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Concrete railway bridges – taxonomy of degradation mechanisms and damages identified by NDT methods

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ABSTRACT: The aim of this work is creating basis for unified and more objective assessment of bridge condition and for application of expert tools in evaluation process. The degradation processes and the relevant NDT techniques are presented on the background of the causes and the effects of these processes, taking into account: factors which influence degradation processes, mechanisms of degradation and effects of degradation with proposed methodology of identification and classification of the damages in concrete bridge structures. The proposed uniform taxonomy of degradation processes of the concrete railway bridges as well as presented analysis of the available NDT methods can be applied in evaluation of bridge condition and in modelling of structure lifetime.

1 INTRODUCTION

This paper presents an approach of defining and classifying degradation processes in concrete railway bridges and also their relations with damages classified in regard to their effects. This work focuses also on the references to the NDT methods, which can be used for identification of damages and degradation processes. The aim of this work is creating basis for unification of bridge condition assessment and for application of expert tools supporting evaluation process.

The time we live is intensive integration between European countries. In the framework of the European research project "Sustainable Bridges" there are built various tools applied in evaluation of railway bridges. Until now each country has own ways of classification of bridge damages and degradation mechanisms, e.g. (Biliszczuk et. al. 1994, Bridge Inspection Manual 1996, Enright et. al. 2000, Hearn et. al. 1995, Lauer 1991, Muller 1991, PN-80/B-01800, PN-86/B-01802). In order to use a common procedure of structure condition assessment an unified taxonomy – accepted on international level – is needed.

The big part of the instruments supporting assessment, decision process and prediction for railway bridges of concrete are the expert tools. Presented methodology has wide application in designing of the expert tools (Bień 2001, Bień et. al. 2004, Bień 2004).

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

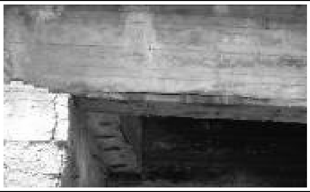
- *Bridge technical condition* - measure of differences between current and designed values of bridge technical parameters, e.g. geometry, material characteristics, etc.;
- *Bridge serviceability* - measure of differences between current and designed values of bridge service parameters, e.g. load capacity, clearance, maximum speed, etc.;
- *Bridge condition* - general measure presenting bridge technical condition and bridge serviceability;
- *Damage* - effect diminishing bridge technical condition and/or bridge serviceability;
- *Degradation mechanism* - the process causing damage(s) to construction; in this paper *degradation mechanism* are often called just *mechanism*;

- *Degradation causes* – factors or conditions conducive to initiation as well as development of *degradation mechanisms* during operation of the bridge;
- *Non-Destructive Tests (NDT)* – techniques of testing without any interference in integrity of tested structure.

2 DAMAGES OF CONCRETE RAILWAY BRIDGES

The term *damage* describes here every observable and measurable effect of the degradation processes diminishing bridge condition. Presented taxonomy of degradation processes is related to the unified classification of damages of railway concrete bridges proposed in (Bień 2004, Bień et. al. 2004). Main types of concrete bridge damages are presented in Table 1.

Table 1 Basic types of concrete bridge damages

DESTRUCTION	Deterioration of physical and/or chemical structural features with relation to designed values	
DISCONTINUITY	Inconsistent with a project break of continuity of a structure material	
LOSSES	Decrease of designed amount of structure material	
DEFORMATIONS	Geometry changes incompatible with the project, with changes of mutual distances of structure element points	
DISPLACEMENTS	Displacements of a structure or its part incompatible with project but without changes of distances of structure element points, also restrictions in designed displacement capabilities	
DAMAGES OF PROTECTION	Partial or total dysfunction of a protection coat	
CONTAMINATIONS	Appearance of any type of a dirtiness or not designed plant vegetation	

