Possibilities of unification of bridge condition evaluation

Background document SB3.3
This report is one of the deliverables from the Integrated Research Project "Sustainable Bridges - Assessment for Future Traffic Demands and Longer Lives" funded by the European Commission within 6th Framework Programme. The Project aims to help European railways to meet increasing transportation demands, which can only be accommodated on the existing railway network by allowing the passage of heavier freight trains and faster passenger trains. This requires that the existing bridges within the network have to be upgraded without causing unnecessary disruption to the carriage of goods and passengers, and without compromising the safety and economy of the railways.

A consortium, consisting of 32 partners drawn from railway bridge owners, consultants, contractors, research institutes and universities, has carried out the Project, which has a gross budget of more than 10 million Euros. The European Commission has provided substantial funding, with the balancing funding has been coming from the Project partners. Skanska Sverige AB has provided the overall co-ordination of the Project, whilst Luleå Technical University has undertaken the scientific leadership.

The Project has developed improved procedures and methods for inspection, testing, monitoring and condition assessment, of railway bridges. Furthermore, it has developed advanced methodologies for assessing the safe carrying capacity of bridges and better engineering solutions for repair and strengthening of bridges that are found to be in need of attention.

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General remarks

This report is prepared on the basis of Contract No. TIP3-CT-2003-001653 between the European Community represented by the Commission of the European Communities and Skanska Teknik AB contractor acting as coordinator of the Consortium.

The content of the report is related to workpackage WP3 “Condition Assessment and Inspection” and deals specifically with the condition assessment part based on the traditional inspection techniques nowadays extensively used by the railway administrations in Europe. The most advanced inspection and monitoring techniques will be the subject of other deliverables within the project.

The aim of WP 3 is to develop unified condition assessment methods. WP3 concentrates only on the condition assessment and condition rating in order to get a ranking of the condition state of the bridge stock. The ranking may be the basic for rehabilitation and repair plans for bridge owners with respect to the economical most effective and cost saving solution.

The condition can be expressed in terms of condition characterising marks, which are the result of a condition rating. The marks include all information obtained from the inspection.

Presented analysis of possibilities of harmonization in procedures of bridge condition assessment is stimulated by needs of comparable results of condition evaluation obtained in each European country.
Summary

Procedure of bridge condition evaluation is essential for all decisions in bridge management and is directly connected with the main goals of the Project:

a) increase of the train speed and increase of the axle loads require precise and objective assessment of the condition of existing bridges as a basis for decisions on conditions of safety operation, needs of rehabilitation or necessity of structure replacement;

b) extension of the safe lifetime of the bridges requires uniform methodology of bridge condition assessment as a basis for modelling and monitoring of the degradation as well as rehabilitation process;

c) international cooperation creates opportunity of harmonization of bridge condition assessment based on common system of identification and classification of bridge damages to achieve comparable results of assessment.

This report is presenting possibilities as well as some conceptions of European harmonization in the area of bridge condition assessment. The proposals are addressed to all railway authorities to stimulate discussion on potential needs and possible directions of the unification process. Solutions developed by the Project can be recommended for implementation in the next versions of the existing bridge management systems or in the anew created systems. The proposed concepts can be also applied as independent external computer-based tools of bridge condition assessment supporting the existing bridge management systems.

Conceptions and proposals described in this report are based on the results of the extensive analysis of condition assessment procedures applied for bridge structures. Description, comparison and critical review of existing condition assessment methods is presented in deliverable D3.2 “Updated inventory on condition assessment procedures for bridges”, document nr WP3-28-T-040801-F-D3.2. The main objectives of the presented report can be listed as follows:

- presentation of proposed basic terminology in the field of bridge condition assessment;
- presentation and comparison of bridge geometry models which can be applied in computer systems supporting assessment of bridge condition;
- presentation of proposal of hierarchical classification of bridge damages as a first step to harmonization of the procedure of bridge condition assessment;
- presentation of proposal of quantitative measures for all basic types of bridge damages for improvement of precision and objectivity of condition assessment;
- presentation of conception of bridge condition evaluation based on numerical quantification of damages and supported by the computer expert tools.

Modelling of bridge structures in the computer-based systems supporting bridge evaluation is of great importance for efficiency of the condition assessment process. Precision of numerical representation of the structure geometry influences accuracy of the description of bridge technical parameters in the inventory model and is also crucial for accuracy of the damage location on the structure. Advanced geometry models enable detailed description of damages as well as precise monitoring of damage changes and as a result an objective and reliable assessment of bridge condition can be achieved. Higher cost of the advanced models is usually compensated by the higher precision of the condition rating. Proposed taxonomy of the available models of bridge geometry is presented in the report. On the background of the review of the modelling possibilities the main attention is paid to the improvements of condition assessment procedures by means of the non-dimensional (E0) models of geometry.

The uniform rules of damages classification are fundamental for comparable rating of bridge condition. Taking into account conclusions of deliverable D3.2 “Updated inventory on condi-
tion assessment procedures for bridges" the conception of common classification of bridge damages is proposed. Presented classification of railway bridge damages is based on observed changes of technical parameters of structure condition in comparison with designed parameters. The effects of damages can be identified during visual inspections as well as by means of advanced testing methods. A multi-level damage classification is proposed for all types of damages of bridge components. Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

In the proposed strategy of damage classification a multi-level hierarchical order of damages is considered, with the following levels:

- level I: basic types of damages;
- level II: kinds of damages defined for each basic type;
- level III: damage categories proposed for each kind of damage;
- level IV: classes of damages for category;
- level V: sub-classes for each distinguished class of damages.

On level I of the classification seven basic types of damages are distinguished: destruction, discontinuity, losses, deformations, displacements, damages of protection, contaminations. On the lower classification levels the individual taxonomy is proposed for:

- concrete structural elements,
- steel structural elements,
- masonry structural elements,
- concrete bearings,
- steel bearings,
- composite bearings,
- non-structural elements.

Basic definitions of bridge damages are proposed to keep the common understanding of the terms being used in the report.

For each type of damages the following qualitative measures are proposed and defined:

- damage intensity $I$;
- damage extent $R$;
- damage location $L$.

Qualitative measures of the damages are based on the "segment method" described in the report.

Evaluation of bridge condition is one of the most important and the most difficult challenges in bridge engineering. Results of the evaluation, done by the large group of bridge inspectors participating in assessment process, should be consistent and comparable. All of the evaluation procedures based on manuals and written rules occur to be too subjective – the result of evaluation of the same structure by various inspectors differs often very much. For this reason the system based on expert tools supporting bridge condition evaluation is proposed as a target solution.

Presented analysis of possibilities of harmonization in procedures of bridge condition assessment is stimulated by needs of comparable results of condition evaluation obtained in each European country.

Presented analysis of possibilities of harmonization in procedures of bridge condition assessment is stimulated by needs of comparable results of condition evaluation obtained in each European country.
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1 Introduction

This technical report is prepared on the basis of Contract No. TIP3-CT-2003-001653 between the European Community represented by the Commission of the European Communities and the Skanska Teknik AB contractor acting as Coordinator of the Consortium.

Presented report is contribution of Wroclaw University of Technology (WUT) and Universidade do Minho (UMINHO) to WP3 “Condition Assessment and Inspection” which fulfils requirements of deliverable D3.3 according to Annex I to the Consortium Agreement.

Procedure of bridge condition evaluation is essential for all decisions in bridge management and is directly connected with the main goals of the Project:

- d) increase of the train speed and increase of the axle loads require precise and objective assessment of the condition of existing bridges as a basis for decisions on conditions of safety operation, needs of rehabilitation or necessity of structure replacement;
- e) extension of the safe lifetime of the bridges requires uniform methodology of bridge condition assessment as a basis for modelling and monitoring of the degradation as well as rehabilitation process;
- f) international cooperation creates opportunity of harmonization of bridge condition assessment based on common system of identification and classification of bridge damages to achieve comparable results of assessment.

