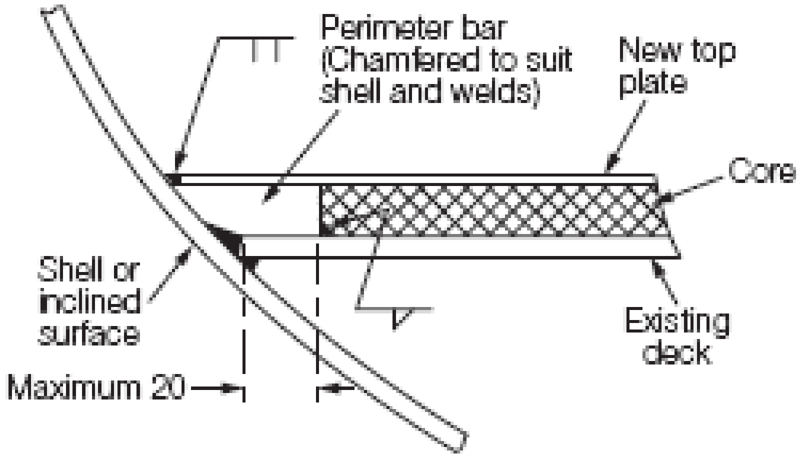


Figure 5.1.2–3 - example of a joint between a new overlay top plate and the existing shell structure (Lloyd's Register 2006).

The transition between a sandwich panel and a conventional stiffened plate structure must also be designed in such way that onboard welding is relatively easy. Note that attaching temporary lugs, etc. for bringing the two plates into line should not be used on the sandwich side as this may easily damage the thin sandwich facings and/or the non-metallic core material.

Assembly and joining may sometimes also be performed using techniques other than welding, such as bonding, bolting or riveting. Normally this is not recommended, but in some situations (e.g. where heat is to be avoided), it is a good alternative.

Other hybrid sandwiches use lightweight concrete as a core material. The fabrication of such panels is addressed in section 4.2. At present, little information has been published concerning aspects of their joining and assembly. It may be anticipated, however, that the joining techniques will be broadly similar to those described in this section. It is reasonable to assume that a concrete-filled sandwich system will be a bit more forgiving with respect to heat input into the core material during welding. It should be noted that the public descriptions of the system suggest an on-site filling of the cores rather than the pre-assembly of individual panels.

To summarise, some general guidelines for the joining and assembly of hybrid sandwich panels are as follows:

- Select, in consultation with the sandwich supplier, edge stiffeners that take into account the welding and assembly possibilities onboard (e.g. one-sided or two-sided welding).

- Care should be taken not to damage (locally or globally) the sandwich panels during handling.

- At a sandwich-to-stiffened plate connection, temporary means of alignment (e.g. lugs) should not be welded to the sandwich faceplates as they may easily damage the sandwich.

- Do not use bolts or other penetrations through the sandwich facings, unless the joint has been specially designed.

- Always ensure that edge stiffeners provide sufficient heat insulation / absorption capacity to prevent damage to non-metallic core materials during welding. Alternatively employ welding techniques that limit the heat input to the panel.

- Ensure that a good weld quality is maintained throughout the joint to reduce the risk of fatigue cracking in service.

- If pre-heating of the edge stiffeners is necessary prior to welding, make sure that it is applied in such a way that damage to the core material is avoided.

- In repairs or refurbishments that use the “overlay” technique, care must be taken that the joint welds comply with the basis used in the original design analysis.

5.1.3. Joining and Assembly of Composite Sandwich Structures

A typical cross-section of a boat of **composite** sandwich construction is shown in figure 5.1.3-1. It is evident that there are several examples of **joints** between sandwich panels. The important structural joints are the connections between major sections of the hull, between two panels butted in-plane, and between two orthogonally oriented members such as the hull and a bulkhead (i.e. a tee connection). The following sections address the fabrication issues associated with each of these joint types.

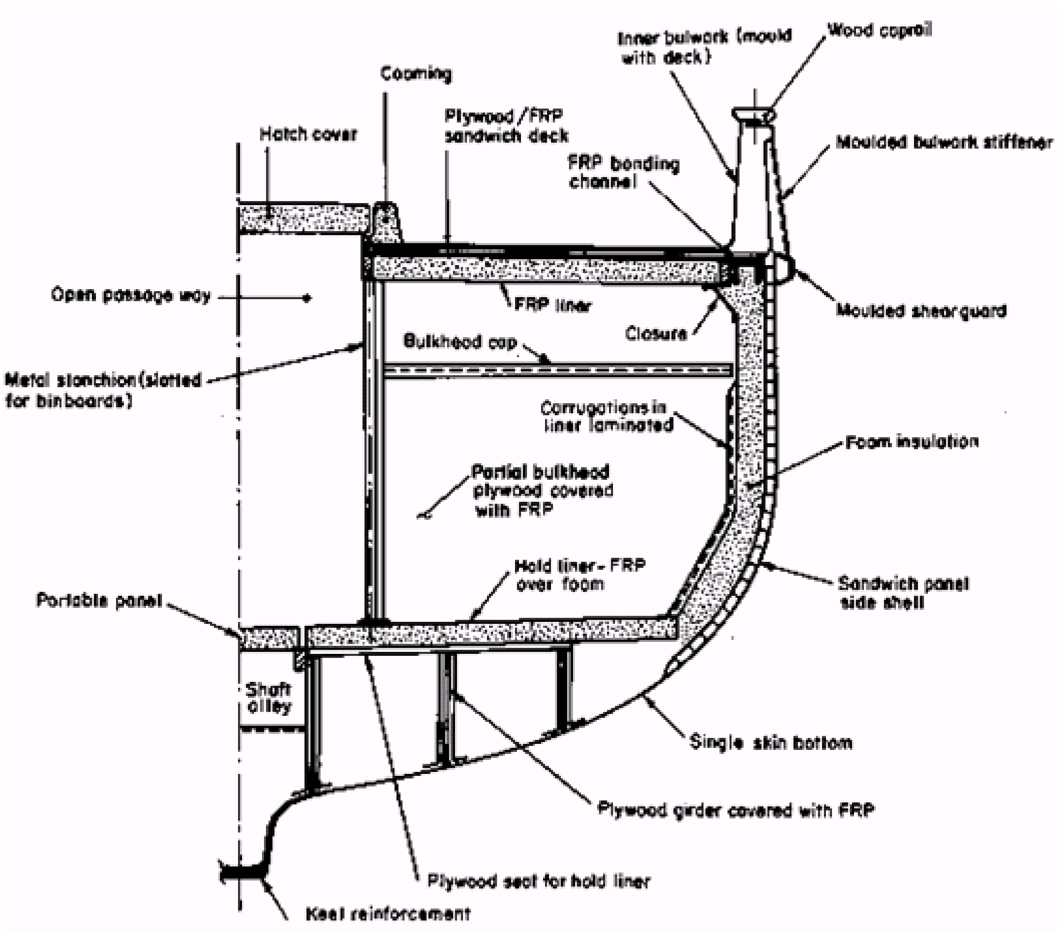


Figure 5.1.3-1 - cross-section of a composite sandwich boat (from www.fao.org).

5.1.3.1. Hull Sections

One approach to producing composite boat hulls is to make them in female moulds. Generally, the port and starboard sides are made in two separate moulds using hand lay-up, vacuum assisted resin infusion, or prepreg material (see section 4.3). The two cured halves are then brought together and joined through a combination of in-plane laminating and bolting at the keel section. Figure 5.1.3-2 shows a joined hull being taken out of its mould.

Figure 5.1.3-2 - boat hull being removed from a mould.

5.1.3.2. In-plane Butt Connections

In some cases it is necessary to join two flat panels, or even two curved panels (with common connecting slopes / curvatures). These joints are performed using the generic designs outlined in section 3.5.1.3. For hull connections however, further reinforcement, in addition to the overlaminating strips of the external and internal patch, is required. This is illustrated schematically in figure 5.1.3-3 below.

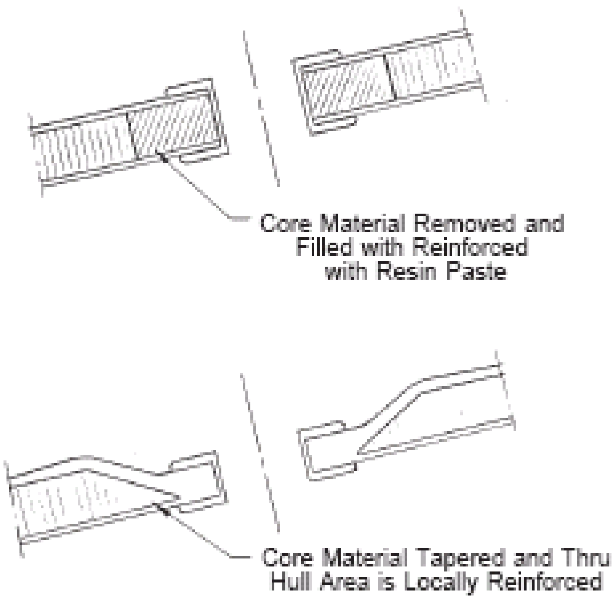


Figure 5.1.3-3 - recommended through-hull connection (from www.marinecomposites.com).

5.1.3.3. Tee Connections

A typical composite sandwich tee connection is shown schematically in figure 5.1.3-4.

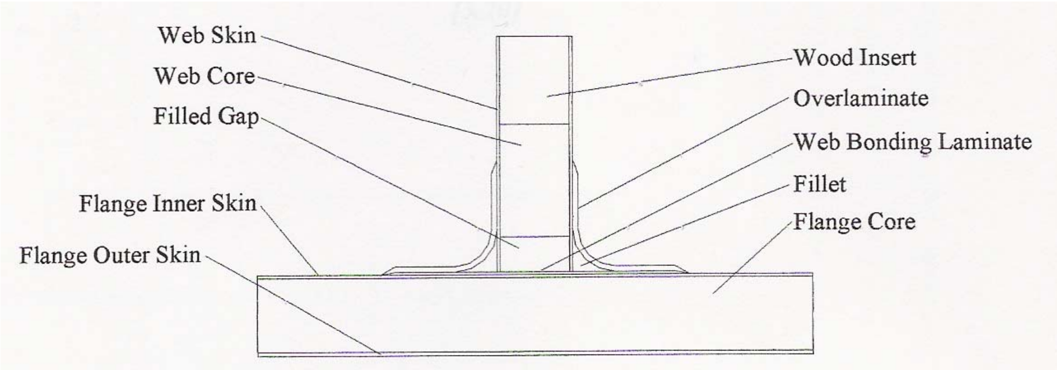


Figure 5.1.3-4 - tee connection.

In this context, the two panels forming the web and flange assemblies are moulded and cured separately. They are then brought together, held in position (usually by a crane), and overlaminated using one of three approaches: (a) hand laminating using pre-cut strips of reinforcement; (b) reinforcement strips infused with resin using assisted means; or (c) the application of prepreg laminae. In all three cases, the laminations are then cured using the material suppliers' guidelines.

5.2. Outfitting

Outfitting and finishing consists of installing into completed hull and deckhouse structures a wide variety of items necessary for making a vessel functional and comfortable. Such outfitting and finishing activities might include instrumentation, flooring, pipework, insulation, painting, etc. All of these items must be accommodated by the surrounding (sandwich) structure. Common outfitting activities associated with **sandwich structures** are:

- Surface treatment and cladding.
- Insulation.
- Penetrations and intersections (e.g. of cables / pipes through sandwich components).
- Attachment of outfitting items to sandwich panel surfaces.

- Foundations and local supports to carry the loads from outfitting elements into sandwich panels.

More care must generally be given to the outfitting and finishing of sandwich materials than is normally the case for more conventional structures. The reason for this is that sandwiches often involve relatively thin faceplates and non-traditional materials.

As many of the aspects relating to outfitting are similar for all-metal, hybrid and composite sandwiches, they are treated together in this section.

5.2.1. Surface Treatment and Cladding

Painting is probably the most ubiquitous way of giving a pleasing appearance to a structure whilst simultaneously providing protection against external influences, particularly corrosion. Paints may be applied to sandwiches, whether of steel, aluminium or composite, in the same way as conventional structures. Some types of vessel, for reasons of aesthetics, require especially smooth surfaces and this may require the substantial use of fillers. This is often the case with luxury yachts (figure 5.2-1). Using composite sandwiches allows the required aesthetic and finish quality to be achieved at a much lower cost compared to aluminium or steel construction. Indeed, often the shapes desired are practically impossible to fabricate in metal. Note that in such situations, the entire composite structure is normally built-up from a limited number of shaped components.

Figure 5.2-1 - sandwich superstructure for a luxury yacht produced from carbon/glass fibre reinforced epoxy facings and a polymer foam core (Rhebergen Composiet Constructies).

Some naval vessels, for reasons of diminished radar signature, also require very smooth and flat surfaces. The use of filler in such vessels is generally avoided. Instead, higher fabrication standards are demanded. The use of sandwiches may diminish the need for fillers and improve the surface quality (see the superstructure application case in section 8.1).

Interior partition walls in accommodation areas have for some decades been built using sandwich systems (e.g. thin steel skins with mineral wool cores). Generally, such sandwich panels cannot be described as load-bearing. Rather, they provide integral thermal and noise insulation, together with an aesthetic finish. Present-day hybrid-metal load bearing sandwiches offer the potential to integrate the same requirements concerning finish and insulation. Solid elastomer-filled sandwiches (SPS) have inherent A-60 fire insulation characteristics and possess very good vibration and noise (probably) insulation properties, albeit at a relatively high weight.

Conventional welded decks typically require an underlay of cement, latex mastic or similar for the purpose of smoothing out surface irregularities in the steel before a floor covering can be laid. Using sandwich structures for decks reduces or removes the need for an underlay because of their inherent flatness, thereby saving a substantial amount of weight. A special way to use sandwiches for deck smoothing is the so-called *SPS-Overlay* technique, which is used mainly for the refurbishment of decks, bulkheads and similar. The old, deteriorated deck structure is overlaid with an elastomer layer and a new deck plate (see sections 4.2 and 5.1.2). This can be done in a very short time, significantly reducing the direct and indirect costs of such refurbishment. Furthermore, the deck structure becomes much more impact resistant and possibly provides better fire insulation.

5.2.2. Insulation

Insulation can be applied to the outside of sandwich panels in the same way as for conventional structures. However, sandwiches also offer some additional possibilities. A solid or foamed sandwich core may inherently possess noise and temperature (or even fire) insulation properties. This may also be achieved by filling otherwise empty sandwiches with foam, wood or other materials. Note that metal stiffeners, such as those found in I-Core, may reduce the insulating effectiveness of a filling material by providing facing-to-facing routes of high thermal conductivity. However, measures can be taken to counteract this such as the inclusion of large openings.

In terms of noise and vibration insulation, it should be noted that many sandwich structures have superior vibration damping characteristics compared to single-plate structures. Also the high stiffness of sandwiches often results in higher natural frequencies than for the equivalent single-plate structures. This may be beneficial with respect to noise.

5.2.3. Penetrations

Penetrations through bulkheads and decks pose some special problems when using sandwich panels, particularly with respect to tightness and transverse strength. Normally, all-metal panels such as I-Core are supplied by the manufacturer with edge profiles that close the sandwich interior in an airtight way. If a penetration through a panel is subsequently made as part of an outfitting process, care must be taken to ensure that the sandwich interior is made airtight again. If not, internal corrosion might occur, which is difficult to detect and even more difficult to protect against. Ideally, openings for piping, access, ducts, etc. should be included in the pre-fabricated panels (figure 5.2-2). However, this sets strict requirements for early design, as well as design (and fabrication) control. Alternatively, a part of the panel may contain a single plate area for the purpose of facilitating later penetrations (figure 5.2.3).

Non-metallic cores, whether in hybrid metal or composite sandwiches, are less susceptible to humid air ingress. However, some non-metallic core types, such as balsa wood, may experience similar problems in terms of water ingress. This is, of course, particularly important for penetrations through tank bulkheads or outer shells.

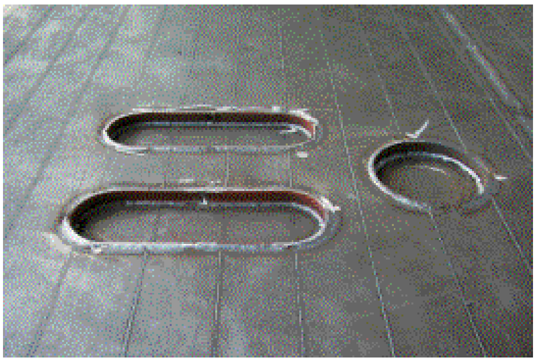


Figure 5.2-2 - manholes pre-installed in an I-Core panel (Meyer Werft).

Figure 5.2-3 - a concentrated bundle of pipes passing through a single plate area in I-Core (Meyer Werft).

A second problem with penetrations through sandwiches arises from the inherently thin face plates and light, but generally not very strong, core material. Many penetrations require stressing in order to prevent loose connections and to ensure tightness. Generally, this is provided by screwing a nut or similar onto the penetration (figure 5.2-4). This leads to through-thickness compression of the sandwich. Often local reinforcement will be needed to allow the sandwich to accept such through-thickness compression. High-density foam fulfils that role in the composite case shown in figure 5.2-4.

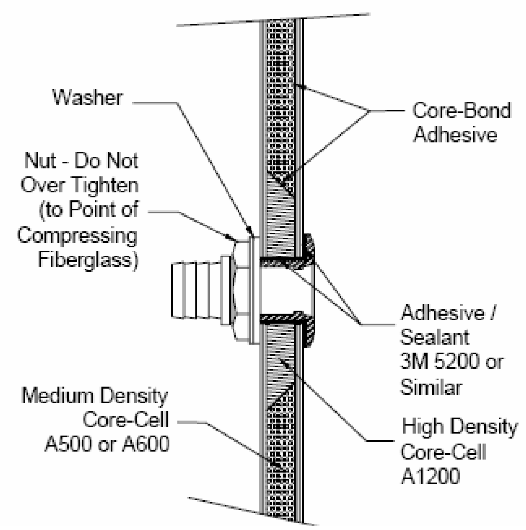


Figure 5.2-4 - pipe penetration through a composite sandwich (Horsmon & Bernhard 2003).

5.2.4. Attachments

With conventional steel plate structures, the relatively thick steel plates often allow attachments to be welded directly at any location, with little concern given to local strength (although welding over a stiffener is generally preferred). If the same attitude was applied to the outfitting of sandwich structures, serious problems might arise. *Welding* on the skins of all-metal and hybrid metal sandwich panels is possible. However, the heat input must be restricted to avoid burning a hole in the faceplate and/or melting or burning a non-metallic core material. In this respect, *adhesive bonding* may be preferable.

Experience with adhesive bonding in marine applications exists through the BONDSHIP project, but it is not yet widespread in its application. If adhesive bonding is used, sufficient contact area must be provided between an attachment and the sandwich skin. A temporary means of applying pressure (and sometimes heating) during cure must also be provided. For composite sandwiches, the adhesive bonding of attachments is more common. In such situations, the bonding is not normally directly between an attached item and the sandwich skin, but around the item using fibre mats to reinforce the connection (figure 5.2-5). The resulting connection is similar to that between a main sandwich and a stiffener as shown in figure 5.2–6

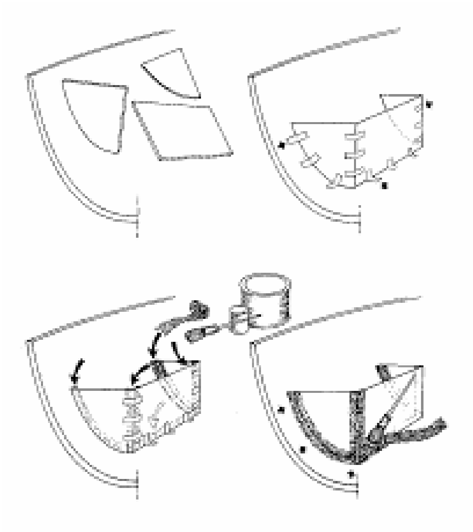


Figure 5.2-5 - a bench laminated into a composite hull (Lok 2001).