3 DAMAGES AND DEGRADATION MECHANISMS

In available literature about degradation mechanisms e.g. (Bień 2001, Biliszczuk et. al. 1994, Enright et. al. 2000, Fagerlund 1997, Gaal 2004, Hearn et. al. 1995, Diagnosis of Concrete… 2003, Lauer 1991, Mitzel 1982, Muller 1991, Polder 2000, REHABCON 2004, Ściślewski 1999) authors propose several ways of classifying these mechanisms: classification in regards to the kind, the time, the general reason and of subjecting and the character of concentration. In this paper, taking into account nature of the degradation processes, the following main groups of degradation mechanisms are distinguished:

- *chemical mechanisms* – causing degradation of bridge structures as a result of chemical reactions;
- *physical mechanisms* – diminishing condition of bridge structures by influence of physical phenomena;
- *biological mechanisms* – reducing condition of bridge structures by influence of biological phenomena.

The proposed taxonomy of basic degradation mechanisms identified in concrete railway bridges is presented in Fig. 1.

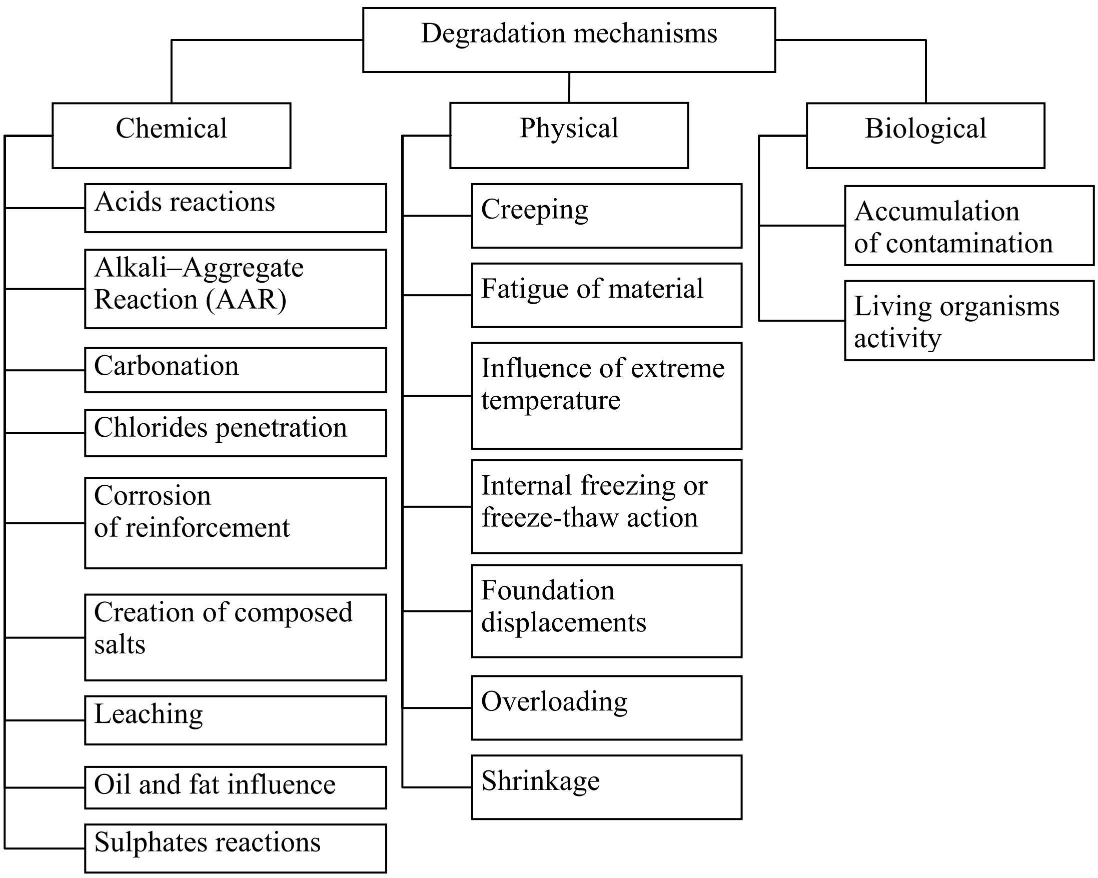


Fig. 1 Degradation mechanisms of concrete railway bridges

The most frequent *chemical degradation mechanisms* can be defined as follows:

- *Acids reactions* – corrosion of concrete caused by the reaction of the concrete components with the aggressive acid environment at the external layer of concrete (Bijen 1989, Fagerlund 1997, Gaal 2004, PN-80/B-01800, PN-86/B-01802, Ściślewski 1999). This reaction is caused by: presence of carbon dioxide, sulfates, ammonium or magnesium and also strong mineral acids like: sulphuric, hydrochloric, nitric even diluted. The factors which increase activity of this mechanism are: hydrated cement and bad maintenance – organic materials can release sulphuric acid.

- *Alkali – Aggregate Reaction (AAR)* - the mechanism caused by presence of aggregates and alkali, which leads to an expansive reaction and destruction of the concrete (Bijen 1989, Fagerlund 1997, Gaal 2004, REHABCON 2004).
- *Carbonation* – mechanism where carbon dioxide, from the atmosphere, enters to concrete and reacts with the hydroxides to form carbonates and water (Bijen 1989, Fagerlund 1997, Gaal 2004, PN-86/B-01802, Ściślewski 1999). Due to the consumption of these hydroxides the pH value is reduced below 9.0. The straight cause of Carbonation is the presence of CO_2 in the surrounding air and porosity of concrete. The factors which increase ability of concrete to carbonate are: lower content of CaO, higher diffusion constant of CO_2, higher w/c value, cracks, lower strength of concrete, presence of mineral additives and also the lack of curing of concrete in moist environment.
- *Chlorides penetration* - loosing the passivation causes by presence of chloride ions, which locally breaks down the passive film. Chlorides mechanism is caused by: marine see environment – permanent penetration of chlorides and de-icing salts. The factors which increase activity of this mechanism are: high value of w/c, carbonization and moisture, low concentration level of OH(-), mineral additives like: silica dust, fly-ash, blast furnace slag, lower content of C_3A (Fagerlund 1997), the curing of concrete in moist environment even of small salt content, the salting on the construction surfaces subjected to the activity of the atmospheric factors (Fagerlund 1997, Gaal 2004, Polder et. al. 2000, Ściślewski 1999).
- *Corrosion of reinforcement* – the oxidation of steel initiated by the loosing of rebars passivation at the high electrolytic conductivity of concrete (high humidity) and the permanent supply of oxygen from outside. The expansive character of producing oxides induces cracks and loss of the concrete cover. The factors which increase activity of this mechanism are: carbonization of concrete, chlorides and cracks (Fagerlund 1997, Gaal 2004, PN-80/B-01800, REHABCON 2004).
- *Creation of composed salts* – mechanism caused by the reaction of aggressive substances from the surrounding environment with the concrete components. This mechanism causes creation of the salts in concrete pores. When the salts crystallize, they enlarge their volume. This leads to the increase of the tensile stress and cause destruction of the pore walls and strength reduction. The partial humidity of concrete and the possibility of the temporary steaming of water increase the activity of this mechanism (Ściślewski 1999).
- *Leaching* – destruction of concrete caused by soft water. The components of concrete are dissolved and leached. The mechanism is caused by water, especially clear, distillated and condensation and also by the mountain streams and precipitations. Factors which increase activity of this mechanism are: cracks, higher value of w/c index, higher content of $Ca(OH)_2$ and higher permeability of concrete (Fagerlund 1997, PN-80/B-01800, PN-86/B-01802, Ściślewski 1999).
- *Oil and fat influence* – reaction of oils and/or fats with the calcium hydroxide. During this reaction calcium soaps are created, which are the greasy substances and do not have binding features (Ściślewski 1999).
- *Sulphates reactions* – corrosion of concrete caused by the reaction of concrete components with aggressive sulphate environment like water, contaminated groundwater, soils, seawater, decaying organic substance or industrial effluent. This mechanism can be caused also by or aggregate that contains sulphates (Bijen 1989, Gaal 2004, PN-80/B-01800, PN-86/B-01802).