Conceptions and proposals described in this report are based on the results of the extensive analysis of condition assessment procedures applied for bridge structures. Description, comparison and critical review of existing condition assessment methods is presented in deliverable D3.2 “Updated inventory on condition assessment procedures for bridges”, document nr WP3-28-T-040801-F-D3.2.

Following the terminology proposed in deliverable D3.2 two basic assessment processes are distinguished:

- condition assessment – process of evaluation of global state of bridge conservation expressed in the form of condition rating, either numerical (scale: 0-5, 1-10, 1-100 or other) or linguistic (good, poor, acceptable, etc.);
- safety assessment – process of evaluation of remaining bridge safety measured in terms of partial safety index, reliability index or probability of failure.

Condition assessment is the aim of Work Package 3 and safety assessment is one of the goals of Work Package 4. Common part of both assessment processes is identification, classification and quantification of damages influencing condition as well as safety of bridges.

The main objectives of the presented report can be listed as follows:

- presentation of proposed basic terminology in the field of bridge condition assessment (Chapters 1-9);
- presentation and comparison of bridge geometry models which can be applied in computer systems supporting assessment of bridge condition (Chapter 2);
- presentation of proposal of hierarchical classification of bridge damages (Chapter 3 to 8) as a first step to harmonization of the procedure of bridge condition assessment;
- presentation of proposal of quantitative measures for all basic types of bridge damages (Chapter 9) for improvement of precision and objectivity of condition assessment;
• presentation of conception of bridge condition evaluation based on numerical quantification of damages and supported by the computer expert tools (Chapter 10).

Presented analysis of possibilities of unification in procedures of bridge condition assessment is stimulated by the main goals of the Project and by needs of comparable results of condition evaluation obtained in each country of EU. This report is presenting possibilities as well as some conceptions of European harmonization in the area of bridge condition assessment. The proposals are addressed to all railway authorities to stimulate discussion on potential needs and possible directions of the unification process. Solutions developed by the Project can be recommended for implementation in the next versions of the existing bridge management systems or in the anew created systems. The proposed concepts can be also applied as independent external computer-based tools of bridge condition assessment supporting the existing bridge management systems (Chapter 10).
2 Taxonomy of bridge models in computer systems

2.1 Introduction

Modelling of bridge structures in the computer-based systems supporting bridge evaluation is of great importance for efficiency of the management process. Precision of numerical representation of the structure geometry influences accuracy of the description of bridge technical parameters in the inventory model and is also crucial for accuracy of the damage location on the structure. Applied models of structures are fundamental for correct and efficient assessment of the bridge condition, safety, serviceability, etc.

In almost all contemporary Bridge Management Systems only non-dimensional models of bridge structures are applied (see deliverable D3.2 "Updated inventory on condition assessment procedures for bridges" and [12], [17], [24], [25], [29], [33], [34], [35], [37]). It means that the structure is geometrically represented by a set of non-dimensional points modelling the bridge components, e.g. support No. 1, span No. 1, support No. 2, etc. Characteristics of each component (dimensions, material data, inspection data, etc.) are not oriented in the space but are only assigned to the “name tag” of the component. Such a model of geometry does not enable very precise spatial orientation of the collected information.

Current development of the computer technology offers more advanced models. Models created of one-, two- and three-dimensional elements oriented in n-dimensional space can be implemented in the computer systems supporting assessment of condition and safety of the bridge infrastructure. This means possibility of practical integration of the geometry models applied in the Bridge Management Systems and models used in the Computer Aided Design (CAD) systems based on the Finite Element Method (FEM) [26].

Advanced geometry models enable detailed description of damages as well as precise monitoring of damage changes and as a result an objective and reliable assessment of bridge condition can be achieved. Higher cost of the advanced models is usually compensated by the higher precision of the condition rating.

In this chapter of the report selected advanced models of geometry, created of one-, two- and three-dimensional elements oriented in n-dimensional space, are presented. Taxonomy of the available models, based on concepts presented in [5] and [11] is proposed. Presented pilot implementations of the advanced models confirm their practical usefulness, particularly for precise numerical representation of damages.

2.2 Modelling of bridge geometry

Classification of the models of bridge geometry can be based on two parameters [26]:

- elements used for creation of a model: non-dimensional (e0), one- (e1), two- (e2) or three-dimensional elements (e3);
- dimension of the space needed for model creation – from non-dimensional space (s0) to three-dimensional space (s3).

Proposed taxonomy of the geometric models useful in the computer systems [5] is presented in Fig. 2.1 on the example of the box bridge span. Combinations of the parameters (e1) and (s1) give ten basic classes of the geometric models denoted as (e1, s1). The distinguished classes of the models can be divided into four main types with respect to the applied elements:

- type E0 – including all models created of non-dimensional elements (e0), that is classes: (e0,e0), (e0,e1), (e0,e2), (e0,e3);
- type E\(^1\) – including all models built of one-dimensional elements (e\(^1\)) and forming classes: (e\(^1\), s\(^1\), (e\(^1\), s\(^2\)), (e\(^1\), s\(^3\));
- type E\(^2\) – encompassing classes (e\(^2\), s\(^2\)), (e\(^2\), s\(^3\)) associated with the models using two-dimensional elements (e\(^2\));
- type E\(^3\) – including only (e\(^3\), s\(^3\)) models based on the three-dimensional elements (e\(^3\)).

<table>
<thead>
<tr>
<th>SPACE DIMENSION</th>
<th>ELEMENT DIMENSION</th>
</tr>
</thead>
<tbody>
<tr>
<td>s(^1)</td>
<td>e(^0)</td>
</tr>
<tr>
<td>s(^X)</td>
<td>e(^1)</td>
</tr>
<tr>
<td>s(^X,Y)</td>
<td>e(^2)</td>
</tr>
<tr>
<td>s(^X,Y,Z)</td>
<td>e(^3)</td>
</tr>
<tr>
<td>e(^0), s(^0)</td>
<td></td>
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<td>e(^1), s(^1)</td>
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<td>e(^2), s(^3)</td>
<td></td>
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<tr>
<td>e(^3), s(^3)</td>
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</tr>
</tbody>
</table>

Figure 2.1. Classification of geometrical models of bridge structures in BMS [5], [11]

In the majority of the existing BMS the bridge components are modelled as non-dimensional (e\(^0\)) elements and all applied models can be classified as the type E\(^0\). The inventory data (length, width, material, construction type, etc.) as well as the inspection data (damsages, maintenance works, etc.) in the models based on the non-dimensional elements are collected in the data base as a set of parameters (numbers or linguistic values) identified with the considered bridge component. In the models of the simplest class (e\(^0\), s\(^0\)) belonging to the type E\(^0\) each bridge structure and each component are identified in the BMS only by the specific number or other label (inventory number). Class (e\(^0\), s\(^1\)) includes models which are oriented by means of the one-dimensional space parameter, usually by the kilometre of the road or the railway track. To the class (e\(^0\), s\(^2\)) are qualified models based on the classic geographical co-ordinates (longitude and latitude) and to the class (e\(^0\), s\(^3\)) – models utilizing three-dimensional Geographical Information Systems (GIS).

Representation of bridge structure by means of the one-dimensional elements (e\(^1\)) enables location of the collected information in relation to the length of the structure components. In the models of the class (e\(^1\), s\(^1\)) the bridge component (e.g. span) is represented by a single element (e\(^1\)) as shown in Figure 1. More advanced models like: grillage, two-dimensional truss, two-dimensional frame, etc. belong to the class (e\(^1\), s\(^2\)). The most complex models created of elements (e\(^1\)) in full three-dimensional space (s\(^3\)) are defined as the (e\(^1\), s\(^3\)) class.
Application of two-dimensional elements (e²) in the models of geometry improves precision of the information collected and processed in the computer-based systems. All information can be defined in relation to the length and width (or height) of the structure component. Examples of the models representing class (e², s²) and class (e², s³), belonging to the general type E², are shown in Fig. 2.1.