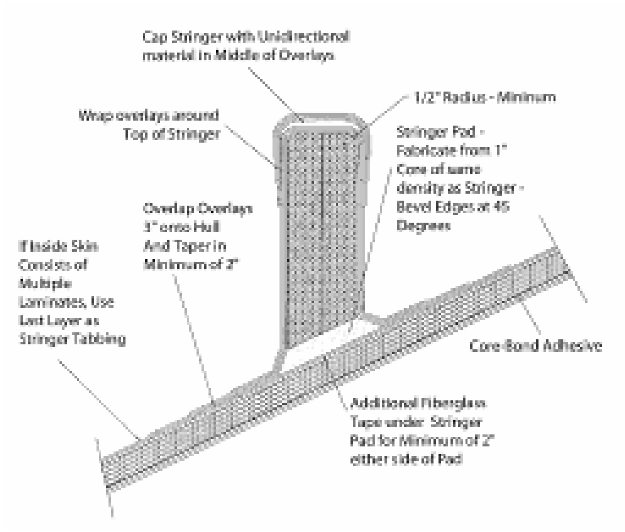


Figure 5.2-6 - connection between a web frame and a hull (Horsmon & Bernhard 2003).

Mechanical fastening, such as bolting or riveting, is also a possibility, even with all-metal sandwiches (figure 5.2-7). Self-tapping screws are sometimes an option for use with composite sandwiches. For naval use, a special composite "nail" (screw) was developed for allowing attachments to composite sandwich hulls without completely penetrating the sandwich. In this way the water-tightness of the sandwich was maintained.

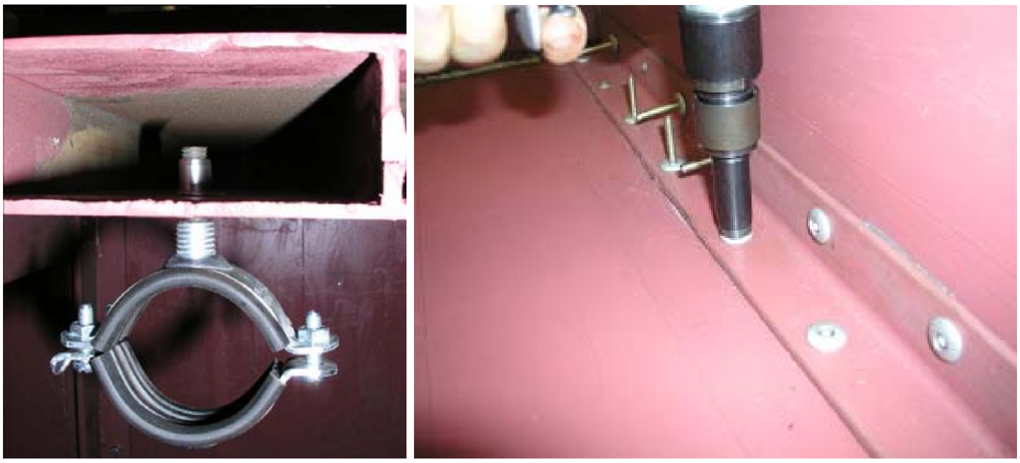


Figure 5.2-7 - bolted connection (left) and riveting (right) to the faceplate of an all-metal sandwich (Henkel et al. 2005).

When the loads exerted are somewhat large or more dynamic in nature, it is preferable that attachments are not positioned over an unsupported part of a sandwich faceplate. For an all-metal sandwich, the attachment should, if possible, be situated over an internal stiffener. This provides additional stiffness and strength.

When a direct connection to a faceplate is considered insufficient, a few alternative solutions exist. One is to spread the contact of the attachment over a larger area, thereby reducing the concentrated load. This is a similar approach to that used for adhesively-bonded attachments. In hybrid sandwiches with a solid core (SPS), attachments applied directly to a faceplate tend to exert a tension that may cause core-facing debonding. In such situations it is common to use inserts in the sandwich. For example, lashing pots for cars in a RoRo ferry might be installed prior to application of the SPS overlay technique (figure 5.2-8). In this way the lashing pots are directly connected to the elastomer core over a large area. If this area is insufficient, additional plates connected to the pot may be used.

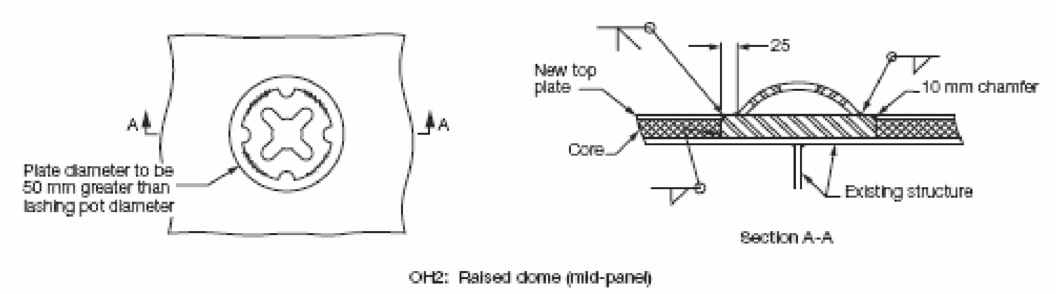


Figure 5.2-8 - lashing pot in an SPS panel (Lloyd's Register 2006).

Some attachments are so heavily loaded, or the core material is sufficiently weak, that a connection through the total thickness of the sandwich is necessary. This can be the case with composite sandwiches. Generally this will involve bolting. The bolts may introduce additional compression to the core material in the same way as the penetrations described earlier. A reinforcing “hard point”, such as a piece of metal or an area of more compression resistant core (e.g. high-density foam, balsa or other wood) may be used to take this compression force (figure 5.2-9).

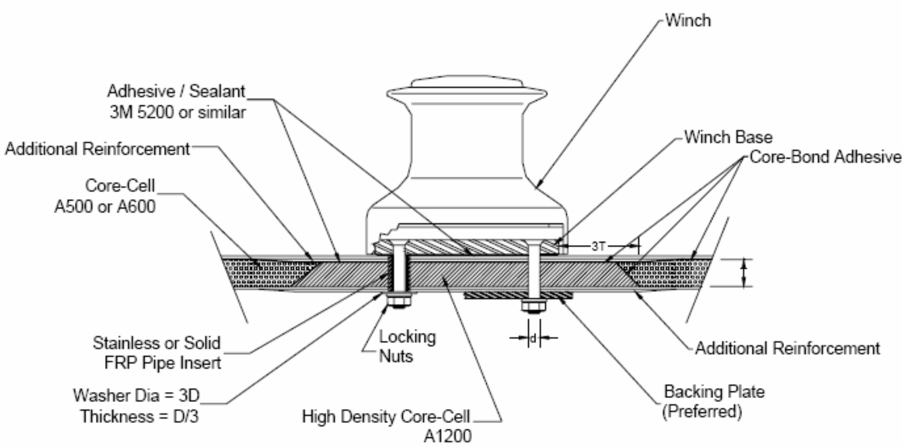


Figure 5.2-9 - attaching a small winch to a composite sandwich using through-thickness bolting (Horsmon & Bernhard 2003).

5.2.5. Foundations

If outfitting items exert loads on the structure that are too high for the sandwich to transmit, foundations must be provided as in conventional ship structures. This will mean a load transfer directly to bulkheads, web frames or similar through foundations designed as in conventional structures. The sandwich generally will be omitted in the vicinity of the foundation.

5.2.6. Recommendations for the Outfitting of Sandwich Structures

- Identify outfitting items at an early stage of the design process and attempt to incorporate the necessary reinforcements, if any, in the prefabrication of the sandwich panels.

- Select the location of outfitting attachments carefully with respect to internal core stiffeners (if present) in order to minimise the flexibility of the attachment and the resulting risk of vibration and fatigue.

- If the prefabrication of outfitting attachments is not possible (or too late in the production process), consider a relatively large external support area that distributes the load over the sandwich

- Avoid damaging (e.g. denting or burning-through) the sandwich facings during the installation of outfit items.

- Avoid damaging any non-metallic core materials though excessive welding on the faceplates.

- Avoid opening the faceplates for the installation of outfit items. If unavoidable, take preventative or corrective action to re-establish air- or water-tightness as appropriate.

- Check the air-tightness of a sandwich after outfitting (where appropriate) by air pressure testing or similar.

6. Inspection and Repair

For sandwich structures to be accepted by end users (e.g. ship owners), clear guidelines for the **inspection, repair and maintenance** of a sandwich throughout its life cycle will be required. Customers will normally expect quality based on EN ISO 9001:2000, as well as formally documented quality plans and handbooks. This section summarises current best practice for the inspection and repair of sandwich structures to assist potential users in their discussions with owners and classification societies.

6.1. Inspection

6.1.1. Visual Inspection

6.1.1.1. Visual Inspection of All-Metal Sandwich Structures

The **visual inspection** of **all-metal** sandwich structures should be performed throughout the production process, starting with the base material of the core and the facing sheets, and ending with the outfitting of the finished panel. According to Macro 2000, there are two approaches to visual testing – **direct** and **remote**.

6.1.1.1a. Direct Visual Inspection

Direct visual inspection can be performed when there is an uninterrupted optical path from the observer's eye to the test area. The inspection can be aided, for example, by a mirror or magnifying lens (figures 6.1.1.1-1 – 6.1.1.1-3).

Figure 6.1.1.1-1 - direct visual inspection of laser welded I-Core panels.

Figure 6.1.1.1-2 – aid to visual inspection (from www.schneiderkreuznach.com/ neuheiten/lupen.htm).

Figure 6.1.1.1-3 - Agfa Lupe 8x photographers' stand magnifier.

6.1.1.1b. Remote Visual Inspection

Remote visual inspection is when there is an interrupted optical path from the observer's eye to the test area. Remote visual inspection includes the use of photography, video systems and robots.

The **endoscope** is a small instrument that uses visible light to create an optically magnified image on a monitor. The endoscope technique can be used to detect defects that are not visible to the naked eye. Endoscopes are optically sensitive and their images are obvious and therefore easy to interpret. Endoscopes are also employed to access places that are otherwise difficult to inspect, which has made them valuable tools for producers and end-users of sandwich panels (figures 6.1.1.1-4 and 6.1.1.1-5).

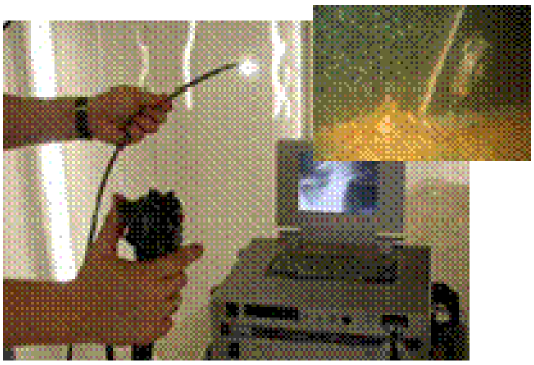


Figure 6.1.1.1-4 - remote visual testing with an endoscope (from www.timemax-rostschutz.de/endoskopie.html).

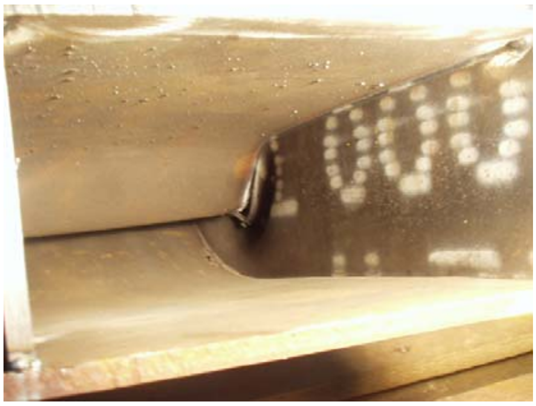


Figure 6.1.1.1-5 – an endoscope image from inside an I-Core sandwich panel.

6.1.1.1c. Guidelines on the Visual Inspection of All-Metal Sandwich Structures

A documented visual inspection procedure should consider the following aspects as a minimum:

- The object to be tested, its location and other relevant details.
- The extent of the test coverage.
- The technique and the sequence of performing the test.
- The surface condition and preparation.
- The stage of manufacture or service life when the test is carried out.
- The requirements of personnel.
- The acceptance criteria.
- The illumination (type, level and direction).
- The visual testing equipment to be used.
- The post-test documentation to be used.

Independent from the production process of the sandwich panel (welding, bonding or mechanical fastening), visual inspection can be used to assess the following possible imperfections:

- Base material (geometry, tolerances, surface quality).
- Condition of consumables (e.g. filler material or adhesive).
- Joint design (e.g. surface preparation, weld penetration, adhesive thickness).
- Quality of the connection (e.g. welding scraps).
- Optical imperfections.
- Dimensions of the panel (tolerances).

The evaluation of suitability should be performed by skilled personnel in accordance with the quality handbook.

The following norms provide further guidance on visual inspection:

- EN 473 - Qualification and Certification of NDT Personnel - General Principles.
- EN 970 - Non-Destructive Examination of Fusion Welds - Visual Examination.
- EN ISO 8596 - Ophthalmic Optics - Visual Acuity Testing - Standard Optotype and its presentation.
- pr EN 1330-1 - Non-Destructive Testing - Terminology - List of General Terms.
- pr EN 1330-10 - Non-Destructive Testing - Terminology - Terms Used in Visual Testing.
- pr EN 13018 - Non-Destructive Testing - General Principles - Visual Testing.
- pr EN 13927 - Non-Destructive Testing - Visual Testing Equipment.

6.1.1.2. Visual Inspection of Hybrid Metal Sandwich Structures

With respect to the **visual inspection** of **hybrid metal** sandwich structures, most of the information provided in this section is based on experiences with SPS (section 2.3). However, in many cases the guidelines can be adapted to other hybrid sandwich types as well.

One of the most critical aspects of hybrid metal sandwich panels is the bond between the core and the faceplates. For this reason, visual inspection should be used to assess aspects that are critical to the integrity of the core-to-faceplate bond. Some of these are discussed in the sub-sections that follow.

6.1.1.2a. Visual Inspection During Panel Production

During the **production process**, visual inspection can be used to deliver the following information:

- **Surface quality of the faceplates**: for a good bond with the core, a certain roughness of the faceplates is necessary. Grit blasting is the most common method for achieving this required roughness. Visual inspection can be used to check the following points:
  - No rust on the inner surfaces of the faceplates.
  - Appropriate use of a primer (according to the specification of the core material supplier).
  - Surface roughness. The core material supplier will normally provide guidance on the required surface roughness. The achieved roughness can be checked using the procedure outlined in ISO 8501-1. This document describes various surface preparation grades, including photographs.

- **Cleanliness of the face plates**: the inner surface of the faceplates should be free from dirt and dust as these can compromise bond strength. They should be wiped with a cleaner before closing the cavity and injecting / bonding the core material.

- **Humidity inside the core cavity prior to injection / bonding**: high humidity (or even water) inside the core cavity will adversely affect the production process. The water will react with the core material during injection to give a poor quality core. To remove moisture, warm air can be blown through the cavity. As a further check, the humidity of the air leaving the cavity can be measured using an appropriate sensor.

6.1.1.2b. Visual Inspection During Assembly and Outfitting

During the **assembly and outfitting** of hybrid metal sandwich panels, the most important consideration is (once again) the maintenance of the bond between the core and the faceplates. High impact loads (e.g. through the careless transport of panels) or high heat input (e.g. through welding) should be avoided. To check such aspects visually, the following points should be considered:

- Inspection of the panel faceplate surfaces prior to installation:
  - No buckles or dents in the faceplates due to mechanical damage after the production process.
  - No marks caused by flame cutting on the faceplates.
  - No marks caused by welding (e.g. from the fitting of brackets, etc.).

- Inspection during the assembly and outfitting of panels:
  - Before welding: the weld preparation at the panel edges should follow the instructions of the panel manufacturer or design office (see figure 6.1.1.2-1 for example).

- During welding: to minimise heat input to the core / adhesive, the weld volume should be reduced to a minimum and the weld procedure should follow the instructions of the panel manufacturer or design office. A fillet weld gauge can be used to measure the weld throat thickness (for example) - see figure 6.1.1.2-1.

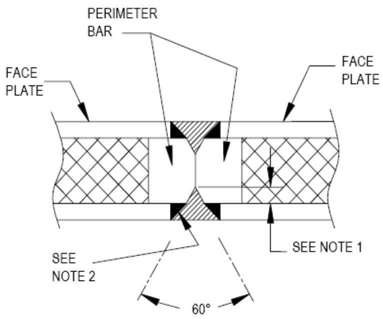


Figure 6.1.1.2 - 1 - panel weld preparation drawing (left) and fillet weld gauge (right).

- Inspection of the panel faceplate surfaces after assembly:
  - No buckles or dents in the faceplates arising from assembly work.
  - All parts attached to the panel during outfitting have been welded using procedures approved by the panel manufacturer or design office.

6.1.1.2c. In-service Visual Inspection

During service, hybrid metal sandwich panels may deteriorate if not properly maintained. This can occur due to inadequate design or as a result of abnormal circumstances such as grounding, collision or fire. Deterioration is not always easily visible in hybrid panels and regular checks should be made. Through visual inspection, information can be gained to estimate the safe working condition of hybrid panels and guard against deterioration from:

- Local dents due to small impacts or concentrated loads.

- Larger deformations due to overload in normal operation or following accidents.

- Corrosion.

- Corrosion streaks (which may indicate leakage) -see figure 6.1.1.2-2.

- Fatigue and other cracks.

- Excessive vibrations (which may be indicated by core-to-facing debonding).

Figure 6.1.1.2–2 - corrosion streaks developed by a sandwich panel in service.

In many cases, more detailed **non-destructive examination** methods will need to be applied when visual inspection indicates potential damage. For hybrid metal panels, such techniques are described in section 6.1.2. If the size of the damage detected is deemed to be critical, the panel will have to be repaired (section 6.2.2).

6.1.1.3. Visual Inspection of Composite Sandwich Structures

In **composite** sandwich production, **visual inspection** is an important aspect of quality assurance. It should be incorporated into a quality assurance strategy that includes:

- Monitoring the production process.
- Documentation.
- Following procedures.
- Checking values, and evaluating discrepancies.

Even though visual inspection is the most commonly used examination method, it can be problematic because it relies on the senses of a human being. Furthermore, results cannot always be interpreted objectively. The qualitative nature of visual inspection relies on the training and experience of the inspecting personnel, the level of alertness of personnel, the operating conditions, and the accessibility / visibility of the structure to be inspected. The challenge is often the translation of non-measurable data into objective acceptance / failure criteria.

Instruments that help the human eye with visual inspection include:

- Endoscopes (see section 6.1.1.1).
- Rigid and flexible video scopes, along with television systems.
- Optical fibres.

In the aerospace industry, the usefulness of visual inspection for composite sandwich parts is sometimes questioned. This is because in-service damage that might compromise the structural integrity of a sandwich component is not always readily visible. However, in the marine industry, visual inspection is regarded as a meaningful and cost-effective instrument, particularly if it is conducted by expert personnel. It is predominantly a monitoring tool that seeks to identify potentially problematic areas which can then be examined further (e.g. by non-destructive examination – section 6.1.2.3).

6.1.1.3a.Visual Inspection During Production

Visual inspection can provide insights into the following aspects of composite sandwich **production**:

- Raw material quality (e.g. inclusion solids, porosity, cracks, etc.).
- Resin formulations and mixing - checking and recording the amounts of base resin, catalysts, hardeners, accelerators, additives and fillers.
- Environmental conditions.
- Foreign material inclusions.
- Wetting out of fibre reinforcements.
- Voids and delaminations in facing laminates.
- Surface quality.

- Cure of adhesive and matrix systems.
- Surface preparation (prior to bonding).
- Assembly errors (e.g. positioning accuracy, delaminations, misalignments, etc.).
- Insufficient preparation of core surfaces for resin absorption resistance.
- Improper core contact with first facing, especially in female moulds.
- Application of second facing before a core bedding compound has cured.
- Insufficient bedding of core joints.
- Contamination of the core material (e.g. dirt or moisture).