In the group of *physical mechanisms* the following main processes causing degradation of concrete bridge can be distinguished:

- *Creeping* – inelastic strains caused by long-time load (Mitzel A. et. al. 1982).
- *Fatigue of material* – mechanisms of sequential degradation of material, by crack initiation and its increasing to critical size, from which unstable escalation is started. This phenomenon is caused by recurrent loads (Rykaluk 2000).
- *Foundation displacements* – mechanism causing changes in the global geometry of the structure. This phenomena leads to the danger redistribution of internal forces and

consequently – stresses, which can exceed designed values of the load capacity and cause serious damages. Mechanism can by caused by floods, mine activity, earthquakes or wrong parameters of the ground taken into consideration in the project (Mitzel A. et. al. 1982).

- *Influence of high temperature* – phenomenon caused for example by a rail or truck mounted tanker getting ignited accidentally in the vicinity of a bridge (Mitzel A. et. al. 1982).
- *Internal freezing or freeze-thaw action* – mechanism caused by the expansion of pore water due to freezing. This mechanism cause deep cracks. Factors which increase the effects of this mechanism are: the w/c ratio > 0.6; decreased air content; continuous storing of concrete in permanent contact with water without drying time; fine porous aggregate; alkalis content; mineral additives like cinder, fly-ash without aerating substances; cracks; structures sucking ground water; railway bridge troughs filled with moist ballast (Fagerlund 1997, Gaal 2004, Diagnosis of Concrete… 2003, REHABCON 2004).
- *Overloading* – exceeding of the acceptable designed values of the load. Overloading can be caused by: changing of the load class; floods, earthquakes, collisions or any other accident.
- *Salt-frost scaling* – mechanism caused by the expansion of pore water due to freezing in the presence of salt water; factors which increase the effects of this mechanism are: the w/c ratio > 0.4; lower air content in fresh concrete before the cementation; presence of silica dust; continuous storing of concrete in permanent contact with water without drying time; fine porous aggregate; leaching; acid attack (Fagerlund 1997, Diagnosis of Concrete… 2003, REHABCON 2004).
- *Scour of foundation* – mechanism caused by the moving liquid (for instance river) through the support zone and causing losses of support material as well as the soil.
- *Shrinkage*. This mechanism is caused by the internal constraint of element deformation by reinforcement resistance. It is caused also by the external constrainment of element movement by supports and can be caused by badly performed curing of concrete exposed to the sunbeams (Mitzel A. et. al. 1982).

Biological degradation mechanisms form the smallest but important group of processes diminishing condition of concrete railway bridges. The following main processes can be listed:

- *Accumulation of contamination* – mechanism of organic and non-organic contaminants increase caused by environmental and/of human activities:
- *Living organisms activity* – mechanism causing the damages as a result of living organisms activity like bacteria, plants and animals (Ściślewski 1999).

All described degradation mechanisms can be also classified taking into account duration of the degradation processes. The following groups can be distinguished:

- incidental mechanisms – when the degradation process is very short (duration even below a second), e.g. overloading by collision or by earthquake;
- short-time mechanisms – acting during hours or days, e.g. influence of extreme fire temperature, foundation displacement because of scour during flood;
- long-time mechanisms – majority of considered chemical, physical and biological processes.

Relationships between the degradation mechanisms and the basic types of damages, based on analysis of many practical cases, are presented in the Table 2. Shown results confirm very complicated nature of degradation processes applied to concrete railway bridges. Identified damages are usually caused by more that one degradation mechanism and correct understanding of the processes needs very precise analysis.

Presented methodology is a powerful tool which can be used in order to explaining phenomena of degradation mechanisms as well as avoiding these damages in the future.