The highest accuracy of the geometry modelling offer models of the class (e³, s³). In the models of the type E³ all dimensions of each bridge component can be directly represented in the computer-based systems (Fig. 2.1).

Selection of the geometry model also defines method of damage modelling. The following parameters describing each damage can be distinguished [5]:

- damage intensity \( I \),
- damage extent \( D \),
- damage location \( L \).

Relationships between model of structure geometry and numerical representation of the damage parameters are presented in Table 2.1.

**Table 2.1. Modelling of damages depending on model of geometry**

<table>
<thead>
<tr>
<th>Damage parameter</th>
<th>Type of geometry model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E⁰</td>
</tr>
<tr>
<td>Damage intensity</td>
<td>( I )</td>
</tr>
<tr>
<td>Damage extent</td>
<td>( D )</td>
</tr>
<tr>
<td>Damage location</td>
<td>( L )</td>
</tr>
</tbody>
</table>

Varieties of the available advanced models of geometry requires selection of the most rational solutions for specific applications, taking into account increasing accuracy as well as increasing complexity of representation of the bridge structures in the computer systems.

### 2.3 Implementation of advanced models

Applications of the advanced models of structure geometry need specialized tools supporting creation and utilization of the models belonging to the type E¹, E² or E³. Selected examples of the advanced geometry model applications (see [5], [11], [17]) are presented below.

The first example presents simple model (e¹, s¹) applied for representation of the plate girder of a bridge. Figure 2.2 shows technology of defining of the technical parameters of the structure used in the pilot implementation in the system SEZAM, developed for testing of new solutions [5]. In the presented application the main steps of the inventory model creation are as follows:

- selection of the static scheme and defining of the span length,
- selection of the construction and material type,
- selection of the cross-section types,
- defining of each element (plate component) of each distinguished cross-section type.
On the similar way the numerical model of structure damages can be defined in two steps:

- identification of the types of all existing damages,
- description of the damage intensity function $I(x)$ for each damage by means of the graphic editor (Fig. 2.3).

![Figure 2.2. Model $(e^1, s^1)$ - defining of technical parameters of bridge girders [5]](image)

![Figure 2.3. Model $(e^1, s^1)$ – representation of damages by the damage intensity function $I(x)$ [5]](image)
In the presented example other parameters of damages can be automatically defined on the basis of the damage intensity functions $I(x)$:

- **damage extent function**
  $$D(x) = \begin{cases} 
  1 & \text{for } I(x) \neq 0 \\
  0 & \text{for } I(x) = 0 
  \end{cases} \quad (2.1)$$

- **damage location function**
  $$L(x) = \begin{cases} 
  1 & \text{for } I(x) \neq 0 \\
  0 & \text{for } I(x) = 0 
  \end{cases} \quad (2.2)$$

Example of the application of the $(e^2, s^3)$ model in the Bridge Monitoring and Management System RUBIKON is presented in Fig. 2.4. System RUBIKON was designed and implemented as a tool supporting maintenance of the Vistula River Bridge on the Motorway A1 near Torun [8]. A model of each component of the structure (span, support) is created of two-dimensional elements $(e^2)$ in three-dimensional space $(s^3)$. Considered components can be selected on the top view of the bridge shown in Fig. 2.4a. A graphic editor is applied for presentation of damages, separately for each element of the bridge component, e.g. for top plate, bottom plate as well as for both walls of the box span presented in Fig. 2.4b. Orientation of the currently edited part is displayed in the top-right corner of the screen.

Figure 2.4. Model $(e^2, s^3)$ applied in the RUBIKON system [8]: a) model of the whole structure - selection of the bridge component, b) modelling of damages of the selected span by means of the graphic editor
In the presented application the damage location functions $L(x, y)$ are directly defined for each type of the damages. The damage intensity functions $I(x, y)$ are assumed constant (mean value) on the area of the damage

$$I(x, y) = \begin{cases} I \text{ for } L(x, y) \neq 0 \\ 0 \text{ for } L(x, y) = 0 \end{cases} \quad (2.3)$$

and the damage extent functions are defined as

$$D(x, y) = \begin{cases} 1 \text{ for } L(x, y) \neq 0 \\ 0 \text{ for } L(x, y) = 0 \end{cases} \quad (2.4)$$

Damages of very diverse intensity can be modelled by dividing into few parts (areas) with various but constant intensity within each distinguished area.

A prototype of the most advanced, fully three-dimensional, model of geometry ($e^3, s^3$) is presented in Fig. 2.5 [11]. The whole bridge structure is modelled in three-dimensional space ($s^3$) by means of three-dimensional elements ($e^3$). The axonometric view of the model is shown in the top-right corner of the screen. For each selected component the damages can be modelled by means of the graphic editor as presented in the bottom part of Fig. 2.5. In the presented solution, implemented in the SEZAM system, the damage location functions $L(x, y, z)$ are directly edited and other damage characteristics are calculated as follows:

$$I(x, y, z) = \begin{cases} I \text{ for } L(x, y, z) \neq 0 \\ 0 \text{ for } L(x, y, z) = 0 \end{cases} \quad (2.5)$$

and

$$D(x, y, z) = \begin{cases} 1 \text{ for } L(x, y, z) \neq 0 \\ 0 \text{ for } L(x, y, z) = 0 \end{cases} \quad (2.6)$$
Aside from the homogeneous models of geometry – created of one type of elements – also non-homogeneous models can be applied. Proposed taxonomy of the geometry models (Fig. 2.1) can be easily extended and the proposed notation can also be used to the non-homogeneous models. For example models built of one- and two-dimensional elements in the three-dimensional space belong to the class ($e^1+e^2,s^3$).

### 2.4 Concluding remarks

Proposed taxonomy of the geometric models and presented notation of the distinguished classes enable uniform classification of all models. The classification system can be used to the homogeneous and non-homogeneous models.

Review of the geometry models presented in this chapter as well as experience from the pilot implementations of the selected advanced models form the basics for the following general remarks and conclusions:

- all considered models of bridge structures can be implemented using the currently available computer technologies,
- existing BMS, based on the $E^0$ models, can be supplemented by the advanced models applied when higher precision is required,
- integration of the models of geometry applied in the CAD systems and in the BMS is expected in the near future [9].

On the basis of the presented analysis we can suppose that a new generation of computer systems will enable free selection of the geometry model applied to each bridge and even to each component of the structure.

The advanced geometry models and precise modelling of damaged bridge structures can be very useful for solving some of the basic problems considered in the Project:

- modelling of damages and precise condition assessment by higher loads and speed,
- more effective planning of inspections and maintenance based on more reliable information,
- monitoring of deterioration processes for better prediction of bridge lifetime.

On the background of the review of the modelling possibilities the main attention in the next chapters will be paid to the improvements of condition assessment procedures by means of the non-dimensional ($E^0$) models of geometry.
3 Strategy of damage classification

3.1 Criteria of damage classification

The uniform rules of damages classification are fundamental for comparable rating of bridge condition. Taking into account conclusions of deliverable D3.2 "Updated inventory on condition assessment procedures for bridges" the conception of common classification of bridge damages is proposed in this chapter.

The following specific requirements according to damage taxonomy can be distinguished [5]:

- damage classification should cover all structural and non-structural components of railway bridges as well as all types of construction materials;
- method of identification and classification of damages should be useful for numerical modelling of damaged bridge components in all types of bridge geometry models (see Chapter 2),
- the system should enable identification and classification of damages on various levels of precision both, on the basis of visual inspection as well as on the basis of specialist tests,
- the classification system should be flexible and open for new categories of damages,
- presented methodology and examples should enable an unambiguous identification of all damages.