The following techniques can be applied in the production of sandwich structures to facilitate easier visual inspection:

- By avoiding the use of gel coats and pigments in the facings of a glass-reinforced polymer sandwich, the laminate remains transparent, thereby making voids, pits, cracks, crazing, inclusions, delaminations, and debonding of the core more clearly discernible. After inspection of the product, a top coating should then be applied for the protection and avoidance of UV degradation, osmosis, etc.
- Vacuum infusion with a transparent foil allows for easy monitoring of the resin flow. Air inclusions, voids and dry spots are clearly visible, and can be rectified during the production cycle. This is an advantage over other closed mould systems.
- Where possible, adhesives should be injected into closed cavities. In this way, the adhesive can be injected up until the point at which it becomes visible at the out-gassing locations, thereby ensuring that the cavity is filled with adhesive.

Figure 6.1.1.3-1 provides an overview of the scope of composite sandwich visual inspection throughout the production process.

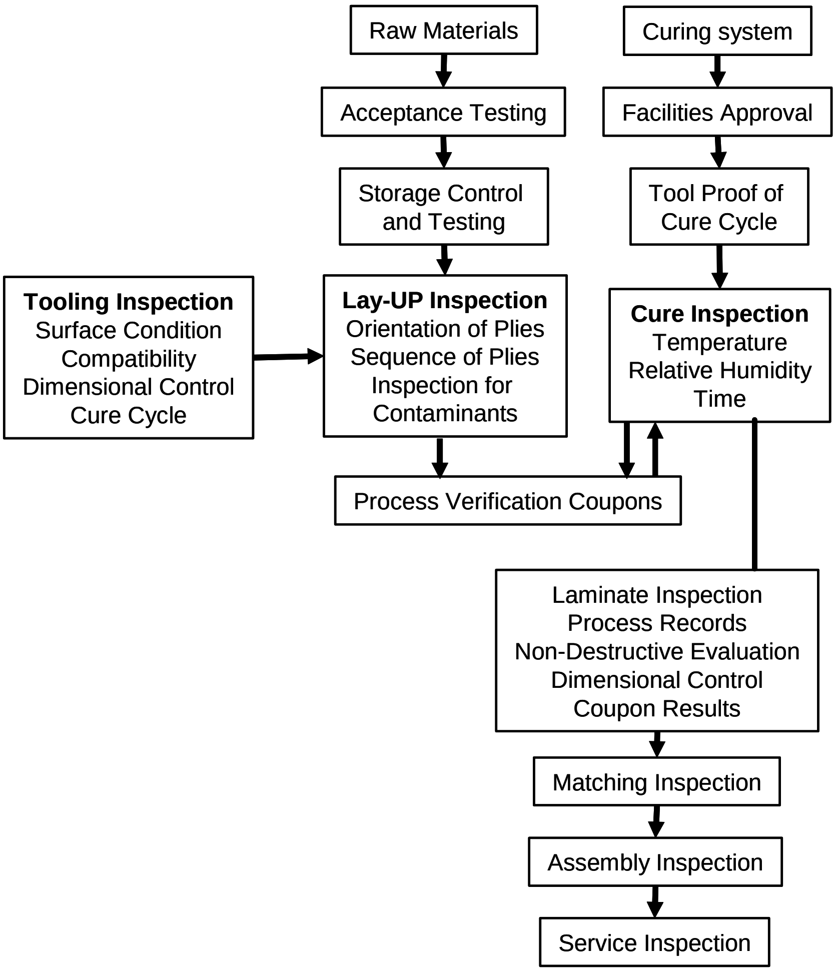


Figure 6.1.1.3-1 - inspection requirements for composite materials (from: U.S. Air Force - Advanced Composite Design).

6.1.1.3b. Visual Inspection During Operation

Regular visual inspection during **operation** provides insight into the condition of a composite sandwich with respect to:

- Blistering, osmosis and UV degradation.
- Impact damage - dents, folds, disbonds, delaminations and cracks.
- Debonding of the core and joints within a sandwich part.
- Debonding between a composite part and an adjacent structure.
- Failure of functions - visual inspection hopefully provides advanced warning.

- Poor fit – pull-out of inserts, aging, hardening, disbonds.

- Matrix cracking, delamination, fibre breakage and interfacial debonding providing insight into degradation due to cyclic loading.

It should be stressed that visual inspection cannot pick up all of the potential defects in a composite sandwich structure. For example, typical defects in a composite sandwich that cannot be easily detected via visual inspection are core failure and core-to-facing debonding. Therefore, the manufacturing process should always be monitored carefully, and non-destructive examination (NDE) methods should also be applied as required (see section 6.1.2.3).

6.1.2. Non-Destructive Examination

Non-destructive examination (NDE) involves the investigation of the mechanical integrity of materials and structures without affecting their functionality and quality. Terms also used for this type of examination are **non-destructive inspection (NDI)** and **non-destructive testing (NDT)**. NDE technologies include x-ray analysis, ultrasonics, eddy currents, penetrant dyes, magnetic particle inspection, thermal inspection, holography, microwave and others. Those that are most relevant to **sandwich structures** are discussed here.

6.1.2.1. Non-Destructive Examination of All-Metal Sandwich Structures

Many different types of defects in **all-metal** sandwich structures can be inspected by **non-destructive examination (NDE)**. These include:

- Raw materials (gas / solid inclusions, porosity, cracks).

- Assembly errors (positioning accuracy, debonding).

- Stress and heat stress (fatigue cracks).

- Corrosion (pitting, stress, galvanic).

- Impact damage.

- Leakages.

There are a wide range of NDE techniques available that can be applied during the production and operation of all-metal sandwich structures. Some of the more effective methods are described below. Some of these may also be applicable to hybrid metal (section 6.1.2.2) and composite (section 6.1.2.3) sandwich panels.

6.1.2.1a. Leakage Testing with Pressure or a Vacuum

An effective way to ensure the leak-tightness of empty all-metal panels is a **pressure** or **vacuum** test (figure 6.1.2.1-1). These tests are important when the sandwich panels are used for applications such as watertight bulkheads or tanks.

Figure 6.1.2.1-1 - pressure test on an I-Core panel (left) and vacuum testing equipment (centre & right – from www.mr-chemie.de/wEnglisch/produkte/Lecksuche.shtml?navid=25)

6.1.2.1b. Ultrasonic Inspection (Through Transmission)

Ultrasonic inspection uses a transducer to transmit a high frequency mechanical vibration into the part under evaluation. When the wave strikes a flaw perpendicular to the direction of the wave, a portion of the wave is reflected back to the transducer. By measuring the time between the transmitted and the received wave, the depth of the flaw is determined. The strength of the returned signal relates to the size of the flaw. Ultrasonic inspection is one of the most widely used NDE techniques for quality control and service-integrity evaluation because it is relatively inexpensive and also convenient for data acquisition. Generally, ultrasonic testing can be used to detect flaws, determine the size, shape and location of defects, and identify discontinuities in materials. The technique is especially suitable for detecting air pockets and distributed air inclusions, such as porosity.

There are three types of ultrasonic inspection techniques, namely A, B and C-scans. The most widely used is the C-scan technique which can be automated and provide information on flaw location using a two dimensional image of the component under test.

One of the features of the ultrasonic technique is the requirement for a liquid film coupling between the ultrasonic probe and the component under test. C-scanners couple the ultrasound into the material using water jet probes. The detected peak values in the transmission signals are stored on computer and may be visualised in colour. Several applications are shown in figures 6.1.2.1-2 – 6.1.2.1-5.

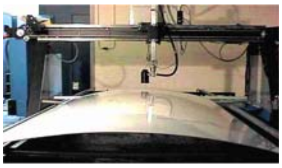


Figure 6.1.2.1-2 - C-scan instrument Midas 3m x 1.5 m.

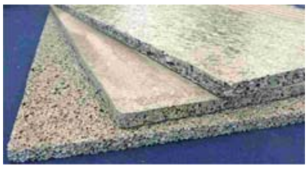


Figure 6.1.2.1-3 - metal foam sandwiches

Figure 6.1.2.1-4 - cross section of a metal foam sandwich.

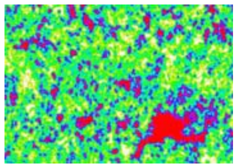


Figure 6.1.2.1-5 - C-scan image of a metal foam showing big voids in red.

The C-scan technique is very sensitive, capable of accurate defect sizing, and is easy to interpret. For example, a defect with an effective size of 3 mm can still be detected. The detection limit for small defects in the axial direction of irradiation is half a wavelength, which depends on both the material and the frequency. For example, in aluminium the detection limit is about 0.3 mm.

One of the limitations of the technique is that one flaw could obscure another one situated directly beneath it, thus requiring both sides of a test object to be accessible. This problem can be overcome by conducting a B-scan (linear inspection) in the region of question using an “angle probe”. The C-can technique has been employed to inspect steel, aluminium, fibre-metal laminates, composites, thermoplastics and sandwich-honeycombs.

6.1.2.1c. Eddy Currents

Eddy currents are alternating electrical currents, usually of high frequency, which can be induced to flow in any metallic section, their flow pattern being disturbed by the presence of cracks or other discontinuities (figure 6.1.2.1-6). The flow pattern of the eddy currents is either circumferential, using encircling or concentric coil configurations, or tangential or circular when using a surface or pancake coil configuration. The eddy currents have their own associated magnetic field pattern, which is detectable by electromagnetic means. The presence of a flaw in the material affects the flow pattern of the eddy current, which in turn affects its associated magnetic field, and the change is detected by a suitable search coil arrangement. The search coils are usually wound in the form of a differential transformer, with the primary or excitation winding being fed from an oscillator. Two secondary windings observe the eddy current effects at displaced sections of the material under test, and automatically compare the cross-sections for any differences which may occur.

The inspections are carried out with a portable instrument which has an impedance plane (figure 6.1.2.1-7). A rotor probe can be connected for (rivet) hole inspections.

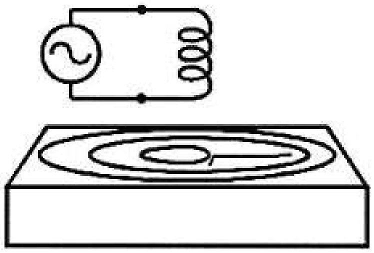


Figure 6.1.2.1-6 - eddy current principle (from www.vm.lr.tudeflt.nl).

Figure 6.1.2.1-7 - eddy current probe (from www.rd-tech.com/probes.html).

The limitation of the technique is that the sensitivity decreases quickly with increasing crack depth. The technique is mainly applied to metal products of relatively small thickness. More advantages, applications and limitations of eddy current testing can be found at www.geocities.com/raobpc/index.html.

6.1.2.1d. Liquid Penetrant Inspection

Liquid (or dye) penetrant inspection is an extension of visual inspection and is used for detecting surface-breaking flaws on any non-absorbent material's surface.

The basic stages of liquid penetrant inspection are shown in figure 6.1.2.1-8. Firstly, the surface to be inspected is cleaned thoroughly to remove all traces of dirt and grease. A brightly coloured or fluorescent liquid is then applied liberally to the component surface and allowed to penetrate any surface-breaking cracks or cavities. The time the liquid is allowed to soak into the material's surface is normally about 20 minutes. After soaking, the excess liquid penetrant is wiped from the surface and a developer applied. The developer is usually a dry white powder, which draws penetrant out of any cracks by reverse capillary action to produce indications on the surface. These (coloured) indications are broader than the actual flaw and are therefore more easily visible. If applied correctly, liquid penetrant testing offers a fast, cheap and relatively simple means of surface inspection. It can also be used as a quick and simple method for checking that welds and other susceptible areas are free from surface-breaking flaws (figure 6.1.2.1-9).

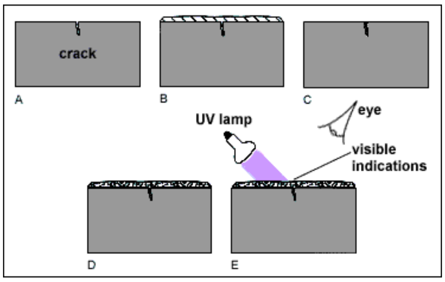


Figure 6.1.2.1-8 - Principles of liquid penetrant inspection (from Munns).

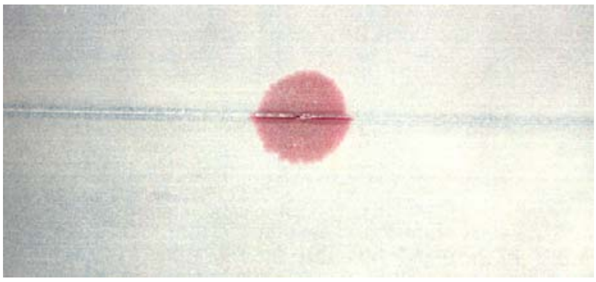


Figure 6.1.2.1-9 - detected crack in a laser welded I-Core sandwich panel (from Reinert 1996).

6.1.2.2. Non-Destructive Examination of Hybrid Metal Sandwich Structures

The strength of **hybrid metal** sandwich panels is strongly influenced by the quality of the bond between the core and the faceplates. Whilst visual inspection (section 6.1.1.2) can provide an indication of potential damage sites, **non destructive examination (NDE)** may be necessary for the verification and evaluation of the nature of the damage.

This section focuses on the NDE techniques that are specifically relevant to hybrid metal sandwich panels. More general approaches for assessing weld quality are described in section 6.1.2.1 (NDE of all-metal sandwiches). The information provided is based on experiences with SPS panels (section 2.3), but can easily be adapted to other types of hybrid metal sandwich.

6.1.2.2a. Pre-Injection Tests

The bond strength between the core and the faceplates is strongly influenced by the surface preparation of the faceplates. Generally, a certain roughness of the plate surface is required to ensure a good bond strength. This is usually carried out by visual inspection (section 6.1.1.2), but if a more precise evaluation is required, the surface roughness can be measured using a surface roughness measurement device (e.g. www.taylor-hobson.com). Examples of such instruments are shown in figure 6.1.2.2-1. Briefly, the operation of these devices relies on a sensor which is slid over the plate surface and detects the actual surface form. This surface form is then translated to a numerical display of an average surface roughness value.

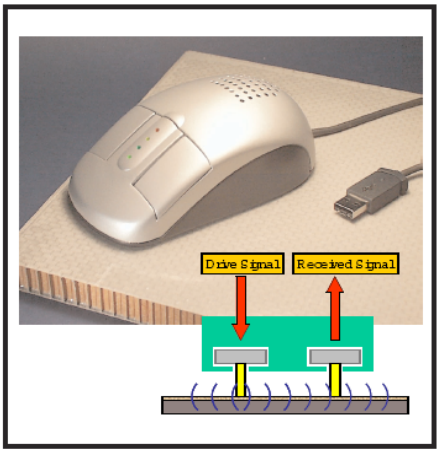
Figure 6.1.2.2-1 - surface roughness measurement devices: Surtronic 25 (left) and Form Talysurf Intra (right).

6.1.2.2b. Post-Injection Tests

Once the core material has been injected or bonded-in, the quality of the joint between the faceplates and the core has to be checked. Delaminated areas, unfilled areas and bubbles inside the core materials need to be detected. There are two possible testing methods to "review the inside" of sandwich panels:

- Acoustic testing (vibration, less than 100 kHz).
- Hammer tapping.

In the **acoustic testing** method, a vibration with a frequency of less than 100 kHz is induced via a probe into the panel. A range of probes are commercially available - they are generally known as "acoustic probes" (e.g. www.cip.csiro.au/IMP/SmartMeasure/baNDIcoot_ pamphlet.pdf). One example is the "pitch-catch" probe shown schematically in figure 6.1.2.2-2 (left). This has two contact tips approximately 10 mm apart. One is used to excite the panel and the other is the detector. With these devices, very small delaminations or bubbles inside the core material (down to millimetres) can be detected. Figure 6.1.2.2-2 (right) shows a typical image output depicting bubbles detected in a core material.



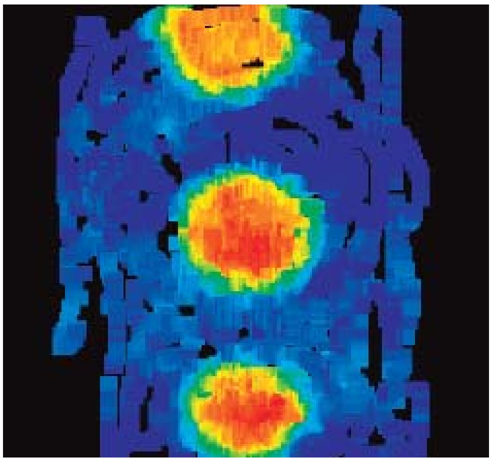


Figure 6.1.2.2-2 - acoustic pitch catch probe (left) and detected bubbles in a core material (right).

Hammer tapping is a very simple way of acoustic testing in which a small hammer is used to lightly tap the faceplates and the resulting sound is listened to. This method can help detect delaminated areas. It is less accurate than the acoustic testing method, but nearly always possible if no probe is available. If the core and facings are well adhered, the resulting sound is of a "dull" character. The sound gets clearer if there is a delaminated area in the panel. Delaminated areas down to a size of a few centimetres can be detected by this method, which is also the easiest and most efficient way for inspecting panels on ships in service.

6.1.2.3. Non-Destructive Examination of Composite Sandwich Structures

In this section, some of the **non-destructive examination (NDE)** methods that are suitable for **composite** sandwich inspection are highlighted. They include:

- Hammer tapping.
- Ultrasonic inspection.
- Radiography.
- Shearography.
- Damage detection with embedded optical fibres.

6.1.2.3a. Hammer Tapping (Hammer Sounding, Coin Tapping)

Hammer tapping, as discussed in section 6.1.2.2 for hybrid metal sandwiches, is also an effective way to detect delaminations in composite sandwich structures. The technique involves tapping the area of concern repeatedly with a hammer (making sure not to damage the composite facing) and listening to changes in the pitch of the tapping sound. Undamaged regions should be sounded to establish a contrast between damaged and undamaged laminates. An undamaged laminate produces a dull sound when struck, whilst delaminations tend to ring out louder. The operator should make sure that the contrast in sound is not due to physical features of the structure, such as an underlying stiffener. If one places a hand over the surface being sounded, it is possible to feel the damaged laminate vibrate when struck.

The extent of damage can be fairly accurately determined by hammer sounding. The damaged region may be clearly marked with a permanent ink marker pen.

In highly specialised sandwich products used in aerospace applications, it has been reported that hammer sounding might cause local delaminations. However, in the marine industry hammer sounding is considered to be a very effective way of examining large surfaces in a relatively short amount of time.

Recent developments include an electronic digital tap hammer that has been developed by Wichitech Industries (www.witchitech.com). The device supplements the subjective tonal discrimination of the operator with a quantitative, objective readout that can be correlated to delaminations in a composite sandwich.

6.1.2.3b. Ultrasonic Inspection (A, B and C-Scans)

The principles of **ultrasonic** inspection, as described in section 6.1.2.1, are also applicable here. Ultrasonic inspection is used in composite sandwich structures to detect voids, delaminations and inclusions.

The C-scan is the most commonly used of the ultrasonic inspection techniques with composite sandwich structures because it provides a two dimensional image of flaw distribution, that can be readily indicated on a drawing of the part being inspected (figure 6.1.2.3-1).

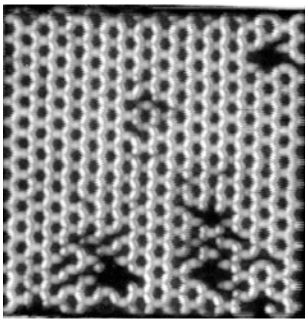


Figure 6.1.2.3-1 – left: honeycomb sandwich; right: C-scan image showing local absences of bonds between the facing and the honeycomb core.

Recent developments in the field of ultrasonic inspection included the Airborne Ultrasonic Flaw Detector from NDT Systems Inc. (www.ndtsystems.com). This offers the following claimed advantages:

- No liquid coupling needed.
- No surface contact needed.
- Can penetrate thick sections (apparently up to tens of millimetres) and foam-cored sandwiches.
- Can detect delaminations, impact damage, foreign inclusions and major deviations in fibre-resin ratio (i.e. resin rich or resin starved areas).