Table 2. Degradation mechanisms and basic types of damages

Degradation mechanisms / Damages	Chemical									Physical									Biological	
	Acids	Alkali – Aggregate Reaction (AAR)	Carbonation	Chlorides penetration	Corrosion of reinforcement	Creation of composed salts	Leaching	Oil and fat influence	Sulphates reactions	Creeping	Fatigue of material	Influence of high temperature	Internal freezing	Foundation displacements	Overloading	Salt-frost scaling	Scour of foundation	Shrinkage	Accumulation of contamination	Living organisms activity
Destruction	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓			✓	✓
Discontinuity		✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓
Losses	✓	✓	✓	✓	✓				✓		✓	✓	✓	✓	✓	✓	✓		✓	✓
Deformations										✓		✓		✓	✓		✓	✓		
Displacements														✓	✓		✓		✓	
Damages of protection	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
Contaminations		✓			✓		✓					✓	✓				✓		✓	✓

4 CONCRETE BRIDGE DEGRADATION AND NDT METHODS

Evaluation of concrete bridge condition needs identification of structure damages and ongoing as well as potential degradation mechanisms. The most popular and efficient tools offer non-destructive testing (NDT) technology, e.g. (Bridge Inspection Manual. 1996, Bungey et. al. 1996, Diagnosis of Concrete… 2003, FIB Bulletin No 22 2003, "Sustainable Bridges"). The NDT methods enable testing without additional damaging the structure.

In Table 3 the application range of the selected NDT methods applied for identification of the basic damage types is presented. Shown comparison of various NDT techniques can be helpful in selection of the testing methods in the process of condition evaluation of concrete railway bridges.

Table 3. Application of NDT methods for identification of concrete bridge damages

Damages / NDT methods	Destruction	Discontinuity	Losses	Deformations	Displacements	Damages of protection	Contaminations
1	2	3	4	5	6	7	8
Acoustic and optic methods							
Acoustic emission	✓	✓					
Endoscopy		✓	✓			✓	
Fibre optic sensors		✓		✓			
Impact-echo	✓	✓				✓	
Low Strain Pile Integrity Testing	✓	✓					
SASW	✓						
Ultrasonic tomography / test	✓	✓				✓	

Table 3. Continuation

1	2	3	4	5	6	7	8
Electrical /electro-magnetical methods							
Potential Mapping	✓		✓			✓	
Electromagnetic test	✓	✓				✓	
Galvapulse			✓				
Ground penetrating radar		✓					
Impulse Radar	✓	✓					
Geodetic measurements							
Global Positioning System (GPS)				✓	✓		
Laser displacement measurements				✓	✓		
Triangulation				✓	✓		
Load tests							
Static load tests	✓						
Dynamic load tests	✓	✓					
Vibration tests	✓	✓	✓				
Radiographic methods							
Radiography with x-ray / cobalt		✓					
Spectral-chemical and potential methods							
Laser induced breakdown spectroscopy	✓						
Test of pollution	✓					✓	
Thermal heat transfer							
Pulse-phase thermography		✓					
Transient thermography	✓	✓					
Visual and simple methods							
Covermeter						✓	
Direct measurement		✓	✓			✓	✓
Displacement gauges					✓		
Hydrostatic levelling system (HLS)				✓			
Mechanical sensors				✓			
Roughness depth test	✓					✓	
Sclerometric test	✓						
Strain measurement	✓			✓			
Tapping	✓	✓	✓				
Torrent permeability	✓						
Visual inspection	✓	✓	✓	✓	✓	✓	✓
Void volume measurement		✓	✓				

5 CONCLUSIONS AND ACKNOWLEDGEMENTS

Presented solutions can be considered as a part of European discussion concerning common methodology of advanced bridge condition assessment and forecasting. The proposed uniform taxonomy can be applied in evaluation of bridge condition and in modelling of structure lifetime. The aim of this work is creation of theoretical background for expert tools supporting decisions in bridge management. The described relations between degradation mechanisms, damages and NDT methods are the basis for creation of the knowledge-based computer tools for evaluation of the current bridge condition or for forecasting the future behaviour of construction.

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