Each of the taxonomy system have to be based on well defined classification criteria. When the bridge damage taxonomy is considered the mostly common criteria of classification can be divided into three groups:

- the reason criteria – connected with the reason (reasons) of damage appearance,
- the effect criteria – connected with results (effects) of the damage,
- the reason-effect criteria – combining both the reasons and the effect as the basis of classification.

In the most cases of damages met in the bridge engineering practice the reasons of their appearance are not evident. It is also the common situation when there are more then one reason of observed damages which can be pointed out. This kind of problems with damage identification can lead to the situation when the same damage is differently described by different users – unacceptable in fundamental part of bridge management system where damage description is used for assessment of structure technical condition. That is why both classification criteria systems, the reason criteria and the reason-effect criteria, were abandoned and the effect criteria was chosen and proposed in this report.

After detailed analysis of damage classification methods applied in various procedures of bridge condition assessment (see deliverable D3.2 "Updated inventory on condition assessment procedures for bridges" and [1] [2] [5] [10] [12] [13] [14] [15] [16] [18] [19] [20] [21] [23] [24] [25] [27] [28] [29] [32] [33] [34] [35] [36] [37] [38]) none of them was found to meet all of the above requirements. For this reason the own damage taxonomy system is proposed.

Classification of railway bridge damages proposed in this report is based on observed changes of technical parameters of structure condition in comparison with designed parameters. The effects of damages can be identified during visual inspections as well as by means of advanced testing methods.
In the proposed strategy of damage classification a multi-level hierarchical order of damages is considered, with the following levels:

- level I: basic types of damages;
- level II: kinds of damages defined for each basic type;
- level III: damage categories proposed for each kind of damage;
- level IV: classes of damages for category;
- level V: sub-classes for each distinguished class of damages.

General conception of the proposed classification system (based on [3], [5], [6], [17]) is presented in Fig. 3.1.

Basic types of damages (on level I of the classification) are identical for all types of materials and all types of structures. In the presented proposal seven basic types of damages are distinguished (Fig. 3.2).

Proposed hierarchical system of damage classification enables selection of required precision of damage identification depending on considered geometrical model of the bridge (see Chapter 2).

Detailed hierarchical classifications of all types of damages are proposed in the next chapters of the report. In the proposed classification the following railway bridge components are distinguished:

- concrete structural elements,
- steel structural elements,
3.2 Basic types of damages and terminology in hierarchical classification system

To keep the common understanding of the terms being used in this report the following basic definitions are proposed:

- **BRIDGE TECHNICAL CONDITION**
  - measure of differences between current and designed values of bridge technical parameters, e.g. geometry, material characteristics, etc.,

- **BRIDGE SERVICEABILITY**
  - measure of differences between current and designed values of bridge service parameters, e.g. load capacity, clearance, maximum speed, etc.,

- **BRIDGE CONDITION ASSESSMENT**
  - process of evaluation of global state of bridge conservation expressed in the

For each, listed above, group of components a separate classification of damages is presented in the next chapters.

- masonry structural elements,
- concrete bearings,
- steel bearings,
- composite bearings,
- non-structural elements.
form of condition rating, either numerical (scale: 0-5, 1-10, 1-100 or other) or linguistic (good, poor, acceptable, etc.);

- BRIDGE DAMAGE
  - effect diminishing bridge technical condition,

- BRIDGE SAFETY ASSESSMENT
  - process of evaluation of remaining bridge safety measured in terms of partial safety index, reliability index or probability of failure.

The definitions of the basic types of damages (Fig. 3.2) are proposed as follows:

(1) DESTRUCTION
  - deterioration of physical and/or chemical structural features with relation to designed values,

  - Strength reduction
    - decrease of structure material strength according to the designed values (see example in Fig. 3.5),

  - Frost-resistance decrease
    - decrease of structure material frost-resistance according to the designed values,

  - Permeability increase
    - susceptibility to passing through of water (see example in Fig. 3.3),

  - Embrittlement
    - decrease of plasticity, (see example in Fig. 3.4)

  - Salt concentration increase
    - increase of salt concentration according to the designed values, i.e. : nitrogen compounds, chlorides, sulfates, magnesium compounds or ammonium compounds,

  - Calcium carbonate decrease
    - dissolution of calcium carbonate visible on the structure component surface caused by leaching,

  - pH factor decrease
    - increase of carbon dioxide in concrete producing carbonates and resulting in pH value decrease,

  - Impact resistance
    - changes of designed impact resistance,

  - Hardness
    - changes of designed harness,

  - Loosening
    - changes of designed stiffness of connection,
Fig. 3.3. Permeability increase - example for concrete component

Fig. 3.4. Embrittlement - example for masonry component
(2) DISCONTINUITY
– inconsistent with a project break of continuity of a structure material,

- **Crack**
  – discontinuity of material perpendicular to the element surface ranging a part of the cross-section (see example in Fig. 3.6),

- **Delamination**
  – discontinuity of material parallel to the element surface (see example in Fig. 3.7),

- **Fracture**
  – discontinuity of material perpendicular to the element surface ranging the whole cross-section, dividing it into separate parts (see example in Fig. 3.8),

- **Irregular discontinuity**
  – discontinuity of material not related to the main force direction in structure element

- **Parallel discontinuity**
  – discontinuity of material parallel to the main force direction in structure element,

- **Perpendicular discontinuity**
  – discontinuity of material perpendicular to the main force direction in structure element,

- **Skew discontinuity**
  – discontinuity of material skew to the main force direction in structure element,
Fig. 3.6. Crack - example for steel structure

Fig. 3.7. Delamination - example for concrete structure
(3) LOSSES
– decrease of designed amount of structure material (see examples in Fig. 3.9, Fig. 3.10 & Fig. 3.11),
Fig. 3.10. Losses - example for concrete component

Fig. 3.11. Losses in block and in joint - example for masonry component
(4) DEFORMATIONS
– geometry changes incompatible with the project, with changes of mutual dis-
tances of structure element points,

- Deflection
  – deformation caused by bending forces (see examples in Fig. 3.13 & Fig 3.14),

- Torsion
  – deformation caused by torsional forces.

- Dilatation
  – deformation caused by axial forces,

- Slip
  – deformation caused by shearing forces,

- Distortion
  – deformation connected with change of cross section shape (see example in
    Fig. 3.12),

- Swell
  – deformation connected with spatial increase of the volume,
Fig. 3.13. Deflection - example for concrete component

Fig. 3.14. Deflection - example for masonry component
(5) DISPLACEMENTS
– displacements of a structure or its part incompatible with project but without changes of distances of structure element points (without deformation), also restrictions in designed displacement capabilities,

  o Rotation
  – rotational displacements of the whole structure part but without its deformation, also restrictions in designed rotational displacement capabilities (see example in Fig. 3.15),

  o Translation
  – translational displacements of the whole structure part but without its deformation, also restrictions in designed translational displacement capabilities (see examples in Fig. 3.16 & Fig. 3.17),
(6) DAMAGES OF PROTECTION
– partial or total dysfunction of a protection coat,

- Adhesion decrease
  – decrease of adhesion of protective coating to the structure element appearing as a spalling,
- **Losses of protection**
  - decrease of designed amount of protective material (see example in Fig. 3.18, Fig. 3.19 & Fig. 3.20),

- **Fading**
  - loss of colour and brightness,

![Fig. 3.18. Losses of protection - example for steel component](image)

![Fig. 3.19. Losses of protection - example for concrete component](image)
(7) CONTAMINATIONS
  – appearance of any type of a dirtiness or not designed plant vegetation,

  o **Presence of salts**
    – presence of salts visible on a structure element surface in the form of weeping caused by environmental influences (see example in Fig. 3.21),

  o **Rusty weeping**
    – weeping including products of rusting of other structure components,

  o **Silt**
    – sediment in form of sand, mud, soil or organic remains carried by water and settled on a structure element,

  o **Graffiti**
    – dirtiness with a paint layer incompatible with project caused by human activity,

  o **Soot**
    – contamination with black powder produced while burning,

  o **Fumes**
    – dirtiness with layer including products of fuel burning (see example in Fig. 3.23),

  o **Oil**
    – contamination with oil,

  o **Petrol**
    – contamination with petrol,
- **Superficial plant vegetation**
  - plant vegetation present only on surface of a structure element,

- **Penetrating plant vegetation**
  - plant vegetation penetrating into structure element material (see example in Fig. 3.22),

---

**Fig. 3.21. Presence of salts - example for concrete component**

**Fig. 3.22. Penetrating plant vegetation - example for masonry component**
Fig. 3.23. Fumes - example for masonry component
4 Damages of concrete structures

Main types of damages identified in the bridge concrete structures are presented below in Fig. 4.1. Definitions of the presented damages are proposed in Chapter 3.2.