6.1.2.3c. Radiography

Radiographic inspection uses high energy radiation (x-ray, gamma, neutron, etc.) to detect cracks parallel to the radiation beam. The radiation passes through the part and exposes a photographic film placed on the opposite side of the component under test. Flaws exposed to the radiation appear as darker areas on the film. Radiography can provide information on flaw width, but not depth. This can be a drawback for double faced sandwich structures.

The non-homogeneous nature of composite sandwich materials limits the usefulness of radiography with respect to the size of detectable defects. Compared to ultrasonic inspection, the use of x-rays is also more costly and poses a radiation hazard.

6.1.2.3d. Shearography

Shearography, also called "speckle pattern shearing interferometry", is based on the phenomenon that coherent waves of light having different path lengths produce a fringe pattern when interference occurs. The fringe pattern represents changes in the out-of-plane displacement derivative of the surface under test. Shearography has been proven to be particularly effective for detecting delaminations in composite materials.

One major difference between shearography and conventional NDE techniques is the method of revealing flaws. Conventional NDE techniques such as dye penetration reveal surface or sub-surface flaws by enhanced visual means, whilst techniques such as ultrasonics and radiography detect internal flaws by finding non-homogeneties in materials. However, these conventional techniques generally provide no direct information on whether or not the detected flaws will weaken a component. Shearography reveals flaws by looking for the flaw-induced strain anomalies, and thus it provides more direct information about the flaw-criticality. Furthermore, shearography is a full-field optical technique which does not require scanning or contact. Thus, the inspection rate of shearography is inherently higher than many other NDE techniques.

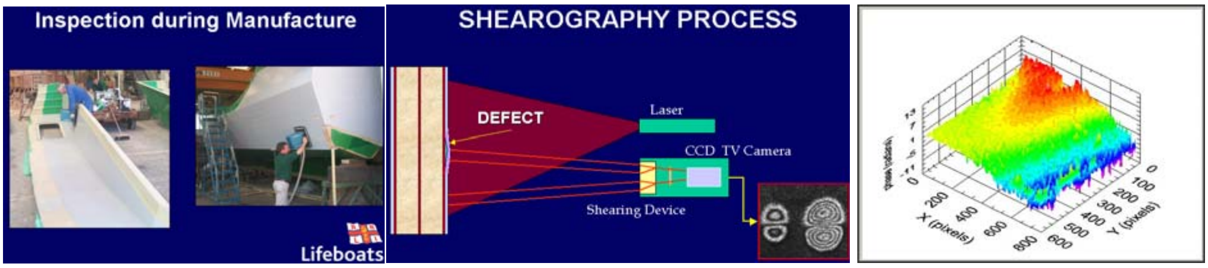


Figure 6.1.2.3-2 - the basic principles of shearography.

Shearography is widely used in the aerospace and motorsport industries. It is also being used increasingly in shipbuilding. In the UK, the Royal National Lifeboat Institution is gathering experience with this technique for manufacture and repair of their lifeboats. Kockum's also used shearography for its Swedish "Visby" naval corvette. Shearography is an attractive option for inspections in which large areas need to be 100% inspected in a relatively short time. Rates of 5-10 square meters per hour, with overlapping scans giving more than 100% coverage, have been claimed by a manufacturer of shearography systems, Laser Technology Inc. (www.laserndt.com).

6.1.2.3e. Damage Detection with Optical Fibres

By embedding **optical fibres** in composites, and incorporating intelligent data processing systems, manufacturers can integrate a non-destructive examination system within a composite sandwich part. Optical fibre sensors can detect internal deformations caused by tension stresses, thermal expansion, or deformations due to internal flaws / delaminations.

Optical fibres are becoming increasingly popular and are currently used for monitoring stresses and flaws in wind turbine blades. In the marine sector, Royal Huisman Shipbuilding, a manufacturer of luxury yachts, is gathering experience in the incorporation of sensors (including optical fibres) in critically-loaded composite structures.

6.2. Repair

6.2.1. Repair of All-Metal Sandwich Structures

This section describes some practical experiences in the **repair** of **all-metal** sandwich structures. It assumes that a decision to undertake a repair has already been made. Hexcel Composites 1999 provides some useful background on the decision making processes surrounding repair strategies.

Figure 6.2.1-1 shows an example of a local repair on the connection between a faceplate and a core stiffner of an-all metal sandwich. The repair was deemed necessary due to an imperfection in a laser weld. The figure (left to right) shows the stages followed during the repair.

Figure 6.2.1-1 - repair of an all-metal sandwich. From left to right: (i) grinding on top of the laser weld, (ii) panel after grinding and chiseling, (iii) TIG repair welding, (iv) grinding after repair welding with a Polyfan-Disc, (v) repaired panel after welding and grinding (from Reinert 2002).

Information about the local repair of bonded connections can be found in Weitzenböck & McGeorge 2005.

Within the SAND.CORe European project, practical repairs on installed all-metal sandwich panels were performed. The damage (a buckle in a sun deck made from I-Core following a grounding) covered an area of 1.4 m x 0.5 m (figure 6.2.1-2).

Figure 6.2.1-2 - all-metal sandwich repair case study. Left: AROSA river cruiser. Centre: damaged area. Right: buckle in the sun deck.

A cooperation between the ship owner (SO) and the panel supplier (PS) resulted in the following repair strategy (figure 6.2.1-3):

- Collection of detailed information about the damage (SO).
- Preparation of a repair manual including drawings, repair materials and technologies / tools (PS).
- Fabrication of a replacement panel and its transport to the shipyard (PS).
- Removal of damaged section by cold-cutting with a grinding machine (PS).
- Installation and welding of the replacement panel (PS).
- Final quality check (PS+SO).

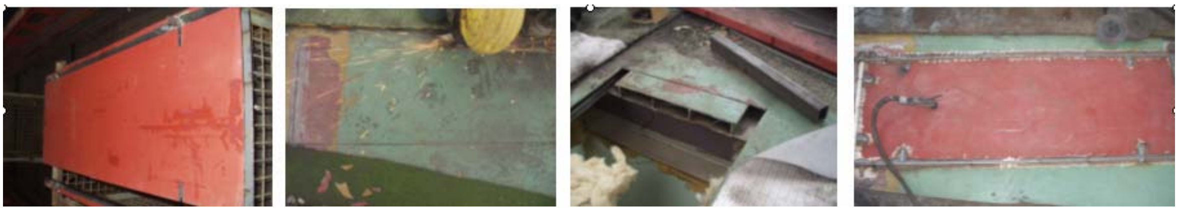


Figure 6.2.1-3 - all-metal sandwich sun deck repair. From left to right (i) the replacement panel, (ii) removal of the damaged panel, (iii) & (iv) installation of the replacement panel.

More information about the repair of all-metal sandwich panels can be found in the SANDWICH project guidelines (Det Norske Veritas 2003). Alternatively, panel suppliers typically offer repair manuals for their products.

Overall, the technology for the repair of a sandwich panel deck can at first seem more complex than a similar repair for a conventional steel deck. The principal reasons for this are:

- The limited experience in conventional shipyards with respect to the use of sandwich structures since they are a still an emerging technology.

- Inexperience with material procurement.

- Missing workshop manuals.

Furthermore, due to the specific requirements of the stiffener-to-faceplate connections in sandwich panels, the dimensions of the repair surface are not freely selectable. Other difficulties are the dependence on ambient temperature (which can introduce unwanted thermal stresses in thin faceplates) and humidity (which can introduce unwanted moisture into the core cavities leading to corrosion).

On the other hand, since the damaged plate removal is performed using mechanical tools, the repair time is greatly reduced, as is the heat input to the structure (no flame cutting). This in turn reduces the risk of fire / thermal damage in adjacent areas, expenditure for fire protection, and improves operator safety.

Generally, the temporal expenditure for the repair of a sandwich panel shifts, when compared to a conventional steel structure, from the local execution to planning and material procurement. It therefore follows that there is a clear cost advantage to ship owners due to a reduction in the time required to complete a repair when it is performed by a yard with appropriate experience and available sandwich materials.

6.2.2. Repair of Hybrid Metal Sandwich Structures

The damage normally sustained by **hybrid metal** sandwich panels can be divided into two types:

- Delaminations between the core and the facings, but with the facings still intact.

- Damage from mechanical impact in which the facings and / or core material are damaged.

The two types of damage require different **repair** strategies. A decision on whether or not the damage detected has to be repaired will depend upon the type, size and influence of the damage. Criteria for evaluating a damaged panel can be found within class rules, (e.g.

Lloyd's Register 2006 or Det Norske Veritas 2003). Alternatively, guidance can be obtained from the panel manufacturer.

6.2.2.1. Repair of Delaminated Areas

A delaminated hybrid metal panel should be repaired as follows:

- Drill injection and venting holes through the faceplate in the area of the delamination. For optimum position of the holes, follow the panel manufacturer's guidelines.
- Inject the liquid core material or sufficient adhesive. The viscosity of the injected material must be low enough to flow into all of the gaps in the delaminated area. It must be ensured that the injected material has reached all of the venting holes.
- Wait for the injected material to cure.
- Check the repaired area using non-destructive examination (see section 6.1.2.2).

6.2.2.2. Repair of a Damaged Facing

The repair process for a damaged hybrid metal sandwich facing can be divided into the following six steps:

- Cut and remove the damaged faceplate.
- Remove the core material.
- Install a new faceplate.
- Inject new core material.
- Wait for the injected material to cure.
- Check the repaired area using non-destructive examination (see section 6.1.2.2).

6.2.2.3. Example: Repair of an SPS panel

Details of the repair processes for a damaged SPS panel are described below. The techniques used can be easily adapted to other types of hybrid metal sandwich panels.

6.2.2.3a. Step 1: Cutting Methods

With hybrid metal sandwich panels, it is most important to control (minimise) the heat input to the structure during the cutting process. Some proven cutting methods are described below:

- Cold cutting:
  - Standard circular steel-cutting saw (for small repairs a grinder can be used).
  - A carbide saw disk can cut the top faceplate only or completely through an SPS panel.

- Air carbon arc gouging:
  - Cut or gouge by melting the base metal with an electric arc and blowing away the molten metal with high velocity compressed air.
  - A 10 mm diameter electrode will cut a 10 mm thick faceplate in one pass.
  - Low heat input compared to oxygen cutting.
  - Only removes the top faceplate of an SPS panel.

- Water jet cutting:
  - A jet of water with an abrasive additive is forced through a nozzle at a very high pressure (approximately 240 MPa).
  - The abrasive additive is quartz sand with a particle diameter of 0.5 - 1.0 mm.
  - The depth of the cut can be regulated by altering the pressure, the amount of water, and the travelling velocity of the cutting unit.
  - Can cut the top faceplate only or completely through an SPS panel.
  - Produces a clean cut.

Figure 6.2.2-1 - from left to right: cold cutting of an SPS panel, air carbon arc gouging of an SPS panel, and water jet cutting of an SPS panel.

6.2.2.3b. Step 2: Core Removal Techniques

To avoid damage to the surrounding core material, core cutting should be performed with minimal heat input. The following techniques can be used:

- Grinding:
  - Simplest method of elastomer removal for small areas.
  - Use a coarse grinding disk to back gouge the elastomer to a nominal depth of 30 mm from the cut edge.
  - A wire wheel may be attached to the grinder for final cleaning.

- Water jet lance:
  - Uses the same pump and compressor equipment as in the panel cutting process described above.
  - However, no abrasive additive is required for core removal.
  - A handheld lance with a 0.8 mm diameter nozzle is used to force water out at a pressure of 250 MPa to gouge the elastomer.
  - The best results are achieved using a pressure head with three jets.

Figure 6.2.2-2 - typical grinder (left) and water jet lance (right).

6.2.2.3c. Step 3-4: Skin and Core Reinstatement

Once the repair cavity is dry and clear from debris, backing bars are tack-welded in place. The replacement faceplate is then welded-in using a square butt weld. New elastomer is injected into the repair cavity and the injection port and vent holes are sealed. The newly injected elastomer bonds to the existing elastomer. If further welding is necessary after injection to finalise the repair process, care has to be taken that permissible temperatures at the inner sides of the faceplates are not exceeded (seek guidance from the panel manufacturer).

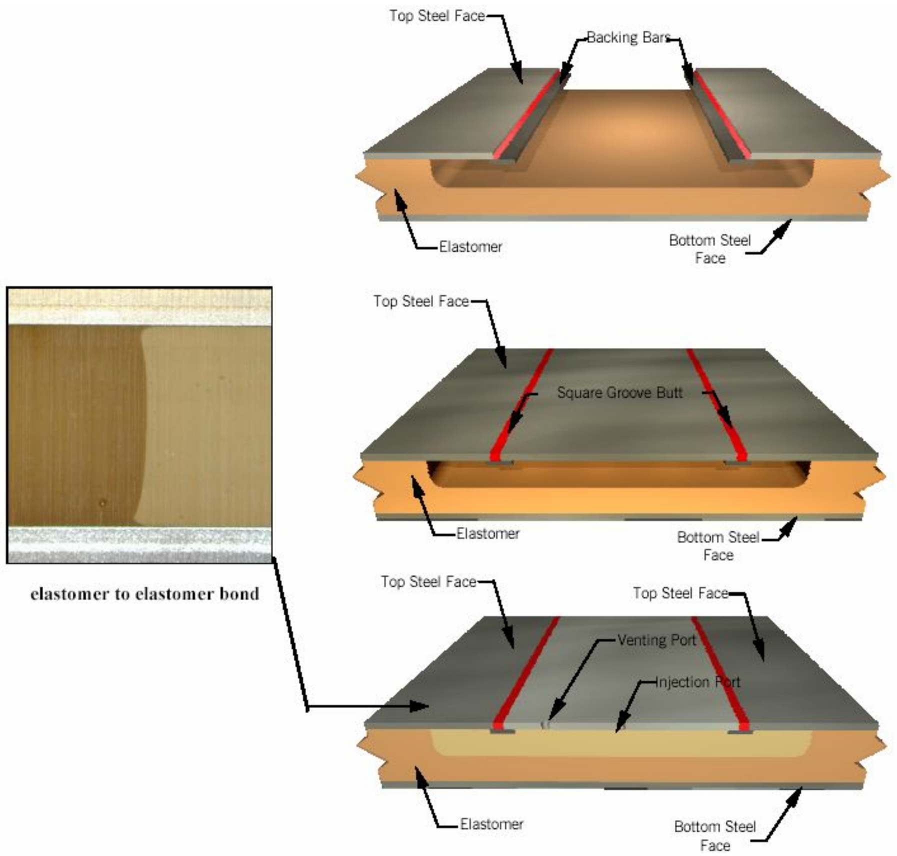


Figure 6.2.2–3 - skin and core reinstatement of an SPS panel.

6.2.3. Repair of Composite Sandwich Structures

It is quite likely that the hull of a **composite** sandwich marine craft will become damaged at some point in its lifetime. In the case of such an event, the sandwich will require a **repair** to restore the integrity of the structure. The main cause of damage to composite structures in service is impact. Impact damage can be classified as either low or high velocity. "Low velocity impact" refers to impact events in the range 1 to 10 m/s in which the contact period is such that the whole structure has time to respond to the loading. "High velocity impact" is an event in which a stress wave is generated that propagates rapidly through the material. The time frame in a high velocity impact event is so fast that the structure is unable to respond to the stress wave resulting in very localised damage.

Marine craft are often subjected to repeated light docking collisions and collisions with floating debris and other vessels. Accidental impact damage might also occur during routine maintenance. These types of impact events can be considered as low velocity.

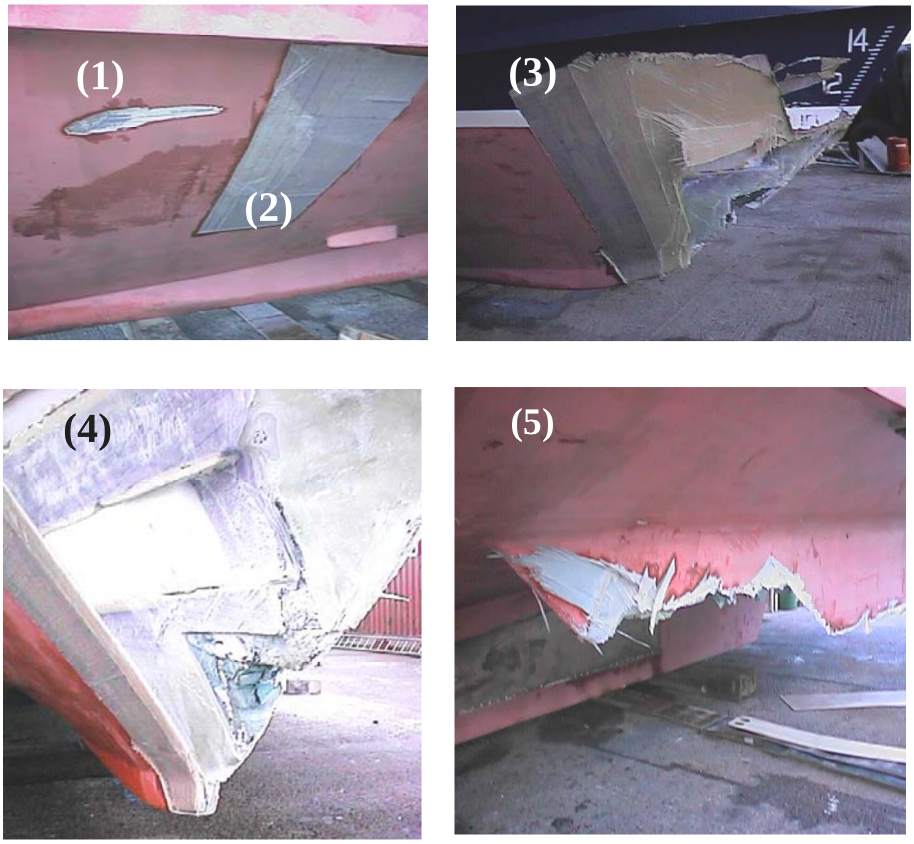


Figure 6.2.3-1 - examples of operational impact damage to marine composite sandwich structures.

In figure 6.2.3.1 above, various types of impact damage are shown and can be identified as follows:

1. The wearing away of a portion of the facing laminate by either natural means (e.g. rain, wind, etc.) or man-made accidents (e.g. over-blasting, slight collisions, etc.). Confined to the outer facing surface.

2. Localised surface indentation. Damage confined to the outer facing laminate. Matrix cracking, fibre breakage.

3. Moderate impact damage that is greater than the damage initiation threshold for core crushing (i.e. permanent deformation). Initiation of core-to-facing debonding.

4. Extended surface indentation resulting from significant impact damage, often associated with witness marks from the impactor and delamination. Penetration of the outer facing, matrix cracking, delamination, fibre fracture, damage to the core material, and core-to-facing debonding.

5. External forces exceed the fibre tensile strength or the compressive strength of the matrix material resulting in the complete failure of the facing. Failure may have occurred from an impact penetration or overload of the structure.

The repair philosophy for damaged composite sandwich structures depends greatly upon the particular component and the extent of the damaged incurred (for example, whether just one facing has been punctured, or both). Since composite structures are employed in different industries with different design philosophies, current repair concepts include a wide range of approaches, ranging from highly refined and structurally efficient (but expensive) flush patch repairs, to externally attached metal or composite patches. See figure 6.2.3-2 for examples of an externally bonded patch repair and a flush scarf repair (Trask et al. 2005).

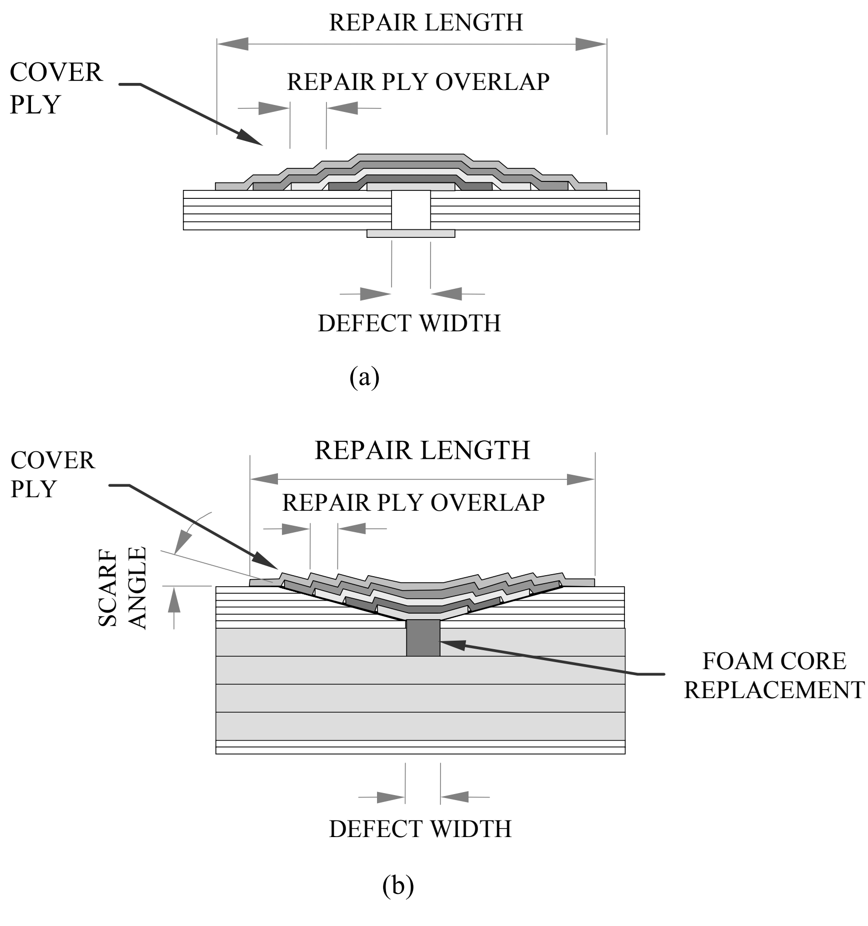


Figure6.2.3-2 - example repair design options: (a) external patch repair, (b) flush scarf repair.

To determine the structural adequacy of a repair that has been performed on a composite sandwich, the flow chart depicted in figure 6.2.3-3 can be used.

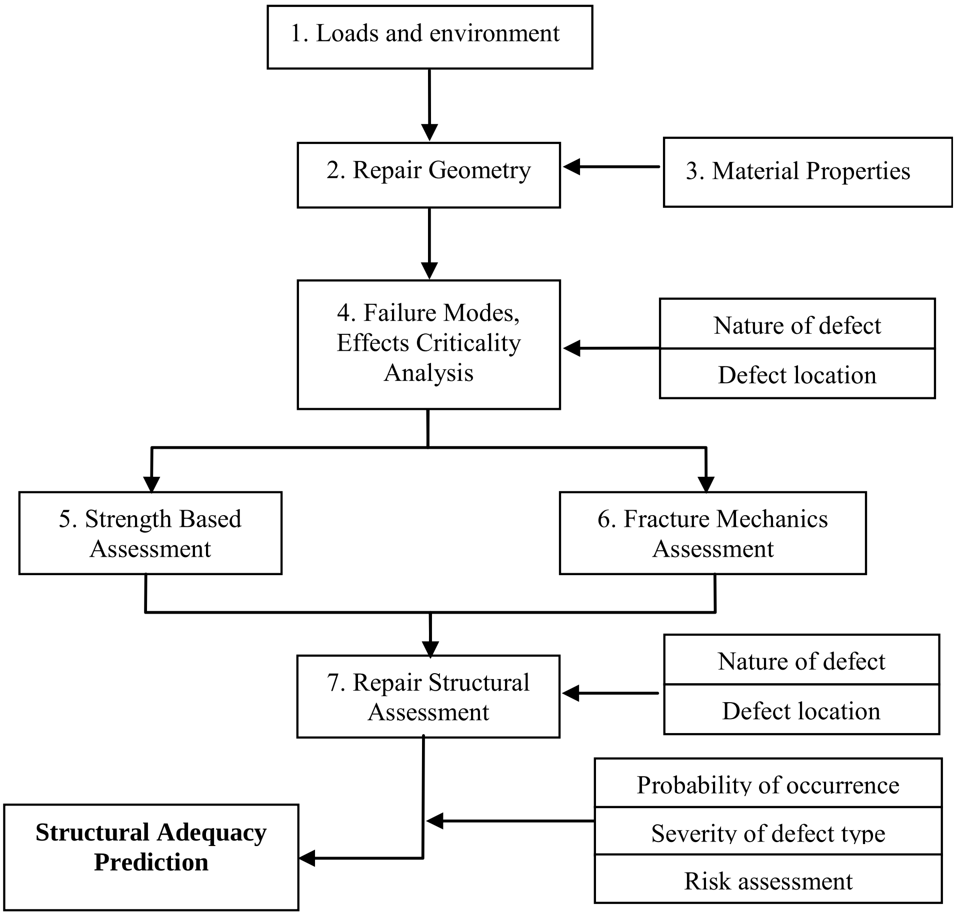


Figure 6.2.3-3 - flow chart design methodology for the assessment of repair structural adequacy.

7. Legislation and Approval

7.1. Class Rules and Other Legislation

Most vessels are required by national laws to comply with the **rules and regulations** of one of the recognised classification societies for structural design. Even when this is not the case (e.g. for naval vessels), many owners like to consider classification rules for at least the hull structure. Most national regulatory bodies follow international rules such as those issued by the International Maritime Organisation (IMO). The structural aspects they consider are different from those covered by classification and relate, for example, to fire protection or noise and vibration reduction.

Apart from any legal requirement, it should be appreciated that classification societies and other organisations possess extensive experience, not only with respect to the theoretical assessment of structures, but also in terms of manufacturing (including quality assurance and testing) and operation. Rules and guidelines from such organisations serve not only to provide a second opinion on the analyses made by a designer, but also to add valuable insights and experiences to issues not normally taken into account.

Given this situation, any designer of sandwich structures should / must consider existing class rules and other legislation in addition to their own calculations. This section provides an overview of the various class rules and other legislation that exist concerning the use of sandwich structures and panels. It first considers rules for **composite** sandwiches because these have already existed for some time. Given the large number of such rules, the intention is not to describe all existing rules, but rather provide a representative overview of what they generally contain. Recently, provisional rules have also been drafted for **all-metal** and **hybrid metal** sandwiches and these will be described in some detail thereafter.

7.1.1. General Overview of Rules Relating to Sandwich Structures

Traditionally, classification societies have based their rules upon a combination of fundamental structural analysis and practical experience in the building and operating of ships. Over recent decades, the approach based upon first principles has gradually replaced the traditional empirical approach. This has brought the basis for the classification rules closer to the approach adopted by designers.

The rules remain largely based upon single plate steel ship structures. Generally, the rules allow alternative and novel structural concepts provided that they have been shown to possess a similar adequacy to the steel equivalent (see section 7.2.2). The way to show such **equivalency** is described, for example, by McGeorge et al. for novel structural plates subjected to local impact. Unfortunately, the term *equivalency* is not generally defined and the criteria must be assessed on a case-by-case basis. It may well be that for sandwich structures, the criteria governing the design are different from those governing conventional steel structures. An example is the response to very high, localised loads such as those generated by high-heel shoes.

Composite sandwiches have already been used for quite some time and, from the outset, the need for dedicated rules and standards was obvious, not only in the maritime field but also in many other sectors of industry as well. A multitude of rules and standards is the result, some of which are described in section 7.1.2 below.

Metal sandwiches are more recent, albeit that some typical ship structures, such as rudders, were actually sandwiches before they were termed that way. Traditionally, such structures have been assessed by classification societies using a combination of practical experience and basic theoretical analysis using a working (allowable) stress approach, possibly complemented with a fatigue assessment. This approach is also sometimes used for modern steel-faced sandwiches. However, the drawback is that it doesn't address all aspects of sandwich design and sometimes makes it problematic to exploit the full benefits of sandwich technology. An example is the minimum plate thickness rule, which, if used as a minimum sandwich facing thickness, compromises the lightweighting potential of a sandwich. A practical solution for this last aspect is, for instance, to make the minimum thickness requirement applicable to the sum of the thicknesses of the *two* faceplates. In this case, the equivalency of the corrosion allowance is considered to be met based upon the assumption that each sandwich faceplate experiences corrosion from one side only. Unfortunately, equivalency for very high concentrated loads in such situations is less clear. The increased interest in metal sandwich structures has led two classification societies to draft provisional rules or guidelines for particular types - I-Core and SPS. These are described in sections 7.1.3 and 7.1.4 respectively.

7.1.2. Rules Relating to Composite Sandwich Structures

All classification societies have rules and regulations for **composite** sandwiches. However, the term "*sandwich*" does not generally appear in the rule title. Commonly the basic material, i.e. "*composite*", is referred to, or the rules are included within the regulations for certain types of vessel for which composite sandwiches are commonly used (e.g. yachts, high speed craft and naval vessels). References to some example rules and regulations for composite sandwich structures are provided below, although the list is certainly not exhaustive. The rules generally cover aspects of structural principles, materials, analysis and manufacturing. The rules are always a mixture of theory and practical experience, with an increased emphasis on theory as the rules have evolved.

Legislation from national and international bodies is relatively limited. The **IMO HSC Code** for high speed craft is the main item of interest. It has been adopted by many national governments and is included, for example, in Germanischer Lloyd's high speed craft rules. The main subject of interest in the IMO HSC Code is that of fire safety. It has direct relevance to composite sandwiches with regard to the acceptability of certain materials, or the way in which compliance with the code has to be demonstrated. Note that many ship types, such as private yachts and naval vessels, do not legally have to comply with the HSC Code.

Semi-governmental organisations may have their own regulations for composite sandwiches. An example is the **Composites Handbook** of the American Department of Defense.

The **International Standards Organisation (ISO)** (www.iso.org) has its own standards for sandwich applications (for instance in their small craft standards). Many national standards organisations have incorporated such international standards.

Industries sometimes set their own standards which have a level of recognition that approaches that of official regulatory bodies. Examples are the testing standards set by **ASTM** (www.astm.org). These include numerous standards for the testing of sandwich materials such as ASTM C 393 – “Standard Test Method for Flexural Properties of Sandwich Constructions”.

7.1.3. Rules Relating to All-Metal Sandwich Structures

Det Norske Veritas (DNV) participated in the European SANDWICH project, which was in many respects the predecessor of SAND.CORe. Largely as a result thereof, they produced guidelines for **laser-welded** sandwiches. By definition these concern all-metal sandwiches, including those with core filler materials (hybrids).

Explicitly the document states that it does *“not form part of the DNV Rules. The content is for information only and has no bearing whatsoever on DNV’s possible acceptance of laser-welded sandwich panels or the process of approval of such panels”*. Notwithstanding this formal statement, it is clear that the document provides a reasonable starting point for their classification process.

The DNV guidelines consist of three parts. Two of them are public. The first part, the Introduction, presents the aim, the scope and the structure of the guidelines. The second part is the Code, which is concerned with the verification of the reliability of the structure to ensure adequate safety and serviceability. The Code contains general requirements, as well as the acceptance criteria necessary to ensure structural reliability. The requirements cover the design, construction and operation phases. They include many formulae to check the structural performance of sandwich panels. These formulae may be used independently, or in conjunction with finite element analyses. Load and stress criteria are provided, as are minimum faceplate thicknesses. Most of these come from normal ship rules, and references to the relevant sections of other rules are provided where appropriate. Such references also concern aspects not otherwise considered in the guidelines, such as fire safety, corrosion and noise and vibration. Some guidelines are also given for the testing of components. Panel fabrication issues and the quality assurance and control issues related thereto are dealt with separately. The same is true for the in-service inspection of panels. The third part of the DNV guidelines is accessible only to SANDWICH partners. It presents the Recommended Practices, describing the tools and procedures that can be used to demonstrate compliance with the requirements set in the Code.

7.1.4. Rules Relating to Hybrid Metal (SPS) Sandwich Structures

Lloyd's Register of Shipping co-operated with Intelligent Engineering (IE) in the development of the **Sandwich Plate System (SPS)**. They have also been involved in many of the subsequent practical applications thereof, particularly the use of the *SPS Overlay* technique for refurbishment (see sections 4.2 and 5.1.2). Together with IE, they recently drafted special provisional rules for this type of sandwich.

The rules are intended mainly for mono-hull ships and come in addition to the normal steel ship rules. An indication is also given to situations in which SPS could be used in aluminium ships. A major aspect of these rules is fabrication (both in-situ as with the overlay technique, and in prefabricated panels), together with the quality assurance aspects that should be considered. The rules provide many structural details that may be used in refurbishment situations or in new-builds. The strength of the sandwich panels is checked through the use of a strength index. Basically this strength index is a check on equivalency against plate thicknesses derived from the rules for normal steel vessels. Similarly, the buckling strength of the panels is checked in an equivalency format against the requirements inherent or explicit in the rules for normal steel vessels. The safety margins in the scantlings are therefore transferred from the normal ship rules and not made explicit.

7.1.5. Recommendations Relating to Rules for Sandwich Structures

- Discuss any new sandwich applications with the appropriate classification society.
- Check at an early stage of the design which rules and regulations need to be complied with in order to obtain class approval.
- Check at an early stage of the design which rules and regulations are useful for further information and as a second opinion to the design.
- Identify early in the design process any equivalency that needs to be demonstrated, either by analysis or by experiments. Note that some experiments may be rather demanding in terms of time and / or cost and that a positive outcome is not always certain.
- Identify at an early stage which design details need to be developed and present these to the classification society together with possible solutions.

7.2. Risk Assessment

7.2.1. Introduction

This guide to **risk assessment** for sandwich panels aims to:

- Explain the very basic principles of risk assessment.
- Assist the user in deciding what type of risk assessment to perform.
- Provide guidance as to how best to complete a risk assessment of a sandwich structure.

This is not a comprehensive guide to completing a risk assessment, but more of an overview of the key elements for a successful risk assessment.

7.2.1.1. What is Risk?

Risk is the product of a **likelihood** and a **consequence**, i.e.:

Risk = Probability x Consequence

However, risk can be broken down into three “types”. These are:

- Risk to humans.
- Risk to the environment.
- Risk to assets.

A risk to a **human** may be a fatality multiplied by the probability of the fatality taking place. Thus, a common unit of risk to humans is expected fatalities per year.

The risk to the **environment** revolves around accidental and non-accidental pollution. For oil, for example, tonnes spilt per year is a usual unit of risk.

Risk to **assets** relates to the loss of property or money. These can be the assets of a business or society. An assessment for asset risk might look at whether a business investment is sound or whether the liability from an accident is acceptable or not. It is, however, a business decision, as opposed to an engineering one, and will therefore not be considered further in this guide.

7.2.1.2. Why Do a Risk Assessment?

Risk assessments have become very popular over the last few years in all areas of life, not just engineering. However, they can be very expensive and time consuming, so it is important to ensure that you are doing a risk assessment for the right reasons.

The main reasons for performing a risk assessment are:

- To control unacceptable risks of a novel or unfamiliar system which are not regulated by other means.

- To find more economic solutions to already controlled risks.

- To provide proof of compliance or "equivalence" (section 7.2.2) with rules and regulations.

In the marine industry there are **prescriptive rules** that detail what is, and what is not, acceptable for designs. Even for relatively new technologies like sandwich panels, some rules do exist (section 7.1). If approval is planned through prescriptive rules, then a risk assessment may not be required.

In addition to prescriptive rules, there are also **functionally-based rules**, i.e. rules that state a functional target that the design must achieve if it is to be approved. This type of rule may also not require a risk assessment to be done. However, it is likely that they will specify how to calculate whether the target has been met and this can include a risk assessment of some form.

However, it is possible that neither the prescriptive rules nor the functional rules are valid for a given sandwich design. In this case it may be necessary to seek approval through equivalence. If this is the case, it is likely that a risk assessment of some kind will be required by the approval body.

In all instances it is advisable to contact the regulator or approval body to discuss the specific requirements of a given design at an early stage. Different bodies apply different rules in different ways. It is best to establish the requirements at an early stage of the design process so that they can be properly addressed.
Finally, even if a risk assessment is not required for regulatory or approval reasons, it may still be a sensible and useful exercise, especially if a sandwich design is new for the application concerned.

7.2.2. Approval and Certification Through Equivalence

As sandwich structures evolve and are used for a broader range of applications, it is likely that instances will arise in which a design does not meet rules as they are written. However, this does not mean that the design cannot be approved or certified. A design team can still move forward by making use of the principle of **equivalence**.

The principle of equivalence is a catch-all clause used in rules. It means that if it can be demonstrated that a design which is outside of the rules has the same or better performance than a design that meets the rules, then it is deemed to be equivalent to the rules.

Equivalence allows designers to be a lot more flexible with their designs. However, the trade-off is that proof of the equivalence must be provided. This is often done through risk assessment.

Most rules in the marine industry now take advantage of the principle of equivalence. An example of a statutory regulation that makes use of equivalence is SOLAS Chapter II – 2, Part F, Regulation 17 which states:

> "2.1 Fire safety design and arrangements may deviate from the prescriptive requirements set out in parts B, C, D, E or G, provided that the design and arrangements meet the fire safety objectives and the functional requirements.
>
> 2.2 When fire safety design or arrangements deviate from the prescriptive requirements of this chapter, engineering analysis, evaluation and approval of the alternative design and arrangements shall be carried out in accordance with this regulation."

This means that if the prescriptive requirements are not met, by using the principle of equivalence the design can still meet the SOLAS requirements.

Class rules also take advantage of the principle of equivalence with a typical class rule book stating:

> "The Society may consider the acceptance of alternatives to these Rules, provided that they are deemed to be equivalent to the Rules to the satisfaction of the Society."

By using the principle of equivalence, no good design should be prevented by inflexible rules. Therefore, this principle is particularly useful for designs that utilise relatively innovative technologies such as sandwich panels.

7.2.3. Selecting a Risk Assessment Technique

Risk assessment should be considered an iterative process. It is unlikely that absolute clarity regarding hazards, risks and their uncertainties will be achieved through a single risk assessment. It is recommended that risk assessments are conducted throughout the design process. This means, however, that the design team may have to utilise more than one type of risk assessment methodology.

As shown in figure 7.2.3-1 choosing the right risk assessment technique depends very much on the progress of the design. It is not necessary to use all the assessment tools. For example, one could perform an initial qualitative assessment, followed by a more detailed quantitative assessment at a later stage.

The leader of the risk assessment, the **facilitator**, should be able to provde advice on the most appropriate technique. It may be necessary to appoint an external risk expert as the facilitator if an organisation lacks someone with the sufficient expertise and experience. It is not recommended that a person tries to facilitate a risk assessment unless they have taken part in previous risk assessments, ideally as an assistant to the facilitator.

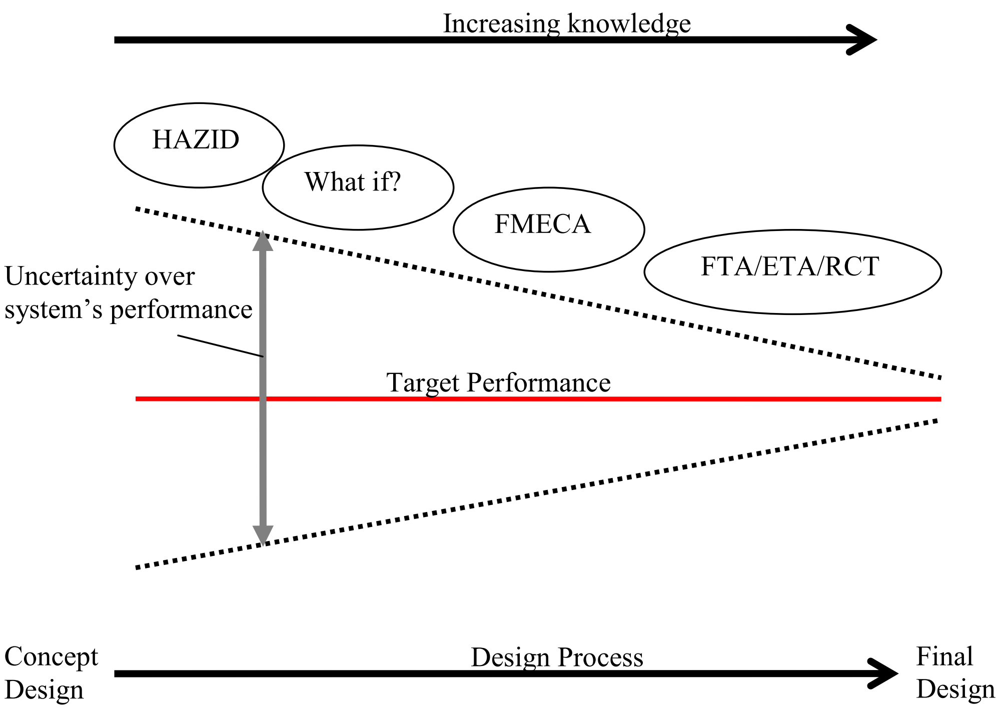


Figure 7.2.3-1 - the risk assessment techniques applicable at different stages of the design process.