![Concrete Structure Element Diagram](image)

Fig. 4.1. Main types of damages of concrete structure

On the next pages a multi-level damage classification is proposed for each main type of damages of concrete structure component (see Fig. 4.2 - 4.8). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

Damages of protection for concrete structures concern plaster and paint, epoxide or other type of coating.
Fig. 4.2. Concrete structure component – classification for damage type destruction
**DISCONTINUITY**

- **CONCRETE**
  - Cracks
  - Fractures
  - Delamination

- **REINFORCEMENT**
  - Main reinforcement
    - Cracks
    - Fractures
  - Secondary reinforcement
    - Cracks
    - Fractures

- **PRESTRESSING TENDON**
  - Cracks
  - Fractures

Fig. 4.3. Concrete structure component – classification for damage type discontinuity

**LOSSES**

- **CONCRETE**

- **REINFORCEMENT**
  - Main reinforcement
  - Secondary reinforcement

- **PRESTRESSING TENDON**
  - Cracks
  - Fractures

Fig. 4.4. Concrete structure component – classification for damage type losses
Fig. 4.5. Concrete structure component – classification for damage type deformations

Fig. 4.6. Concrete structure component – classification for damage type displacements
Fig. 4.7. Concrete structure component – classification for damage type damages of protection
Fig. 4.8. Concrete structure component – classification for damage type contaminations
5 Damages of steel structures

Main types of damages identified in the steel bridge structures are presented below in Fig. 5.1. Definitions of the presented damages are proposed in Chapter 3.2.

![Diagram of Damage Classification]

**Fig. 5.1. Main types of damages of steel structure**

On the next pages a multi-level damage classification is proposed for each main type of damages of steel structure component (see Fig. 5.2 - 5.8). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

Damages of protection for steel structures concern all types of protective coating.
DESTRUCTION

Fig. 5.2. Steel structure component – classification for damage type destruction

DISCONTINUITY

Fig. 5.3. Steel structure component – classification for damage type discontinuity
**LOSTES**

- **BASIC COMPONENTS**
- **BOLTED/RIVETED CONNECTORS**
- **WELDED CONNECTORS**

Fig. 5.4. Steel structure component – classification for damage type *losses*

**DEFORMATIONS**

- **BASIC COMPONENTS**
  - DEFORMATION
  - TORSION
  - DILATATION
  - SLIP
  - DISTORTION

- **BOLTED/ RIVETED CONNECTORS**
  - DEFORMATION
  - TORSION
  - DILATATION

- **WELDED CONNECTORS**
  - DEFORMATION
  - TORSION
  - DILATATION

Fig. 5.5. Steel structure component – classification for damage type *deformations*

**DISPLACEMENTS**

- **EXCESSIVE DISPLACEMENTS**
  - TRANSLATION
  - ROTATION

- **DISPLACEMENT LIMITS**
  - TRANSLATION
  - ROTATION

Fig. 5.6. Steel structure component – classification for damage type *displacements*
**DAMAGES OF PROTECTION**

- **DESTRUCTION**
  - THICKNESS DECREASE
  - ADHESION DECREASE
  - EMBRITTLEMENT
  - FADING

- **DISCONTINUITY**
  - CRACKS
  - FRACTURES
  - DELAMINATION

- **LOSSES**

**Fig. 5.7.** Steel structure component – classification for damage type damages of protection

**CONTAMINATIONS**

- **DIRTINESS**
  - ENVIRONMENTAL
    - PRESENCE OF SALTS
    - RUSTY WEEPING
    - SILT
  - HUMAN ACTIVITY
    - GRAFFITI
    - SOOT
    - FUMES
    - OIL
    - PETROL

- **PLANT VEGETATION**
  - SUPERFICIAL
  - PENETRATING

**Fig. 5.8.** Steel structure component – classification for damage type contaminations
6 Damages of masonry structures

Main types of damages identified in the masonry bridge structures are presented below in Fig. 6.1. Definitions of the presented damages are proposed in Chapter 3.2.

MASONRY STRUCTURE ELEMENT

- DESTRUCTION
- DISCONTINUITY
- LOSSES
- DEFORMATIONS
- DISPLACEMENTS
- DAMAGES OF PROTECTION
- CONTAMINATIONS

Fig. 6.1. Main types of damages of masonry structure

On the next pages a multi-level damage classification is proposed for each main type of damages of masonry structure component (see Fig. 6.2 - 6.8). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

Damages of protection for masonry structures concern both paint coating and/or plaster.
Fig. 6.2. Masonry structure component – classification for damage type destruction
Fig. 6.3. Masonry structure component – classification for damage type discontinuity

Fig. 6.4. Masonry structure component – classification for damage type losses
Fig. 6.5. Masonry structure component – classification for damage type *deformations*

Fig. 6.6. Masonry structure component – classification for damage type *displacements*
Fig. 6.7. Masonry structure component – classification for damage type damages of protection
Fig. 6.8. Masonry structure component – classification for damage type *contaminations*
7 Damages of bearings

7.1 Concrete bearings

Main types of damages identified in the concrete bearings are presented below in Fig. 7.1. Definitions of the presented damages are proposed in Chapter 3.2. To this category belong bearings made of plain or reinforced concrete (see example in Fig. 7.2 and Fig 7.3) as well as concrete hinges in RC structures.

<table>
<thead>
<tr>
<th>CONCRETE BEARING</th>
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</thead>
<tbody>
<tr>
<td>DESTRUCTION</td>
</tr>
<tr>
<td>DISCONTINUITY</td>
</tr>
<tr>
<td>LOSSES</td>
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<td>DEFORMATIONS</td>
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<td>DISPLACEMENTS</td>
</tr>
<tr>
<td>DAMAGES OF PROTECTION</td>
</tr>
<tr>
<td>CONTAMINATIONS</td>
</tr>
</tbody>
</table>

Fig. 7.1. Main types of damages of concrete bearings

On the next diagrams a multi-level damage classification is proposed for each main type of damages of concrete bearings (see Fig. 7.4 - Fig. 7.10). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

Damages of protection for concrete bearings concern each type of surface coating.
Fig. 7.4. Concrete bearing – classification for damage type destruction

Fig. 7.5. Concrete bearing – classification for damage type deformations
**DISCONTINUITY**

- **CONCRETE**
  - CRACKS
    - PERPENDICULAR
    - PARALLEL
    - SKEW
    - IRREGULAR
  - FRACTURES
    - PERPENDICULAR
    - PARALLEL
    - SKEW
    - IRREGULAR
  - DELAMINATION

- **REINFORCEMENT**
  - MAIN REINFORCEMENT
    - CRACKS
    - FRACTURES
  - SECONDARY REINFORCEMENT
    - CRACKS
    - FRACTURES

---

**LOSSES**

- **CONCRETE**

- **REINFORCEMENT**
  - MAIN REINFORCEMENT
  - SECONDARY REINFORCEMENT

---

**DISPLACEMENTS**

- **EXCESSIVE DISPLACEMENTS**
  - TRANSLATION
  - ROTATION

- **DISPLACEMENT LIMITS**
  - TRANSLATION
  - ROTATION

---

Fig. 7.6. Concrete bearing – classification for damage type *discontinuity*

Fig. 7.7. Concrete bearing – classification for damage type *losses*

Fig. 7.8. Concrete bearing – classification for damage type *displacements*
Fig. 7.9. Concrete bearing – classification for damage type damages of protection
Fig. 7.10. Concrete bearing – classification for damage type *contaminations*
7.2 Steel bearings

Main types of damages identified in the steel bearings (constructed of steel components – see Fig. 7.12 and Fig. 7.13) are presented below in Fig. 7.11. Definitions of all presented damages are proposed in Chapter 3.2.

![STEEL BEARING Diagram]

Fig. 7.11. Main types of damages of steel bearings

On the next diagrams a multi-level damage classification is proposed for each main type of damages of steel bearings (see Fig. 7.14 - Fig. 7.20). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

Damages of protection for steel bearings concern all types of protective coating.
DESTRUCTION

- BASIC COMPONENTS
  - STRENGTH REDUCTION
  - IMPACT RESISTANCE
  - HARDNESS
- CONNECTORS
  - STRENGTH REDUCTION
  - LOOSENING

Fig. 7.14. Steel bearing – classification for damage type destruction

DISCONTINUITY

- BASIC COMPONENTS
  - CRACKS
    - PERPENDICULAR
    - PARALLEL
    - SKEW
    - IRREGULAR
  - FRACTURES
    - PERPENDICULAR
    - PARALLEL
    - SKEW
    - IRREGULAR
  - DELAMINATION
- CONNECTORS
  - CRACKS
    - PERPENDICULAR
    - PARALLEL
  - FRACTURES
    - PERPENDICULAR
    - PARALLEL

Fig. 7.15. Steel bearing – classification for damage type discontinuity

LOSSES

- BASIC COMPONENTS
- CONNECTORS

Fig. 7.16. Steel bearing – classification for damage type losses
DEFORMATIONS

- BASIC COMPONENTS
  - DEFLECTION
  - TORSION
  - DILATATION
  - SLIP
  - DISTORTION

- CONNECTORS
  - DEFLECTION
  - TORSION
  - DILATATION

Fig. 7.17. Steel bearing – classification for damage type deformations

DISPLACEMENTS

- EXCESSIVE DISPLACEMENTS
  - TRANSLATION
  - ROTATION

- DISPLACEMENT LIMITS
  - TRANSLATION
  - ROTATION

Fig. 7.18. Steel bearing – classification for damage type displacements

DAMAGES OF PROTECTION

- DESTRUCTION
  - ADHESION DECREASE
  - EMBRITTLEMENT
  - FADING

- DISCONTINUITY
  - CRACKS
  - FRACTURES
  - DELAMINATION

- LOSSES

Fig. 7.19. Steel bearing – classification for damage type damages of protection
7.3 Composite bearings

Main types of damages identified in the composite bearings are presented below in Fig. 7.21. Definitions of all presented damages are proposed in Chapter 3.2.
On the next diagrams a multi-level damage classification is proposed for each main type of damages of composite bearings, constructed of steel, elastomers, Teflon, and other similar materials (Fig. 7.22 and Fig. 7.23). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description (see Fig. 7.24 - Fig. 7.30).

Damages of protection for composite bearings concern all types of protective coating.
**DESTRUCTION**

- **BASIC COMPONENTS** → **STRENGTH REDUCTION**
- **CONNECTORS** → **STRENGTH REDUCTION** → **LOOSENING**

Fig. 7.25. Composite bearing – classification for damage type *destruction*

**LOSSES**

- **BASIC COMPONENTS**
- **CONNECTORS**

Fig. 7.26. Composite bearing – classification for damage type *losses*

**DEFORMATIONS**

- **BASIC COMPONENTS** → **DEFLECTION** → **TORSION** → **DILATATION** → **SLIP** → **DISTORTION**
- **CONNECTORS** → **DEFLECTION** → **TORSION** → **DILATATION**

Fig. 7.27. Composite bearing – classification for damage type *deformations*
Fig. 7.28. Composite bearing – classification for damage type displacements

Fig. 7.29. Composite bearing – classification for damage type damages of protection

Fig. 7.30. Composite bearing – classification for damage type contaminations
8 Damages of non-structural components

Main types of damages identified in the non-structural components are presented below in Fig 8.1. Definitions of all presented damages are proposed in Chapter 3.2.

![Diagram of non-structural component damages](image)

Fig. 8.1. Main types of damages of non-structural component

On the next diagrams a multi-level damage classification is proposed for each main type of damages of non-structural components (see Fig.8.2 - Fig. 8.8). Presented hierarchical system of damage classification enables selection of the required level of precision in damage identification and description.

Damages of protection for non-structural components concern all types of protective coating.

![Diagram of destruction damage classification](image)

Fig. 8.2. Non-structural component – classification for damage type destruction
Fig. 8.3. Non-structural component – classification for damage type discontinuity

Fig. 8.4. Non-structural component – no further classification for damage type losses

Fig. 8.5. Non-structural component – classification for damage type deformations
Fig. 8.6. Non-structural component – classification for damage type displacements

Fig. 8.7. Non-structural component – classification for damage type damages of protection
CONTAMINATIONS

**DIRTINESS**
- ENVIRONMENTAL
  - PRESENCE OF SALTS
  - RUSTY WEEPING
  - SILT

**HUMAN ACTIVITY**
- GRAFFITI
- SOOT
- FUMES
- OIL
- PETROL

**PLANT VEGETATION**
- SUPERFICIAL
- PENETRATING

Fig. 8.8. Non-structural component – classification for damage type contaminations
9 Quantitative measures of bridge damages

9.1 General conception of damage modelling in non-dimensional (type E₀) geometry representation

In the most popular non-dimensional geometry model (type E₀ according to the taxonomy proposed in Chapter 2.) any structure can be represented as a point and then its technical condition can be individually evaluated. Bridge structure can be also represented as a set of points, where each point corresponds with construction component (support, deck, etc.) which is individually evaluated.

To each component the following data describing stated damages can be assigned (see Chapter 2.):

- damage intensity \( I \);
- damage extent \( R \);
- damage location \( L \).

The proposed methodology of determining and numerical describing of damage parameters for all damage types is based on solutions presented in [3], [4], [5], [6], [7], [8] presented below. This concept is prepared for the case of non-dimensional geometry model E₀ (see Chapter 2.) and it enables:

- using the same damage modelling methodology for different bridge structure types and different construction materials;
- describing of damage intensity and extent continuously within values range – without any need of discretisation;
- describing of any combination of damages;
- selecting of the method of damage modelling depending on the fuzziness class of the information used.

To unify the rules of determining damage parameters the term segment is introduced – each evaluated construction component is artificially divided into segments. Segment is a part of construction component artificially separated and being individually described. The division into segments should be parallel to the main direction of work of the considered construction component. In the case of construction component where the division into structural elements is clear and easily distinguishable – such structural elements are directly considered as segments and used for damage description. The example of division into segments of span consisted of deck and girders is presented in Fig. 9.1 – the each main girder is considered as individual segment and used for description of damage extent.

For description of damage extent of construction component where the division into natural structural elements can’t be distinguished (e.g. slab span) the division into minimum 10 artificial segments is proposed. The example is presented in Fig. 9.2 for massive support construction.

The same rules should be also used for damages description of any other construction component of bridge structure. The illustration of this rule is presented in Fig. 9.3 showing the division into segments of bridge deck.

The presented way of numerical modelling of damage extent is here called “segment method”.