Very brief overviews of the risk assessment techniques indicated in figure 7.2.3-1 are as follows:

- **Hazard Identification (HAZID)**: Rapidly identifies hazards, consequences and the effectiveness of existing risk control measures. Relies heavily on the active participation of subject area experts, e.g. sandwich panel experts or fire experts.

- **What If?**: Uses brainstorming to question what could happen given a supposed set of events. Identifies hazards, hazardous events and specific accident scenarios. Often combined with checklists to increase the structure.

- **Failure Mode Effect and Criticality Analysis (FMECA)**: This is a systematic methodology that uses tables for evaluating and recording the causes, effects, risk control options and recommendations for ensuring appropriate safeguards are in place against known failure modes. This approach is particularly useful for well defined electrical or mechanical systems. However it can still be used for sandwich panels if the design is sufficiently progressed and information regarding the surrounding environment and systems is available.

- **Fault Tree Analysis (FTA)**: Fault tree analysis uses a graphical structure to model the relationships between different components in a system. Probabilities are inputted at the basic event level and filter through the tree to the top event by way of logic gates. Fault tree analysis is a frequency or probability analysis. It does not look at the consequences of an event happening but purely at the likelihood of it happening. It is therefore good for analysing design details that may provide better reliability or redundancy.

- **Event Tree Analysis (ETA)**: Event trees are similar to fault trees but instead start with a top event and map out all the possible outcomes from that event. They are a form of consequence analysis and are particularly good for analysing mitigation options, e.g. fire proofing.

- **Risk Contribution Tree (RCT, Bowtie Analysis)**: RCTs are a combination of fault and event trees so they are a complete risk assessment model analysing both the likelihood and consequence of an event. They allow a “full” picture to be constructed including how different risk control options interact with each other. However, they require a lot of effort, expertise and detail.

Guidelines for the applicability of the above techniques are as follows:

Risk Assessment Tool	Qualitative Assessment	Quantitative Assessment	Ranks Relative Importance of Hazard	Recommendations for New Safeguards	Level of Complexity	Level of Expertise	Level of Design Detail
HAZID	*				Low-Medium	Low - Medium	Low - Medium
What If?	*			*	Medium	Low - Medium	Medium
FMECA	*	*	*	*	Medium - High	Medium	High
FTA		*	*	*	High	High	High
ETA		*	*	*	High	High	High
RCT		*	*	*	High – Very High	High – Very High	High – Very High

7.2.4. Advice and Guidelines for Conducting a Risk Assessment

Whether a qualitative or a quantitative analysis is planned, there are some basic guidelines that should be followed. These are outlined below.

7.2.4.1. Define the Scope of the Risk Assessment

The first point is to define the scope of the risk assessment. Risk assessments generally look at a complete system. For a risk assessment involving a sandwich structure, this could be a compartment, a fire zone, or an entire ship.

When deciding the scope of the risk assessment, it is essential that all the design details that might affect the sandwich structure in some way are considered. A suggested minimum level of detail would be to assess the compartments or environments on both sides of the sandwich. So for a sandwich panel that is a bulkhead, the risk assessment should identify every system in the two compartments that the sandwich panel separates, and then assess all the risks associated with those systems and their impact on the sandwich panel. This example would also have to consider the fire and flooding performance of the sandwich.

It is important that all the relevant documentation is available. It is incredibly difficult to do a risk assessment without drawings and plans to base discussions or calculations upon. It is impossible to provide a list of everything that might be needed here because it will depend upon the situation being considered. However, it is recommended that as much information as possible is available regarding the design, its production, its operation and its decommissioning. It is also very useful to have the documents circulated before any meetings or brainstorming sessions. The circulated documents should include an overview that identifies the aims and objectives of the upcoming event so that everyone has a clear understanding of the background and the expectations placed upon them.

7.2.4.2. Assemble the Right Team

The second point is to make sure that an adequate team is available to complete the risk assessment. It is no good having 15 structural engineers to do a risk assessment on a sandwich panel. Ideally, a team should consist of around 8 or 9 people and be picked to reflect all the different disciplines involved. It is also important to remember that risk assessment is a team process and that all participants must be actively engaged so that they contribute in a constructive manner.

Each risk assessment will have different team requirements but will commonly involve a facilitator, a recorder and subject area experts. An example team for a sandwich panel risk assessment would be as follows:

- **Facilitator**: the facilitator’s job is to provoke and lead the team members through the risk assessment in an organised and methodical way. The facilitator may or may not be an expert in the risks associated with sandwich panels. The facilitator is there to explain and manage the risk assessment process itself.

- **Recorder**: it is helpful to have someone who has sole responsibility for recording the discussions and conclusions.

- **Structural engineer with sandwich panel experience**: a sandwich panel is a structural element. Therefore, a structural engineer is required to assess how it will react or fail given the events that may occur during the design’s life.

- **Production engineer with sandwich panel experience**: it is essential that a production engineer is present. A good risk assessment will include an assessment of what can go wrong at the production stage of the life cycle. These may be defects that lead to a major event during operation, and also risks associated with the manufacturing and assembly processes, e.g. a fire when welding a hybrid metal panel, or ecological damage caused by certain resins and plastics.

- **An engineer capable of evaluating the loads**: this team member could be a hydrodynamics specialist or, in the case of a military vessel, a weapons specialist. The key is that, as a sandwich panel is a structural element, the team needs some way of assessing the likely loads to which the panel will be subjected. Therefore the team needs to be able to assess whether a panel is likely to fail through either accidental or operational loads.

- **Marine / equipment engineer**: a marine or equipment engineer is required to identify what failures in equipment might lead to events that concern the sandwich panel, or what the consequences of a sandwich panel failure might be with respect to equipment, e.g. flooding of a machinery space, leading to a loss of power generation, leading to a loss of control of the vessel.

- **Fire engineer**: certain structural elements also have a requirement to contain fire. Given that some sandwich panels utilise flammable plastics and resins, it is essential that a fire engineer is present to assess the probability of a fire and the consequences that a fire might have.

- **Vibration engineer**: a vibration specialist may be required to provide input regarding likely vibrations that the panel may be exposed to and how this may affect its performance.

- **A representative of the approval body**: approval bodies often require a presence during risk assessments to ensure that they are conducted in a satisfactory manner. They may or may not take an active role in the assessment. This depends upon the body and the situation.

7.2.4.3. Remember the Life Cycle

There are three stages in the lifecycle of a sandwich structure:

- Production.
- Operation.
- Decommissioning.

All three stages should be considered in a risk assessment. A product may operate perfectly on a vessel, but the human and environmental risks associated with its production may be unacceptable. Similarly, even if the production and operation phases are acceptable, the decommissioning phase may pose problems. Risk assessment is about being proactive and looking at all parts of a product's life cycle.

It is also possible that events that occur in production, such as manufacturing defects, could have a serious impact on the performance of a sandwich structure in operation. In the operation stage, an event that occurs during maintenance may also have an impact on future performance of the sandwich. It is best practice to consider how a sandwich structure will be inspected and maintained as part of the risk assessment process to ensure that there are no risks associated with failures in this respect.

7.2.4.4. Follow the Five Steps of Risk Assessment

Each risk assessment technique varies slightly, but they generally all involve the following five steps:

- Identification of hazards.
- Assessment of the risk level associated with each hazard.
- Identification of risk control options.
- Cost - benefit assessment of risk control options.
- Recommendations for decision-making.

Firstly, those conducting the risk assessment must ask themselves "**what might go wrong?**". This should be considered carefully and extensively, as real world experience often shows that *what can go wrong, will go wrong*! This process will result in a list of hazards to be considered in the remainder of the risk assessment.

The next question to be answered is "**how likely and how bad?**" This is a risk level evaluation. It can be done qualitatively, as described in section 7.2.4.5 below, or quantitatively using detailed data on the likelihood and consequences of a hazard.

The next step is to ask "**how can matters be improved?**" This question asks the participants to identify all the different risk control options. The options may be technical or procedural in nature.

Once a list of risk control options has been identified, the risk assessment team needs to answer "**what would it cost and how much better would it be?**". This is a cost - benefit exercise looking at the effectiveness of the risk control options and their associated costs. It should be as broad as possible taking into account design, build, operation (including maintenance) and decommission costs. It should also include benefits such as increased earnings, reduced insurance premiums and increased operational efficiency. As described in more detail in section 7.2.4.5, the team should also consider new risks that might be introduced if certain risk control options are realised.

After the previous steps have been completed, a list of **recommendations** needs to be prepared. There is little point in completing a risk assessment unless it feeds back into the design process. Ideally these recommendations should be ranked in order of preference so that the design team is clear as to which risk control options have priority.

7.2.4.5. Matrices for Use in Qualitative Risk Assessment

When performing a **qualitative** risk assessment, it is helpful to use a **risk matrix** as a risk level calculator. An example of a risk matrix is shown below. However, it is possible to use more columns or rows in the matrix to achieve a better resolution for the risks.

	Slightly Harmful	**Harmful**	**Extremely Harmful**
Highly Likely	Trivial Risk	Tolerable Risk	Moderate Risk
Unlikely	Tolerable Risk	Moderate Risk	Substantial Risk
Likely	Moderate Risk	Substantial Risk	Intolerable Risk

Risk Level	**Actions Required**
Trivial Risk	No action required.
Tolerable Risk	No additional risk controls are required. However, monitoring is required to ensure current control is maintained.
Moderate Risk	Actions should be taken to reduce risk. Risk controls should be identified and assessed for cost-effectiveness and implemented as appropriate.
Substantial Risk	Urgent action should be taken to ensure the risk is minimised as far as is reasonably practicable. Considerable resources may be required.
Intolerable Risk	This risk must be reduced. May require significant changes to the design or operations.

It is often a good idea to provide a table of examples that illustrate what is meant by the levels of likelihood and level of consequences used in the matrix. Unfortunately, there are different standards, so it is difficult for this document to provide advice as to what should be used. The best practice is to ask the certification body where appropriate, or ensure that the facilitator is capable of advising the team based on the specifics of the risk assessment.

Whilst the above matrix and variations on it are common place, it is considered best practice to also complete a second type of matrix that is not so common. This second matrix is for the analysis of the interdependencies of the risk control options. The **interdependencies matrix** is for use when considering the adoption of several risk control options simultaneously (as is normally the case). The matrix (shown below) lists all the risk control options horizontally and vertically so that cross-referencing can be performed. The user starts at row 1 and considers the impact of risk control option 1 on risk control options 2, 3, 4, etc. before proceeding to row 2 and risk control option 2, and so on. Once this has been done, any interdependencies identified as "strong" should be re-evaluated in terms of whether it is correct and necessary to apply them in tandem. The primary reason for completing this matrix is to ensure that the risk reduction resulting from a risk control option is not compromised by the introduction of another risk control option. It is also possible to complete the table for other costs and benefits.

Risk Control Option	1	2	2	4
1		Strong	Weak	No
2	Strong		Weak	No
3	Weak	Weak		No
4	No	No	No	

7.2.4.6. Expert Judgement versus Historical Data

Engineers have a tendency to want to base decisions on hard data. This often leads to the use of historical data to populate tools such as fault trees. This should be avoided.

Risk assessment is proactive and forward looking. Historical data is reactive and backwards looking. Therefore using historical data negates one of the most important characteristics of risk assessment. It can be very dangerous to base risk assessment decisions on historical data for the following reasons:

- Historical data is the result of differing situations, technologies, rules and regulations. For example, when considering the introduction of sandwich panels to improve the crashworthiness of a tanker, a study could be done of previous incidents that have led to an outflow of oil. However, these figures may be misleading because of the introduction over time of procedural systems (e.g. the International Safety Management Certificate) or technologies (e.g. the Automated Identification System). Therefore the likelihood of such an accident occurring today might be significantly lower than the historical data, for say the last thirty years, would suggest.

- There is often insufficient data available to give a statistically accurate impression of the underlining frequencies or probabilities. If we consider the same tanker example, and we limit the years analysed to the last ten in order to try and limit the effect of changes to procedures and technologies, then we run into a new problem of having insufficient data to accurately state the likelihood of an incident leading to an oil spill.

It is therefore recommended that expert judgment should be used in preference to historical data. However there may be times when historical data is useful. When this is the case, all involved in the risk assessment should be made aware of the historical data's limitations.

7.2.5. Further Information

Risk assessment is an extensive subject area. Therefore, within this concise guide it is inevitable that some points have been treated superficially or omitted completely. To counteract this, here are some references that the authors consider to be good sources of further information:

- The United States Coast Guard has published "**Risk-Based Decision-Making Guidelines**", which is a very comprehensive guide to taking risk-based decisions. Although not directly intended for design decisions, it is still worth reading. It has more detail than was possible to present here, including a more complete list of risk assessment techniques and their selection. There are some differences in the terminology used here. It can be found at www.uscg.mil/hq/gm/risk/e%2Dguidelines/rbdm/html/splashscreen.htm.

- The American Bureau of Shipping's "**Guide for Risk Evaluations for the Classification of Marine-Related Facilities**" is an excellent document that expands upon many of the points made in these pages. It can be downloaded from the ABS website at www.eagle.org.

- The International Maritime Organisation has published "**Guidelines for Formal Safety Assessment for Use in the IMO Rule-Making Process**". It is, as the title suggests, aimed mainly at formal safety assessments for rule making. However, it does give some interesting insights as to how a risk assessment should be performed. It can be found at www.imo.org/includes/blastDataOnly.asp/ data_id%3D5111/1023-MEPC392.pdf.

- The "**Credible Risk Assessment**" guide, published by the Maritime and Coastguard Agency, discusses a methodology for systematically analysing when a risk assessment has been effective. It is particularly useful because it discusses criteria for what is credible and what is not. It can be found at www.mcga.gov.uk/c4mca/mcga-safety_information/mcga-formal_safety_assessment/mcga-dqs-rap-crediblerisk.htm.

8. Application Case Studies

This section describes three **maritime case studies** that illustrate the application of the sandwich technologies described elsewhere in this guide. The case studies are provided as general examples of the procedures that should be followed when a decision to opt for sandwich technologies is being considered.

There are, of course, many sandwich solutions currently available, and new developments continue to appear on the market. Furthermore, design and manufacturing procedures will vary from shipyard to shipyard, and every ship design tends to be slightly different. It is therefore reasonable to state that the guidelines that follow will need to be applied on a case by case basis. Nevertheless, the applications described in this section are fairly diverse and yet all follow a generally common design process.

8.1. Superstructure for Offshore Patrol Vessel

Within the SAND.CORe co-ordination action (www.sandcore.net), a case study of a **superstructure outer shell for an offshore patrol vessel** was investigated. Here, the various aspects that were found to influence the selection of the most suitable type of sandwich for this application are discussed.

The following design steps were identified as a means of providing a structured approach to the exercise:

- Step 1 - definition of the case and setting of the specifications / requirements.
- Step 2 - risk assessment / hazard analysis.
- Step 3 - definition of evaluation criteria.
- Step 4 - selection of candidate sandwich systems.
- Step 5 - evaluation of the candidate sandwich systems.
- Step 6 - selection of sandwich type.

Each of the above six steps is described in the subsections that follow.

8.1.1. Step 1: Definition of Case and Setting of Specifications / Requirements

An important design objective for deckhouses and superstructures, being placed high on a ship, is weight reduction. Normally, stiffened thin plate structures are used. However these can cause production problems such as excessive weld distortions. Superstructure sides are large flat areas in which welding distortions manifest themselves as the so-called "*hungry horse look*" (figure 8.1-1). Welding distortions will always occur, and can only be minimised by appropriate structural design and by the optimisation of welding and assembly processes. In general, the local loads on a superstructure shell are small and therefore the plate thickness will be selected mainly to prevent excessive weld distortions. As a consequence, the use of steel may not be optimal. The combined inherent "flatness" and weight savings that could be realised by the adoption of sandwich panel designs seem an interesting proposition.

Figure 8.1-1 - a typical welded steel structure with the "hungry horse look'.

When defining a new application for sandwich structures, one should pay special attention to the critical boundary conditions. The case study described here is based on a real application, namely the superstructure for an offshore patrol vessel - figure 8.1-2. A detailed examination of the design allows a designer to visualise specific discontinuities and joint types in the panels, as shown in figures 8.1-3 and 8.1-4.

Figure 8.1-2 - selected superstructure module, part of the SIGMA offshore patrol vessel developed by Schelde Naval Shipbuilding.

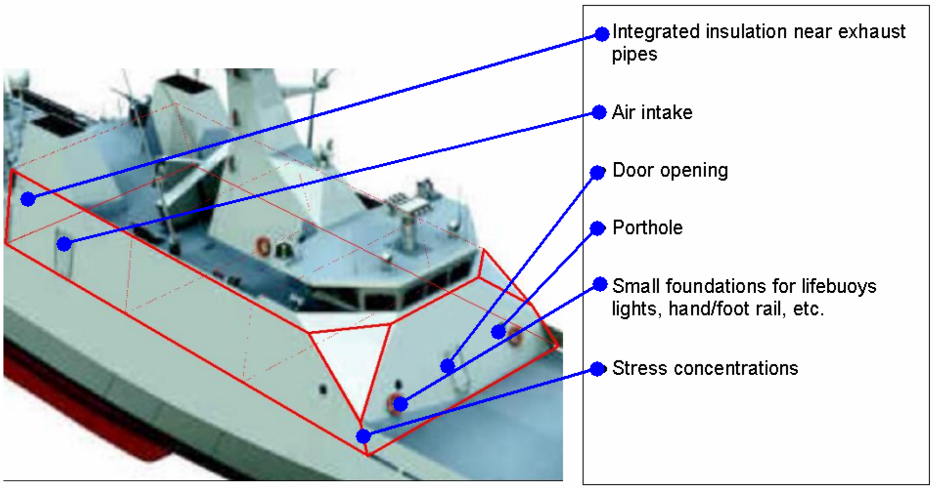


Figure 8.1-3 - discontinuities in the panels.

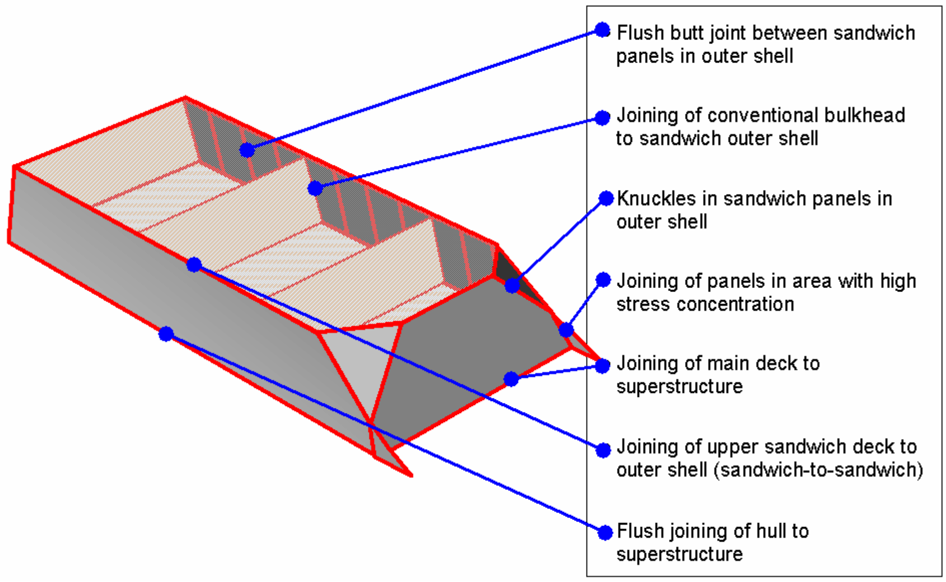


Figure 8.1-4 - identified joint types.

8.1.2. Step 2: Risk Assessment / Hazard Analysis

After the problem definition and specification of the application case, the possible hazards that could lead to a malfunctioning of the superstructure outer shell during service were identified. For this purpose, the methods described in section 7.2 of this guide were employed. A workshop was convened to prepare a series of hazard worksheets. Contributions were provided from a broad range of participants, each with a different field of expertise. Examples of the hazard worksheets are presented here are for illustrative purposes only and are not intended to give a complete overview of possible risks, failure modes and effects.

Function	Failure Description			Means of Detection / Safeguards	Remarks / Recommen-dations
	Mode	Cause	Effects		
Seawater resistant	- Corrosion.	- Failure of paint. - Galvanic corrosion.	- Reduced load bearing capacity.	- Visual inspection. - Maintenance. - Electrical detection.	- Coating. - Use of appropriate materials.
Water tightness	- Mechanical failure of both facings.	- Weapon damage. - Collision. - Green water.	- Loss of ship vital functions. - Loss of global strength.	- Visual inspection.	- Review of design loads.
Stiffness / strength	- Permanent defor-mation & fatigue.	- Poorly designed and/or manu-factured sandwich. - Exceptional loading.	- Potential structural failure. - Potential loss of other design functions.	- Robust design, manu-facturing and validation procedures. - NDT methods.	- Depending on initial sandwich design.
Bearing of loads	- Buckling & fracture of joints.	- Poorly designed and/or manu-factured sandwich. - Overloading due to change in operational conditions. - Brittle fracture due to low temp-erature.	- Loss of redun-dancy (safety factors). - Injuries. - Loss of global strength.	- Routine inspection for localised impact damage.	- Routine inspection is important for the identification of minor damage at an early stage in order to prevent it from becoming more serious over time.

Function	Failure Description			Means of Detection / Safeguards	Remarks / Recommen-dations
	Mode	Cause	Effects		
Durability	- Localised surface damage. - Moisture ingress. - Fatigue and fracture of joints.	- Localised impacts. - Moisture in contact with an exposed surface of the sandwich and moisture ingress. - Insufficient joint quality. - Brittle fracture due to low temp-erature. - Gap corrosion.	- Potential for exposed surfaces to degrade. - Potent-ially reduced structural integrity. - Loss of global strength. - Damage to equip-ment. - Injuries.	- See above	- See above
Equipment mounting	- Secondary equipment becomes detached.	- Incorrect installation of equipment. - Excessive loading of equipment.	- Potential damage to / loss of equip-ment. - Potential follow-up damage of falling equip-ment.	- Robust design, manu-facturing and validation procedures. - Routine inspection of secondary equipment mountings.	- Sandwich hard points and inserts should be validated experimentally using "pull out" and "shear out" tests during development.
Resistance against blast shock and ballistics	- Buckling. - Ductile fracture.	- Explosion – blast - Shock. - Fragmen-tation.	- Ultimate failure. - Failed joints. - Casu-alties. - Equip-ment damage. - Loss of vital functions.	- See above	- Blast panels to release internal pressure - Joint design for shocks. - Use different layers of sandwich
Fire performance	- Loss of structural integrity. - Smoke and toxic products due to com-bustion of a composite sandwich.	- Change of Young's modulus / elongation due to heat. - Incorrect choice of resin system. - Missing / damaged fire barrier or insulation.	- Ultimate failure. - Potential injury or death of crew / pass-engers. - Follow-up damage of functions and equip-ment.	- Robust design, manu-facturing and validation procedures.	- Choice of redundant design and insulation. - Choice of material.

8.1.3. Step 3: Definition of Evaluation Criteria

The third step in the process of determining the most appropriate type of sandwich type was to compile a list of evaluation criteria. These then provide a basis for material selection. Depending on the relative importance of each of the criteria, one can weight them accordingly. It is important to note that a distinction should be made between the benefits for a shipyard, and those for the end-user. A shipyard is more focussed on design and manufacturing aspects, whereas an end-user would focus more on operational aspects. The following evaluation criteria were identified for the superstructure outer shell sandwich:

Weight - Stand alone panel. - Minimal dimensioning / strength. - Redundancy of stiffeners, insulation, etc. **Cost** - Material / panel cost. - Installation cost. - Life cycle cost. **Design** - Design & engineering of loading conditions. - Simplicity / systematic approach. - Less components / geometric dimensioning. **Integration in Ship** - Flush joints. - Joints with conventional structure. - Ease of inserts / discontinuities. **Installation** - Lead time / simplicity. - Shop floor / handling restrictions. - Environmental aspects.	**Maintainability** - Maintenance / robustness. - Worldwide repair. - Onsite / emergency repair. **Fire & Insulation** - Structural integrity. - Toxic materials. - Insulation / thermal / infrared. **Functional Criteria** - Stealth (RCS / infrared / EMS). - Residual strength after local failure. - Survivability (shock / blast / fragment protection). **Marketing** - Selling points to the shipyard. - Selling points to classification authorities. - Selling points to the end-user.

8.1.4. Step 4: Selection of Candidate Sandwich Systems

Based on practical experience, shipyards can make a preliminary selection of the sandwich types that are worthy of further evaluation. For this application, the following sandwich types were considered (figures 8.1-5 to 8.1-8):

Figure 8.1-5 - composite sandwich: fibreglass (GRP) facings and balsa wood core, as applied for the helicopter hangar of the French naval vessel La Fayette.

Figure 8.1-6 - composite sandwich: carbon fibre reinforced polymer (CFRP) facings and polymer foam core, as applied to the Swedish naval vessel Visby.

Figure 8.1-7 - all-metal sandwich: laser welded steel sandwich such as I-Core developed by Meyer Werft, or LW panels developed by Mizar.

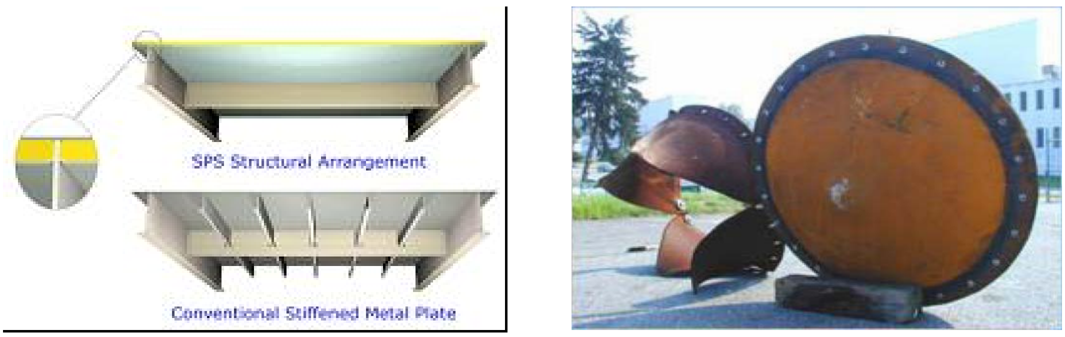


Figure 8.1-8 – hybrid metal sandwich: SPS, with possibly enhanced robustness for a military environment, developed by Intelligent Engineering.

8.1.5. Step 5: Evaluation of the Candidate Sandwich Systems

8.1.5.1. Qualitative Evaluation

The evaluation starts of with a qualitative appraisal based on the criteria defined in Step 3. Here, a five point scale was used, ranging from "- -" (poor) to "+ +" (excellent). As well as providing a high level overview of the capabilities of the different sandwich technologies, this exercise also provides insight into the extent of available knowledge. Recommendations for further studies can therefore be identified in this step.

Evaluation Criteria	GRP	CFRP	Steel	SPS
Weight	+	+ +	+	- -
Cost	+ / -	-	+ / -	-
Design	+	+	+ / -	+
Integration in Ship	+ / -	+ / -	+	+
Installation	+ / -	- / +	+	+
Maintainability	+	+ / -	+	+
Fire & Insulation	+	+ / -	+ / -	+
Functional Criteria	+	+ +	+	+
Marketing	+	+ / -	+ / -	+

The risk assessment performed in Step 2, together with the specification from Step 1, should help with the assignment of weighting factors to the evaluation criteria.

8.1.5.2. Analytical and Quantitative Evaluation

An analytical and quantitative evaluation includes, for example, stiffness and strength analysis, weight calculations, joining details, and a consideration of assembly options. In other words, it provides specific information that was lacking from the qualitative evaluation (section 8.1.5.1). Some example calculations for the weight of the superstructure are provided in figure 8.1-9.

Weight evaluation; preliminary				
type		total kg/m2	decreasement Tons @ 165 m^2	decreasement %
starting point		62,74	*10,4*	0
conventional optimised		50,35	2,0	20
I-core	2,0 - 40 - 2,0 mm	44,48	3,0	29
I-core	2,5 - 45 - 2,5 mm	54,95	1,3	12
I-core	2,5 - 55 - 2,5 mm	53,64	1,5	15
Mizar2mm web	2,0- (2) - 2,0 mm	54,68	1,3	13
Mizar 1mm web	2,0 - (1) - 2,0 mm	45,65	2,8	27
SPS	2,0 - 30 - 2,0 mm	66,63	-0,6	-6
DNV	2,0 - 30 - 2,0 mm	45,63	2,8	27
Hybrid Steel GRP	2,0 - 25 - 2,0 mm	45,93	2,8	27
Hybrid Steel GRP	3,0 - 25 - 2,0 mm	53,78	1,5	14
GRP balsa	4,5 - 60 - 4,5 mm	28,15	5,7	55
GRP balsa	4,0 - 45 - 4,0 mm	24,92	6,2	60
CFRP foam	2,5 - 40 - 2,5 mm	16,93	7,6	73
CFRP foam	2,0 - 40 - 2,0 mm	15,23	7,8	76

Figure 8.1-9 - weight estimates for the various sandwich options.

8.1.5.3. Cost Analysis

For cost analyses, one can distinguish between material costs, production costs, and operational costs. Examples of typical cost parameters are provided in figures 8.1-10 and 8.1-11.

LIFE PHASES			
Main factors			Cost factors
PRODUCTION			
Engineering	7%	1	lead time
		2	man hours in design and planning
		3	skills and tools needed by assembly yard
		4	approval by class society and others
Component	37%	5	material cost (from sandwich supply)
		6	transport cost external
		7	reliability of supplier
		8	complexity of shape
		9	availability of data and documentation
		10	warranty and after sales support by supplier
Assembly	56%	11	lead time
		12	man hours hull assembly
		13	man hours outfitting
		14	painting cost
		15	fairing cost (straightening, fitting, fairing)
		16	auxiliary material
		17	robustness in assembly
		18	ease of insulation (flatness, fire behaviour)
		19	ease for assembly (accuracy)
		20	amount and complexity of joints
		21	prefabricability in workshop
		22	amount of "package" outsourcing
		23	ease of handling and transport
		24	space consumption in production
		25	skills of personnel
		26	outfitting (functional integration, AC, cables, tubes)
		27	singularity of necessary tools and techniques

Figure 8.1-10 - production cost parameters.

OPERATION			
Service	43%	28	corrosion behaviour
		29	inspection accessibility
		30	robustness in operation
		31	worldwide availabilty of technologies for repair
		32	friendliness to repair (repairability)
		33	worldwide availability of spare parts
Money-earning	32%	34	weight
		35	visible appearance
		36	noise and vibration damping
		37	space reduction
		38	thermal / fire insulation
		39	fitness for operational static and fatigue loads
		40	crash worthiness
		41	impact resistance (dynamic)
		42	blast resistance
		43	aerodynamic profile
Re-fitting	25%	44	worldwide availability of "outfitted" package
		45	tolerance friendly connection
		46	size and weight for transport

Figure 8.1-11 - operational costs parameters.

For "new" technologies such as sandwich materials, it can be difficult to accurately quantify all the cost parameters. However, it is useful to prepare a cost list from which an overview of the major cost drivers can be obtained. Currently, customers (end users) do not seem willing to pay significantly higher up-front costs in order to save life cycle costs. In the near future, however, the effect of the design on life cycle costs is expected to play a more dominant role. This would lead to a shift of the main cost factors that would seem to be beneficial for the acceptance of sandwich structures.

8.1.6. Step 6: Selection of Sandwich Type

For each of the evaluated sandwich types, the following main conclusions can be drawn:

8.1.6.1. Fibreglass (GRP) Facings and Balsa Wood Core

- Potential for weight saving of approximately 40-60% for the selected panel structure.
- Large stiffeners are required in order to meet deflection criteria similar to steel.
- Structural decoupling is evident. This is considered feasible for this application.
- Proven technology with widely available calculation methods and experienced manufacturers.
- Can be built following class rules.
- Developments are ongoing with respect to joining methods, modular design and compliance with harsh naval durability requirements.

8.1.6.2. Carbon Fibre Reinforced (CFRP) Facings and Foam Core

- Foam-cored CFRP is a relatively new technology.
- Interesting for major weight savings - up to 80% for the selected panel structure.
- Visby has made many advances in this area, yet there is still room for further progress.
- Stiffness comes close to that of steel.
- About twice as expensive as GRP. Advances are being made towards lower cost solutions. When considering labour costs and specific design criteria, CFRP is becoming a more attractive option.
- Still many unknowns (joining, damage tolerance, costs, etc.).
- The advantages are most attractive if a complete superstructure is built from CFRP sandwich materials.

8.1.6.3. Laser Welded Steel I-Core

- Weight saving of up to 20% compared to the baseline. It would be interesting to see if significant weight savings can really be achieved.
- Further development is needed, and focus should be put into dynamically loaded joint details.
- Problems with inserts and discontinuities can easily be solved if pre-planned. But they are more difficult to handle in the case of later modifications.
- Option to consider: longitudinal framing or transverse framing (replacing secondary stiffeners and / or web frames).

8.1.6.4. Laser Welded Steel V-Core

- A corrugated core may lead to lower weight or less welding distortions (compared to I-Core) if an exceptionally low weight steel sandwich is considered.

- Thinner plating may be difficult to handle at a shipyard (faceplate damage).

- Analytical conclusion: thinner plating more feasible with V-Core; hence most potential for high weight saving.

- Conclusion after finite element modelling: compared to V-Core, I-Core has the potential to offer more significant weight savings, but at the same time has a lower shear stiffness. The reason for the contradiction between this conclusion and that from the analytical calculations above lies in the better coupling of the internal stiffeners of V-Core in a direction perpendicular to the core.

8.1.6.5. SPS Hybrid Metal Sandwich

- SPS is not considered to be a low weight solution for the superstructure. However, the SPS principle has some benefits in terms of other aspects such as insulation, fire performance, and ballistic / fragment protection. SPS also has some possibilities for weight reduction.

- Heavy weight due to core and plating thickness.

- Core weight reduction is possible with foam inserts or spheres.

- The production process seems suitable for the shop floor of a shipyard. However panels can also be delivered by a subcontractor.

8.1.6.6. Conclusions

Overall it can be seen that there are a number of different sandwich options, each with their own advantages and disadvantages. Depending upon the specific requirements of the application, and the extent to which sandwich technology is adopted, different sandwich types would appear to be preferable. For example, I-Core is of interest to Schelde Naval

Shipbuilding where much attention is being given to the reduction of welding distortions. Alternatively, CFRP sandwich structures have the potential for the highest weight saving.

In conclusion, it is recommended that a great emphasis should be placed upon deciding the right specification priorities for the sandwich structure:

- If **surface flatness** is the main design driver, then **laser welded steel sandwich panels** may be the best choice, as this manufacturing process is relatively close to that of traditional steel shipbuilding.

- If **lightweighting** is the main design driver, then a **CFRP sandwich** might be appropriate, as this enables the highest weight savings, especially if stiffness requirements need to be met.

- If **operational costs** are the main design driver, than a **GRP sandwich** could be selected, as this material offers benefits with respect to corrosion resistance and weight saving, and has a long track record on durability, repairability, etc.

- If **robustness** is the main design driver, then a **hybrid sandwich such as SPS** could be used for at least certain parts of the superstructure. Typically this is not considered as a low weight solution. However, when comparing the overall costs and weight of a naval superstructure, including heavy ballistic steel, brittle ceramics, or costly fibrous fragment protection materials, then SPS might be interesting.

8.2. Deck Ramp for RoRo Vessels

A **wheel-loaded truck deck or ramp deck in a RoRo vessel** has two main requirements:

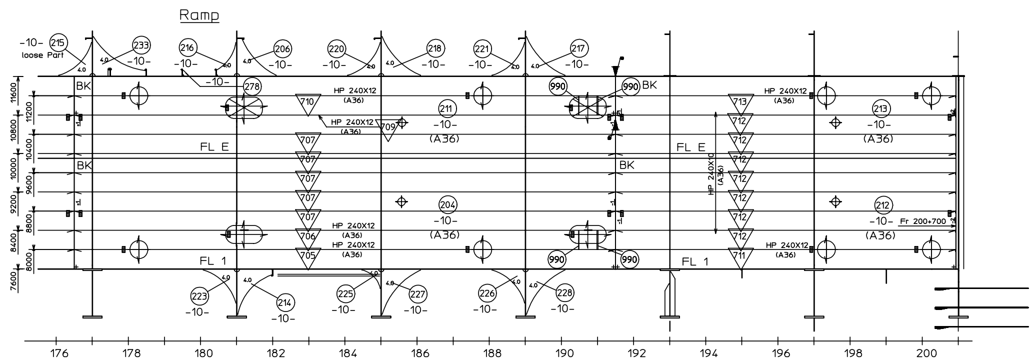
- It must withstand the **global loads** that arise during a ship’s operation, e.g. wave loads, global bending, etc.

- It must withstand the high **point loads** that arise from pneumatic lorry wheels or the all-rubber wheels of flatbed trailers, forklifts, etc.

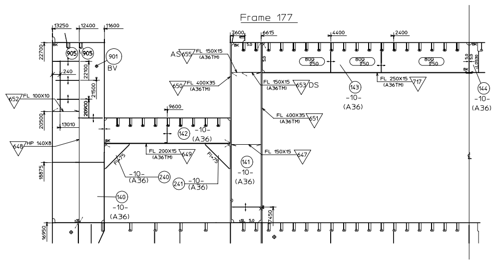
As with the superstructure application described in section 8.2, a sandwich analysis for a ramp deck was performed by following a series of sequential design stages. These are described in the subsections that follow.

8.2.1. Step 1: Definition of Application / Panel Specification

The specific application that was considered for this study was the fixed ramp between the upper and weather decks of a 200 m FSG RoRo vessel design (http://www.fsg-ship.de/ 2product/1prod/pdf/ro-ro_3900.pdf). Details of the design are given in figure 8.2-1.



Top View



Cross-section

Panel length:	18.00 m
Panel width:	4.00 m
Frame spacing:	0.40 m
Web-frame spacing:	3.00 m

Figure 8.2-1 - views of the existing ramp structure.

The scantlings of such decks or ramp structures are mainly dictated by the loads introduced by wheels. A typical load configuration used in this design study is shown in figure 8.2-2.

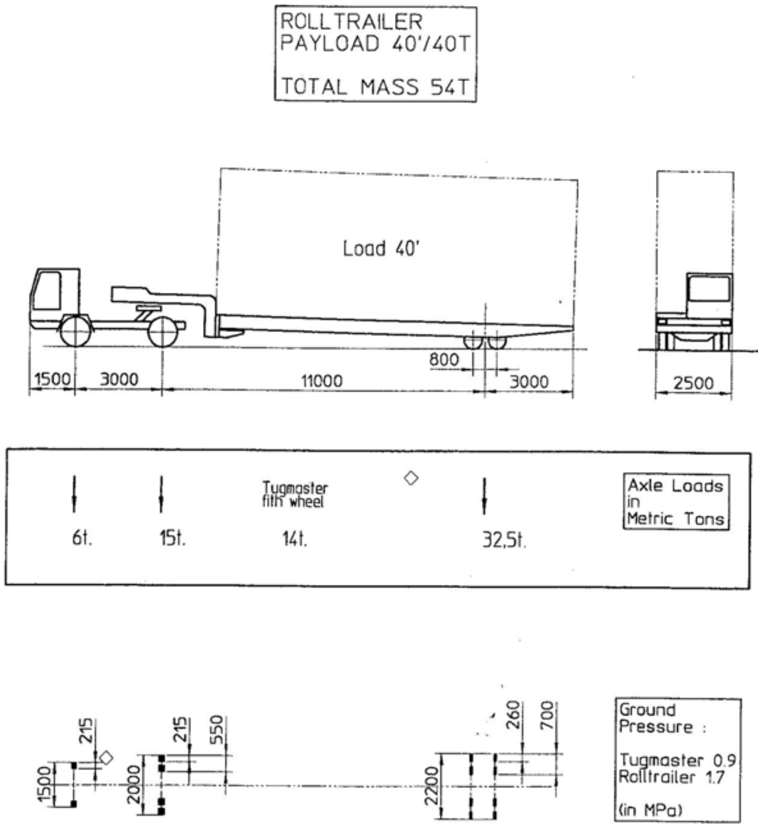


Figure 8.2-2 - loading configuration for a trailer truck used in the analysis.