9.2 Damage extent

There are the following principles of using the presented above segment method for description of damages extent $R$ in the case of non-dimensional type of geometry model $E^0$ (see Chapter 2.):

- extent of each damage should be described in percents and can be equal from 0% (no damage) to 100% (the damage covers the whole evaluated construction component);

- extent of the following damage types: deformation, destruction, discontinuity and displacement should be described as quotient of the number of segments where evaluated damage type can be noticed and the total number of segments of evaluated construction component, described in percents by the formula:

$$R = \frac{m}{n} \times 100\%$$  \hspace{1cm} (9.1)

where:

- $R$ – damage extent [%],
- $m$ – the number of segments where damage can be noticed [piece],
- $n$ – the total number of segments of evaluated construction component [piece];

- extent of the following damage types: protection damages and contamination should be described as quotient of the area covered by the evaluated damage type and whole visible area of the evaluated construction component, described in percents by the formula:
where:

\[ R = \frac{1}{n} \sum_{i} \frac{\Delta A_i}{A_i} \times 100\% \]  \hspace{1cm} (9.2)

- \( R \) – damage extent [%],
- \( n \) – the total number of segments of evaluated construction component [piece];
- \( \Delta A_i \) – the area of the segment “i” of evaluated construction component, covered by the considered damage type [m²],
- \( A_i \) – the visible area of the segment “i” of evaluated construction component [m²].

The example of application of the segment method for determining the main girders damage extent is shown in Fig. 9.1 for damage type *discontinuity*. The damage in form of crack exists only in segment no. 1 – the number of segments where damage can be noticed is then \( m = 1 \), and the total number of segments of evaluated construction component is \( n = 4 \). Following the formula (9.1) the damage extent is equal:

\[ R = \frac{m}{n} \times 100\% = \frac{1}{4} \times 100\% = 25\% \]

Fig. 9.2. Example of the division into segments method in modelling of the massive support damages (damage type: *contamination*)
Other example of the segment method is presented in Fig. 9.2. The division of the abutment into 10 artificial segments is proposed. The areas of segments where contamination can be observed are equal: \( \Delta A_4 = 1.0 \text{ m}^2 \), \( \Delta A_5 = 2.5 \text{ m}^2 \), \( \Delta A_6 = 0.8 \text{ m}^2 \) and \( \Delta A_{10} = 3.0 \text{ m}^2 \). The total visible area of the edge segment is \( A_1 = A_{10} = 8.0 \text{ m}^2 \) and each intermediate segment 4.0 m\(^2\). According to the formula 9.2 extent of the damage is equal:

\[
R = \frac{1}{n} \sum_{i} \frac{\Delta A_i}{A_i} \times 100\% = \frac{1}{10} \left( \frac{1.0}{4.0} + \frac{2.5}{4.0} + \frac{0.8}{4.0} + \frac{3.0}{8.0} \right) \times 100\% = 14.5\%
\]

Similar example of determining the extent of protection damage for the bridge deck is shown in Fig. 9.3. The damage appears in segments no. 2 and no. 4. The areas covered by the considered damage are: \( \Delta A_2 = 2.0 \text{ m}^2 \) and \( \Delta A_4 = 2.8 \text{ m}^2 \). The visible area of the segments where protection damages can be observed are equal: \( A_2 = A_4 = 8.0 \text{ m}^2 \). The extent of damage can be calculated by means of the formula 9.2:

\[
R = \frac{1}{n} \sum_{i} \frac{\Delta A_i}{A_i} \times 100\% = \frac{1}{10} \left( \frac{2.0}{8.0} + \frac{2.8}{8.0} \right) \times 100\% = 6\%
\]

The presented segment method is proposed for determining of extent of all damage types in any construction component of any bridge structure.

Fig. 9.3. Damage modelling of the bridge deck (damages of protection) – division into segments
9.3 Damage intensity

9.3.1 Basic assumptions

In the proposed methodology of damages numerical modelling by means of non-dimensional types of geometry model $E^S$ (see Chapter 2.) the following principles are used for description of damage intensity $I$:

- the damage intensity determined for the mostly damaged cross-section of “$i$” segment (the biggest value of intensity $I_i$) is considered as the damage intensity $I_i$ of segment “$i$”;
- the damage intensity $I_i$ can be various in each segment – in such a case separate values of damage intensity $I_i$ and damage extent $R_i$ should be determined for each segment;
- the damage intensity measures can be different for each damage type, kind, category and class; the damage intensity can be described with numerical or linguistic values.

The damage intensity measures together with general rules of their numerical description are presented below.

9.3.2 Destruction

The intensity of damage type destruction can be described using numerical parameters with the following formula:

$$ I_i^d = D_i^d S_i^d = D_i^d \frac{\Delta F_i^d}{F_i} $$

where:

- $I_i^d$ – the destruction intensity in segment “$i$” of evaluated construction component,
- $D_i^d$ – the level of destruction in the mostly damaged cross-section of segment “$i$”, deciding about the damage intensity of segment “$i$”,
- $S_i^d = \Delta F_i^d / F_i$ – damage range in segment “$i$”,
- $\Delta F_i^d$ – the damaged cross-section area of the segment “$i$” of evaluated construction component [$m^2$],
- $F_i$ – the designed cross-section area of the segment “$i$” of evaluated construction component [$m^2$].

The level of destruction $D_i^d$ within the formula (9.3) is the normalized measure of physical and chemical properties diminishing of construction material in segment’s “$i$” damaged cross-section area $\Delta F_i^d$. When the level of destruction differs inside the damaged area $\Delta F_i^d$ the average value of $D_i^d$ should be used.

The level of destruction is being determined as numerical value from the range 0,00 – 1,00, where 0,00 means that material properties are as designed and 1,00 means complete destruction of material. The mostly damaged cross-section, deciding about the damage intensity of the whole segment “$i$”, should be considered for the level of destruction determination.
The notion of destruction is imprecise – more qualitative then quantitative. That is why the relations between the level of destruction and its symptoms (visual assessment, material test results) are also fuzzy. In this situation the natural measures of destruction level could be the linguistic values – for example from the range (insignificant, medium, significant). When using linguistic values for description of destruction level \( D_i^d \) the resulting damage intensity \( I_i^d \) can be determined by means of expert tools based on fuzzy logic (see Chapter 10.).

### 9.3.3 Discontinuity

For the steel and cast iron structures the intensity of damage type *discontinuity* can be described by the following formula:

\[
I_i^c = \frac{\Delta F_i^c}{F_i}
\]  
(9.4)

where:

\( I_i^c \) – intensity of damage type *discontinuity* in segment “\( i \)” of evaluated construction component,

\( \Delta F_i^c \) – the discontinuity cross-section area in segment “\( i \)” of evaluated construction component [m²],

\( F_i \) – the designed cross-section area of the segment “\( i \)” of evaluated construction component [m²].

The damage intensity \( I_i^c = 1.0 \) means that the segment “\( i \)” is fractured.

For the massive structures (concrete, brick and stone) the width of crack or fracture could be used as a measure of damage type *discontinuity*, described with the formula:

\[
I_i^c = w_i^{\text{max}}
\]  
(9.5)

where:

\( I_i^c \) – intensity of damage type *discontinuity* in segment “\( i \)” of evaluated construction component [mm],

\( w_i^{\text{max}} \) – maximal width of crack (fracture) in segment “\( i \)” of evaluated construction component [mm].

### 9.3.4 Losses

The intensity of damage type *losses* can be determined using the following formula:

\[
I_i^u = \frac{\Delta F_i^u}{F_i}
\]  
(9.6)

where:

\( I_i^u \) – intensity of damage type *losses* in segment “\( i \)” of evaluated construction component,

\( \Delta F_i^u \) – decrease of the segment “\( i \)” cross-section area of evaluated construction component resulting from losses [m²].
$F_i$ – the designed cross-section area of the segment “i” of evaluated construction component [m²].

Modelling of damage type losses is different for each of the structure material and includes:

- for the plain concrete structures – losses of concrete,
- for the reinforced concrete structures – losses of concrete and losses of main and secondary reinforcement,
- for the prestressed concrete structures – losses of structural concrete, losses of reinforcement and losses of prestressing tendons,
- for the steel and cast iron structures – losses of structural element material,
- for the masonry structures – losses of structure material (brick or stone) and losses of material in joints.

The intensity of concrete losses in segment “i” can be described by the following formula:

$$I_{b,j}^u = \frac{\Delta F_{b,j}^u}{F_{b,j}}$$

where:

- $\Delta F_{b,j}^u$ – the loss of concrete cross-section area in the segment “i” [m²],
- $F_{b,j}$ – the designed concrete cross-section area of the segment “i” [m²].

The intensity of reinforcement losses in segment “i” can be described by the following relation:

$$I_{z,j}^u = \frac{\Delta F_{z,j}^u}{F_{z,j}}$$

where:

- $\Delta F_{z,j}^u$ – the loss of reinforcement area at the segment “i” cross-section [m²],
- $F_{z,j}$ – the designed reinforcement area at the segment “i” cross-section [m²].

and the intensity of prestressing bars material losses by:

$$I_{c,j}^u = \frac{\Delta F_{c,j}^u}{F_{c,j}}$$

where:

- $\Delta F_{c,j}^u$ – the loss of prestressing bars material area at the segment “i” cross-section [m²],
- $F_{c,j}$ – the designed prestressing bars material area at the segment “i” cross-section [m²].

Similarly the intensity of losses of steel or cast iron elements material can be described as:

$$I_{s,j}^u = \frac{\Delta F_{s,j}^u}{F_{s,j}}$$

where:
\( \Delta F_{i,j}^u \) – the loss of material area at the cross-section of segment “i” of the steel or cast iron element [m²],

\( F_{i,j} \) – the designed material area at the cross-section of segment “i” of the steel or cast iron element [m²].

and the intensity of material losses of masonry structures:

\[
I_{m,i}^u = \frac{\Delta F_{m,i}^u}{F_{m,i}}
\]  
(9.11)

where:

\( \Delta F_{m,i}^u \) – the loss of material area at the cross-section of segment “i” of the masonry element [m²],

\( F_{m,i} \) – the designed material area at the cross-section of segment “i” of the masonry element [m²].

9.3.5 Protection damages

The intensity of protection damages can be described using numerical parameter with the following formula:

\[
I_i^a = D_i^a S_i^a = D_i^a \frac{\Delta h_i^a}{h_i}
\]  
(9.12)

where:

\( I_i^a \) – the intensity of protection damages in segment “i” of evaluated construction component,

\( D_i^a \) – the level of protection damages in segment “i” of evaluated construction component,

\( S_i^a = \Delta h_i^a / h_i \) – damage range in segment “i”,

\( \Delta h_i^a \) – thickness of the damaged protection layers of segment “i” of evaluated construction component [mm],

\( h_i \) – the designed protection layers thickness of segment “i” of evaluated construction component [mm].

The level of protection damages \( D_i^a \) within the formula (9.12) is the normalized measure of the diminishing of protection layers effectiveness in the zone where damage thickness is \( \Delta h_i^a \). When the level of protection damages differs inside the damaged zone \( \Delta h_i^a \) the average value of \( D_i^a \) should be used within the formula (9.12). The level of protection damage parameter is defined as a numerical value from the range 0,00 – 1,00, where 0,00 means that protection properties are as designed and 1,00 means complete dysfunction of protection layers. The mostly damaged cross-section, deciding about the damage intensity of the whole segment “i”, should be considered for the level of protection damages determination.

Similarly to the damage type destruction the measures of the protection damage level could be the linguistic values. When using fuzzy measures (like linguistic ones) for description of
protection damage level $D^n$ and numerical values for description of damage range $S^n$ size, the resulting damage intensity $I^n$ can be determined by means of fuzzy inference.

9.3.6 Deformations, displacements and contaminations

The information used for description of damage types deformations, displacements and contaminations are the most often fuzzy. Application of linguistic values (for example: low intensity, medium intensity, big intensity) is here proposed. For processing of the data and for evaluation of bridge condition the specialized expert tools will be used (see Chapter 10).

9.4 Damage location

The proposed system of numerical modelling of bridge damages is based on non-dimensional models of geometry. In this solution each distinguished component of the bridge structure (e.g. support, span etc.) is represented by a point. It means that each damage is connected with one specified component of the analysed bridge. Using non-dimensional elements ($e^n$) for geometry modelling causes that each noticed damage location can be described with accuracy to the construction component or element only.
10 Conception of bridge condition assessment based on numerical quantification of damages

Evaluation of bridge condition is one of the most important and the most difficult challenges in bridge engineering. Results of the evaluation, done by the large group of bridge inspectors participating in assessment process, should be consistent and comparable. All of the evaluation procedures based on manuals and written rules occur to be too subjective – the result of evaluation of the same structure by various inspectors differs often very much. For this reason the system based on expert tools supporting bridge condition evaluation is proposed as a target solution.

General conception of the proposed procedure of technical condition evaluation is presented in Fig. 10.1. The following steps in the assessment process can be distinguished:

- selection of the considered structure element;
- identification of the structure material and type of construction (based on inventory data collected in data base);

![Diagram of bridge condition evaluation process](image)

Fig. 10.1 Evaluation process of bridge condition supported by expert tool [5]
• completion of the list of potential damages created automatically by the computer system for each combination of material and construction types;
• identification of each damage according to the common classification system;
• quantitative description of each damage intensity \( I \) and extent \( R \) (see Chapter 9.);
• evaluation of technical condition index for element by means of expert tools;
• repetition of the evaluation procedure for all elements of bridge structure;
• evaluation of the technical condition of the whole bridge structure, based on condition rating of all elements.

The assessment procedure can be based on information stored in the data base as well as in the knowledge base. Technologies, methods and procedures applied in the expert tools can be developed on the basis of solutions proposed during last years, i.e. [3], [4], [5], [6], [7], [9], [22], [30], [31], [39].

Conception proposed in this report can enable harmonization of the different condition assessment methods used in various countries to rank the condition of bridges in different countries on the same basis may derive into an European condition assessment guideline.

One of the conceptions of the possible future application of common assessment method in various national Bridge Management Systems is presented in Fig. 10.2. The following possible actions can be distinguished:

• acquisition of the information on the evaluated bridge from the existing Bridge Management System (in the national format);
• processing of information from existing BMS (inventory, inspection & testing data) by means of the Damage Transformation Module to achieve numerical quantification of damages according to the common system defined in bridge damage catalogue;
• identification and numerical quantification of bridge damages in the common system;
• unified condition rating by means of the expert tools supporting assessment process;

Fig. 10.2 Application of common expert tools supporting condition assessment in national Bridge Management Systems
• conversion of the condition rating to the scale in the national BMS by means of the Rating Transformation Module.

The proposed common methodology of bridge condition assessment enables fulfilment of the following main conditions formulated in conclusions of deliverable D3.2:

• the already existing inspection data base in all Administrations should be easily adapted and used by the new rating system in order to not duplicate a work that has been already done by almost all railway administrations;

• the existing condition assessment guidelines are mainly based on the results of a visual inspection – the proposal of a new condition rating procedure should include the new inspection and testing methods developed in the framework of Work Package 3 as well as the most widely used by the European railway administrations.

The next steps to harmonization of condition assessment procedures need:

• implementation of common system of damage identification and classification,

• implementation of unified numerical quantification of damages,

• elaboration of bridge damage catalogue illustrating defects of railway bridges,

• critical review of testing methods applied in condition assessment process,

• implementation of common system of railway bridge condition rating,

• development of expert tools supporting assessment of bridge condition.
References