8.2.2. Step 2: Hazard Identification

A **hazard identification (HAZID)** analysis was carried out to identify possible risks for the ramp design. Yard designers, owners and researchers provided input to the HAZID. The hazards identified were as follows:

- Denting of face sheets.
- Buckling of face sheets.
- Fracture of joints.
- Slippery ramp.

- Loss of structural integrity as a result of fire.

8.2.3. Step 3: Definition of Evaluation Criteria

The **design drivers** for the analysis were as follows:

- Possible weight reductions through the application of sandwich panels.
- Possible cost reductions through the application of sandwich panels.
- Evaluation of sandwich panel behaviour under global and local loading.
- Fatigue behaviour of welded connections between sandwich panels, and also between sandwich panels and conventional structures.
- Evaluation of panel behaviour under fire load.

8.2.4. Step 4: Selection / Evaluation of Candidate Sandwich Systems

Two different sandwich types, deemed the most suitable for this application, were evaluated:

- Hybrid metal SPS sandwich panels.
- All-metal I-Core sandwich panels.

Class rules (figure 8.2-3) and **finite element analysis** (figure 8.2-4) were utilised to calculate the sandwich scantlings. The local load created by trailer wheels was found to be the governing design case for the ramp.

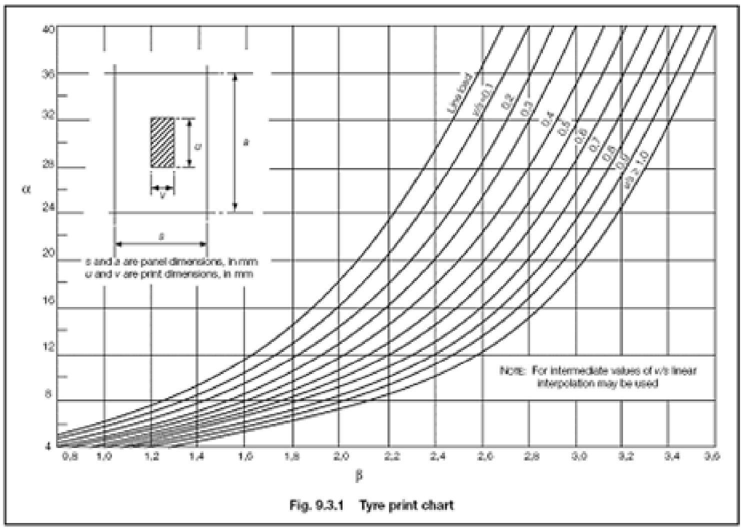


Figure 8.2-3 skin plate thickness according to class rules (Lloyds Register: Rules of Regulation for the Classification of Ships, Part 3).

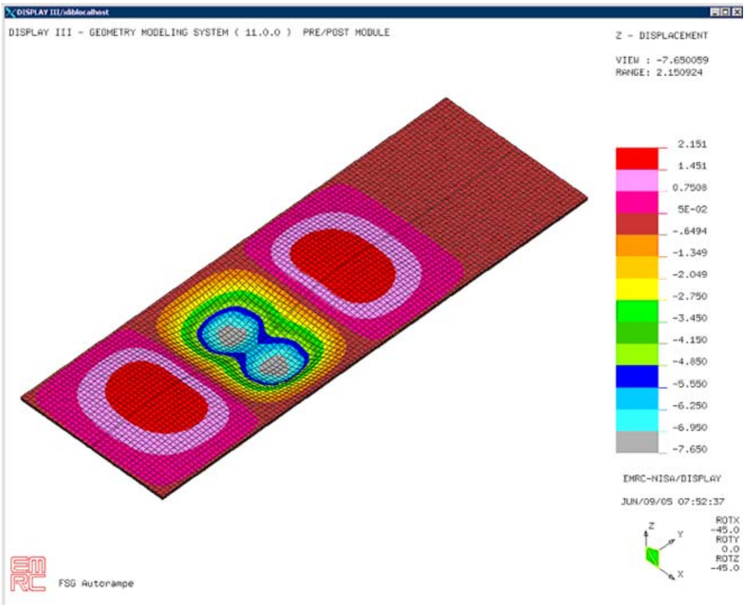


Figure 8.2-4 – results of finite element calculations - deflections due to wheel loads.

An optimisation of the I-Core structure was performed as part of the detailed design (Barkanov et al. 2005). Permissible stress criteria applied within the finite element analyses were used to find an optimal design taking into account the structure's weight.

The main results obtained for the different sandwich types and scantlings are listed in the table below.

	Conventional Design	SPS Design (4.5 / 25 / 4.5)	I-Core (6-70-6)	I-Core (3-60-3)
Weight (kg/m^2)	171	142	108	65
Weld length: plates (m)	66*	132** + 18	132**	132**
Weld length: stiffeners (m)	453	-	-	-
Cross connections	72	-	-	-

** Plates welded from one side.*
*** Sandwich plates welded from both sides.*

The advantages and disadvantages of the different sandwich types were investigated and compared to a conventional (plate and stiffener) design. The focus of the evaluation was the design, production and operation of the panels. In the table below, "+" signs indicate that the sandwich provides a benefit (e.g. a "++" for production costs with respect to the flatness of I-Core panels means that fairing costs could saved due to the inherent flatness of sandwiches). "-" signs mean that the sandwich brings some drawbacks (e.g. "-" for production costs with respect to late design changes means that it will be more expensive to implement late changes with a sandwich design compared to a conventional design).

		Conventional Design	SPS	I-Core	Optimised I-Core
Design	Material costs	0	--	-	
	Weight	0	+	++	+++
	Flatness	0	++	++	++
Production (costs)	Pre-assembly	0	++	++	++
	Flatness	0	++	++	++
	Late design changes	0	-	-	-
	Connections	0	-	-	-
	Robustness	0	+	-	-
Operation	Maintenance	0	++	+	+
	Corrosion	0	++	-	-
	Repair	0	-	-	-
	Durability	0	++	-	-

As a result of the investigation it can be stated that the benefits of the application of sandwich panels to a ship's performance depend upon the relative importance of the different design criteria. For this application, a clear decision for SPS panels should be made if a very robust and maintenance-friendly structure is required. If the main priority is weight reduction, I-Core panels are the best choice.

It should be noted that the optimised I-Core solution does not fulfil actual class requirements (e.g. with respect to minimum thicknesses or corrosion margins). But the analysis gives a good indication of the possible benefits that could be gained if risk based design is applied to take advantage of the principle of equivalence in the class requirements.

8.3. Prefabricated Balconies for New Build Cruise Ships

Here the development of **prefabricated balconies** based on sandwich technology is described with the aim of reducing construction times, weight and cost.

Traditionally, balconies are part of the deck structure. The production of the balcony commences with the rest of the steel production. Subsequent outfitting is then done in the dry dock. This production procedure has some disadvantages, and is the reason that this study was performed. On a typical cruise ship there are approximately 7,000 square meters of balconies. Assuming two ships built annually, this comes to a total of 14,000 square meters of balconies per annum (information from Meyer Werft).

The following subsections provide some guidelines to assist shipyards in the decision processes associated with the use of sandwich panels for prefabricated balconies. Of course these guidelines may have to be modified accordingly from yard to yard.

8.3.1. Step 1: Definition of Application, Specifications and Requirements

The principal **drivers** that might lead a shipyard to consider an alternative approach to balcony construction can be summarised as follows:

- The fabrication and outfitting of balconies is a long process and there is a limited capacity in the dry dock. Any manufacturing operations that could be moved out of the dry dock (e.g. through pre-fabrication) would therefore be beneficial.

- When outfitting takes place in the dry dock, fixtures and fittings have a tendency to become damaged by surrounding production operations.

- Shipyards have good previous experiences with prefabricated cabins in terms of weight and cost savings, and are keen to extend these benefits to other applications.

- The higher stiffness of sandwich panels allows for larger spans between girders.

- The low weight of sandwich panels makes them easier to handle.

- There are aesthetic advantages, since sandwich panels are flat on both sides, and no casing is needed.

However, one should also consider the possible **constraints** on the use of prefabricated sandwich balconies that might be imposed by design or production departments, such as:

- It should be possible to mount the prefabricated balconies outside of the dry dock in all weathers.

- The prefabricated balconies will be mounted on girders that are already fixed to the hull. The span between girders, as well as the width of the balcony, should be variable.

- A mechanical or bonded connection will be used to mount the prefabricated balcony to the hull.

- Other requirements could be: geometry, kinematics, forces, energy, materials, safety, ergonomics, production, verification, assembly, transport, staffing, maintenance and recycling costs.

A typical prefabricated balcony assembly is shown in figure 8.3-1.

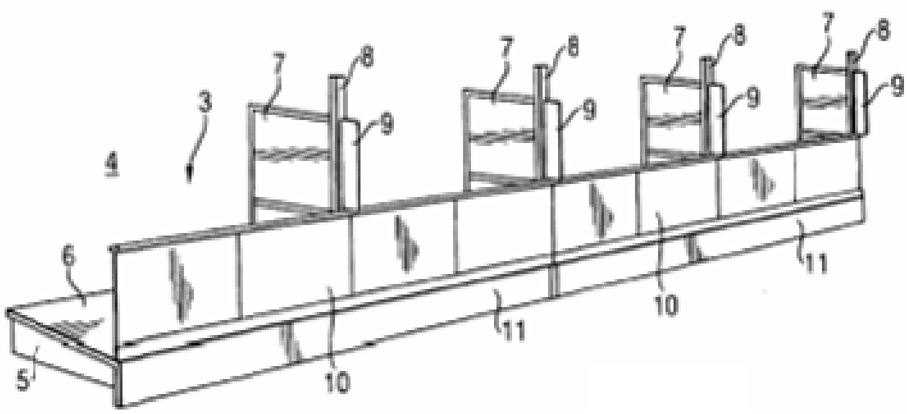


Figure 8.3–1 - typical prefabricated balcony unit (European Patent Specification EP 1 101 693 B1). The individual components within the balcony assembly are identified as follows: 4 = ship hull; 5 = girder; 6 = deck / sandwich panel; 7 = dividing wall / door; 8 = pillar; 10 = railing / hand rail.

8.3.2. Step 2: Risk Assessment / Hazard Analysis

Together with experts from classification societies, a **risk assessment** for each relevant component of the balcony should be performed. Significant risks will include:

- A failure of the connection between the girder and the platform.
- Overthrow of persons.
- Disconnection of the railing from the sandwich panel, etc.

8.3.3. Step 3: Selection of Possible Solutions

Suitable types of sandwich panel for the various components of the balcony (platform, girder and dividing wall) need to be selected. The factors that influence this decision can be weight, total height, maximum span between girders, overall design, behaviour under shipyard conditions, costs, and maintenance requirements.

After a decision concerning the candidate sandwich solutions has been made (e.g. all-metal or composite), a number of drawings and calculations (figure 8.3-2) need to be prepared to satisfy the requirements and restrictions of the shipyard and classification societies.

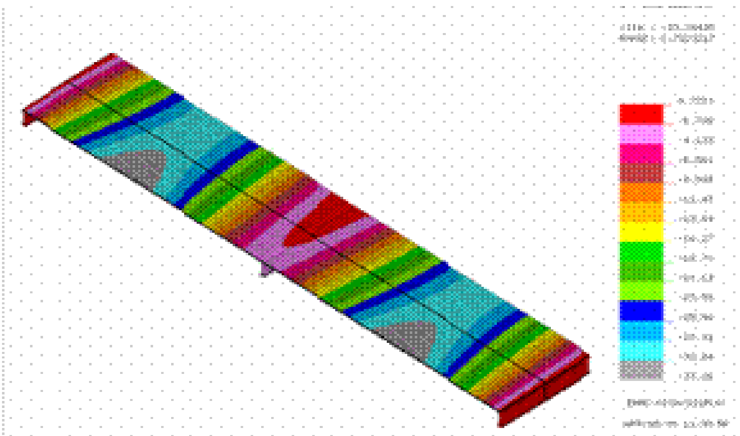


Figure 8.3-2 – finite element model of a prefabricated balcony construction based on an all-metal sandwich.

When planning a new balcony development, a **patent study** is needed. This is because a lot of ideas are protected by patents from the structural engineering industry and from shipyards and their suppliers. Two examples are given in Figure 8.3-3.

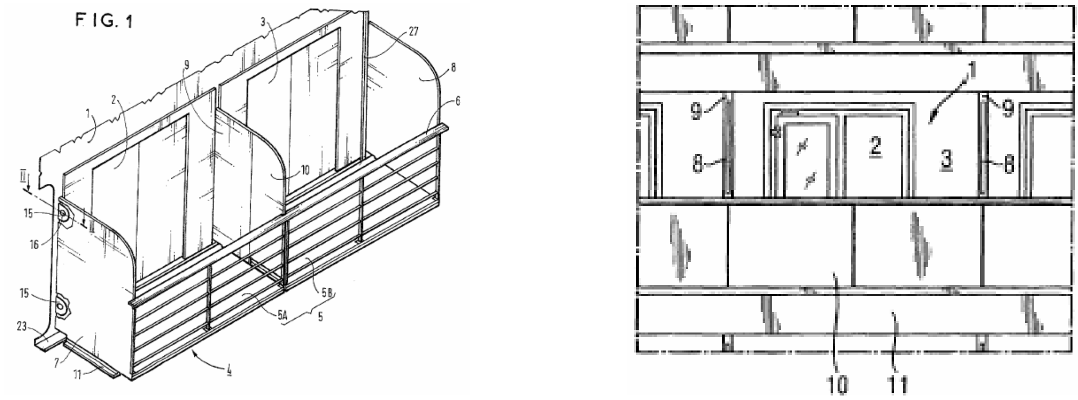


Figure 8.3-3 - Balcony patents from Kvaerner Masa Yards and Alstom (European patents EP 1 101 693 B1 and EP 1 302 397 A1).

If the decision of a shipyard is not to invest in a new development (e.g. due to existing patents), a **market solution** will be needed (figure 8.3-4). There are various companies that specialise in offering such solutions. Examples include Joptek (www.joptek.fi) and Meyer Werft (www.i-core.com).

Figure 8.3-4 - prefabricated balconies by Joptek (pictures on left) and Meyer Werft (pictures on right).

8.3.4. Step 4: Evaluation

When the steps described above have been taken and all the problems addressed, the practical implementation of the chosen solution can proceed. Depending on whether an in-house development or a commercially available solution has been adopted, some of the following steps will be needed:

- Redesign of the conventional structure with the sandwich construction.
- Fabrication of a prototype in the yard with own staff and / or with people from panel suppliers.
- Testing of the prototype to acquire the necessary experience and certificates.

- Final cost estimation.
- Introduction of the sandwich design into daily shipyard production.

9. Nomenclature

Roman Symbols

a	Sandwich length
A_g	Maximum uniform strain relating to the ultimate tensile stress, R_m
b	Sandwich width
b_b	Unsupported span of a plate in buckling
C	Panel support coefficient in a buckling analysis
c	Sandwich core thickness
c_x	Length of a patch load parallel to the stiffeners in an all-metal sandwich
c_y	Breadth of a patch load parallel to the stiffeners in an all-metal sandwich
D	Sandwich flexural rigidity (bending stiffness), or Cowper-Symonds model constant
D_F	Accumulated fatigue damage
D_{HCF}	High cycle fatigue damage
D_{LCF}	Low cycle fatigue damage
d	Distance between the centrelines of opposing facings in a sandwich
E	Young's modulus
e	Natural logarithmic constant
F	Maximum shear force
f	Core stiffener overlap distance (in an all-metal sandwich)
G	Shear modulus
g	Gap between core stiffeners (in an all-metal sandwich)
h_c	Height of the core stiffeners (e.g. in an all-metal sandwich)
h_n	Weibull distribution parameter
I	Moment of inertia
K	Stress concentration factor
k	General coefficient, or the elastic foundation stiffness of a core filler material in an all-metal sandwich
K_0	Buckling coefficient
k_b	Sandwich beam bending deflection coefficient
k_s	Sandwich beam shear deflection coefficient
L	Length of a sandwich panel
l	Sandwich beam span

l_e	Length of a finite element
M	Maximum bending moment
N	Critical buckling load
n	Number of half wave length in a panel buckling analysis
N_i	Number of cycles to fatigue failure
n_i	Number of stress cycles at a certain amplitude (fatigue analysis)
N_{load}	Total number of loading conditions considered in a high cycle fatigue analysis
P	Applied load
p	Pitch of a panel (e.g. distance between stiffeners in an all-metal sandwich)
p_n	Fraction of design life at a certain load condition (fatigue analysis)
Q	Shear force
q	Uniformly distributed load per unit area, or Cowper-Symonds model constant
q_n	Weibull distribution parameter
R_m	Ultimate tensile stress
S	Sandwich shear stiffness
s	Core cell size (e.g. of a honeycomb), or core stiffener spacing
T	General thickness dimension
t	Sandwich facing thickness, or sandwich equivalent stiffness
T_d	Design life of a ship (fatigue analysis)
v	Fibre volume fraction in a composite lamina
x	Distance along the span of a sandwich beam
x, y, z	Global Cartesian co-ordinate system

Greek Symbols

β_1	Sandwich plate deflection coefficient
β_2	Sandwich plate deflection coefficient
δ	Deflection
ε	Direct strain
$\dot{\varepsilon}$	Strain rate
ε_e	Uniform strain
ε_g	Necking strain
Γ	Gamma function (fatigue analysis)

γ	Direct shear strain
ν	Poisson's ratio
ν_0	Long-term average response zero-crossing frequency (high cycle fatigue analysis)
ν_{LCF}	Mean zero-crossing frequency for low cycle fatigue response
ρ	Density, or a sandwich plate constant
σ	Direct stress
$\hat{\sigma}$	Direct strength, or critical normal buckling stress
σ_0	Material yield stress
σ_{ai}	Stress of a certain amplitude (fatigue analysis)
σ_{crit}	Critical buckling stress
σ_e	Elastic buckling stress
$\sigma_{hot\ spot}$	Hot spot stress (fatigue analysis)
σ_{notch}	Notch stress (fatigue analysis)
$\sigma_{nominal}$	Nominal stress (fatigue analysis)
σ_y	Yield strength
τ	Shear stress
$\hat{\tau}$	Shear strength, or critical buckling stress in shear
τ_y	Yield strength in shear
θ	Rotation between a facing sheet and core stiffener at a laser weld in an all-metal sandwich

Subscripts

1, 2	Denotes the directions along two mutually perpendicular axes in the plane of a lamina
b	Pertaining to the bottom facing of an all-metal sandwich, or to values critical for buckling
bend	Pertaining to bending loading
C	Denotes compressive direction of loading
c	Pertaining to a sandwich core
f	Pertaining to a sandwich facing
fi	Pertaining to the fibres in a composite laminate
ma	Pertaining to the matrix in a composite laminate

memb	Pertaining to membrane loading
plc	Pertaining to plastic collapse
Q	Pertaining to the shear force carried by the facing sheets
T	Denotes tensile direction of loading
t	Pertaining to the top facing of an all-metal sandwich
ult	Pertaining to ultimate strength
v	Pertaining to a core filling material (e.g. in a hybrid filled all-metal panel)
w	Pertaining to the web (core element) of an all-metal sandwich
X,Y,Z	Pertaining to the longitudinal, transverse and through-thickness directions of a panel

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