Damages to masonry arch bridges – proposal for terminology unification

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ABSTRACT: Proposal for a standardized classification of damages to masonry arch bridges is presented. The hierarchical classification is based on damage effects. Six main damage types are distinguished: contamination, deformation, destruction, discontinuity, displacement and loss of material. The most common mechanisms of masonry bridge degradation and the relationships between damage types and processes causing them are considered. Finally, basic testing methods useful in identifying such damages are indicated and a range of their applications is discussed.

1 INTRODUCTION

Problems connected with damages and condition of masonry arch bridges are becoming a more and more important issue in almost all European countries. This interest is related to a numerous stock of these structures in Europe reaching 25 % of road bridges and even 45 % of railway bridges as well as to an advanced age of the majority of them.

Bridge condition assessment is based on the identification of structure defects and comparison of current and designed values of bridge technical and operational parameters. The applied methodologies of damage classification and evaluation of their influence on bridge condition are fundamental for the assessment process. In each country bridge owners and administrators develop and use their own system, but at the same time international integration and cooperation requires a uniform system.

The proposed unified system, initially developed by Bień (2002) and continued within *Sustainable Bridges* Project (Niederleithinger et al. 2006), consists of three main components: damage classification, taxonomy of degradation mechanisms and categorization of testing methods. Common terminology for the whole system to improve communication in the considered field of bridge engineering is presented below. The proposal should be considered as a part of discussion concerning unification of methodology of bridge condition assessment.

Basic terms used in this paper can be defined as follows:

- *damage* – a defect diminishing the bridge technical condition and/or bridge serviceability,
- *degradation mechanism* – a process causing damage(s),
- *bridge technical condition* – a measure of differences between the current and designed values of bridge technical parameters, e.g. geometry, material characteristics, etc.,
- *bridge operational condition* – a measure of differences between the current and designed values of bridge operational parameters, e.g. load capacity, clearance, maximum speed, etc.,
- *bridge condition* – a general measure presenting bridge technical and operational condition.

2 HIERARCHICAL CLASSIFICATION OF DAMAGES

Each of the consistent taxonomy system has to be based on well defined classification criteria. When the bridge damage taxonomy is considered, the most common criteria for classification can be divided into three groups:

- *the cause criterion* – related to the cause (causes) for damage appearance,
- *the cause-effect criterion* – combining both the cause and the effect as the basis of classification,
- *the effect criterion* – related to the results (effects) of the defects.

In most cases of damages encountered in the bridge engineering practice the reasons for their appearance are not evident. It is also a common situation when there are more than one reason for the observed damage that could be pointed out. This kind of problems with damage identification can lead to the situation when the same damage is described in a variety of ways by different users – which fact is unacceptable in the fundamentals of bridge management where damage description is used for the assessment of a structure condition. That is why the cause, and the cause-effect criteria were abandoned and the effect criterion was employed in the proposed solution.

All damages to masonry bridges can be precisely defined and categorized according to the rules presented in this section. The proposed classification has a hierarchical layout and at the highest level six main types of damages – presented in Figure 1 – can be distinguished:

- *contamination* – appearance of any type of dirtiness or plant vegetation incompatible with the design for a bridge(Fig. 1a),
- *deformation* – geometry changes incompatible with the design, with changes of mutual distances of structure points (Fig. 1b),
- *destruction* – the deterioration of physical and chemical structural features in relation to the design for a bridge (Fig. 1c),
- *discontinuity* – a break in the structure material continuity (Fig. 1d),
- *displacement* – displacement of the whole structure or its structural component incompatible with the design but without deformation of the structure (Fig. 1e),
- *loss of material* – a decrease in the structure material amount in comparison with the design for a bridge (Fig. 1f).

The detailed classification including all types of masonry bridge damages is shown in Table 1. For all main types of damages except *displacement*, at the second level of the classification, structure components covered by a damage are indicated. At the next levels detailed damage types dependent on the structure components are distinguished.

The names of most of the damages presented in Table 1 can be understood literally, some of them, however, require definitions that are proposed as follows:

- *aggressive/neutral contamination* – inorganic dirtiness provoking/not provoking chemical or physical reaction of the structure,
- *penetrating contamination* – organic contamination (e.g. plants, bacteria) penetrating deep into the structure,
- *superficial contamination* – organic contamination located on the surface of the structure,
- *deflection* – a deformation of the structure element caused by bending forces; without the deformation of the element cross-section,
- *slip* – a deformation of the structure element caused by shear forces, without the deformation of the element cross-section,
- *swell* – an increase in the volume of structural material,
- *absorbability increase* – an increase in the material tendency to absorb water,
- *adhesion reduction* – a decrease in adhesion of protective coating to the structure element,
- *embrittlement increase* – a decrease in material ductility,
- *fading* – a loss of colour and/or brightness,
- *frost-resistance reduction* – a decrease in the structure material frost-resistance according to the designed value,
- *permeability increase* – an increase in the structure material vulnerability to passing through of water,

- *strength reduction* – a decrease in the structural material strength in respect of the designed values; especially compressive and shear strengths,
- *calcium hydroxide reduction* – a decrease in the calcium hydroxide content in the structural material,
- *pH factor reduction* – an increase in carbon dioxide in concrete producing carbonates and the resulting pH value decrease,
- *salt concentration increase* – an increase in the salt content according to the designed values, i.e. nitrogen compounds, chlorides, sulphates, magnesium or ammonium compounds,

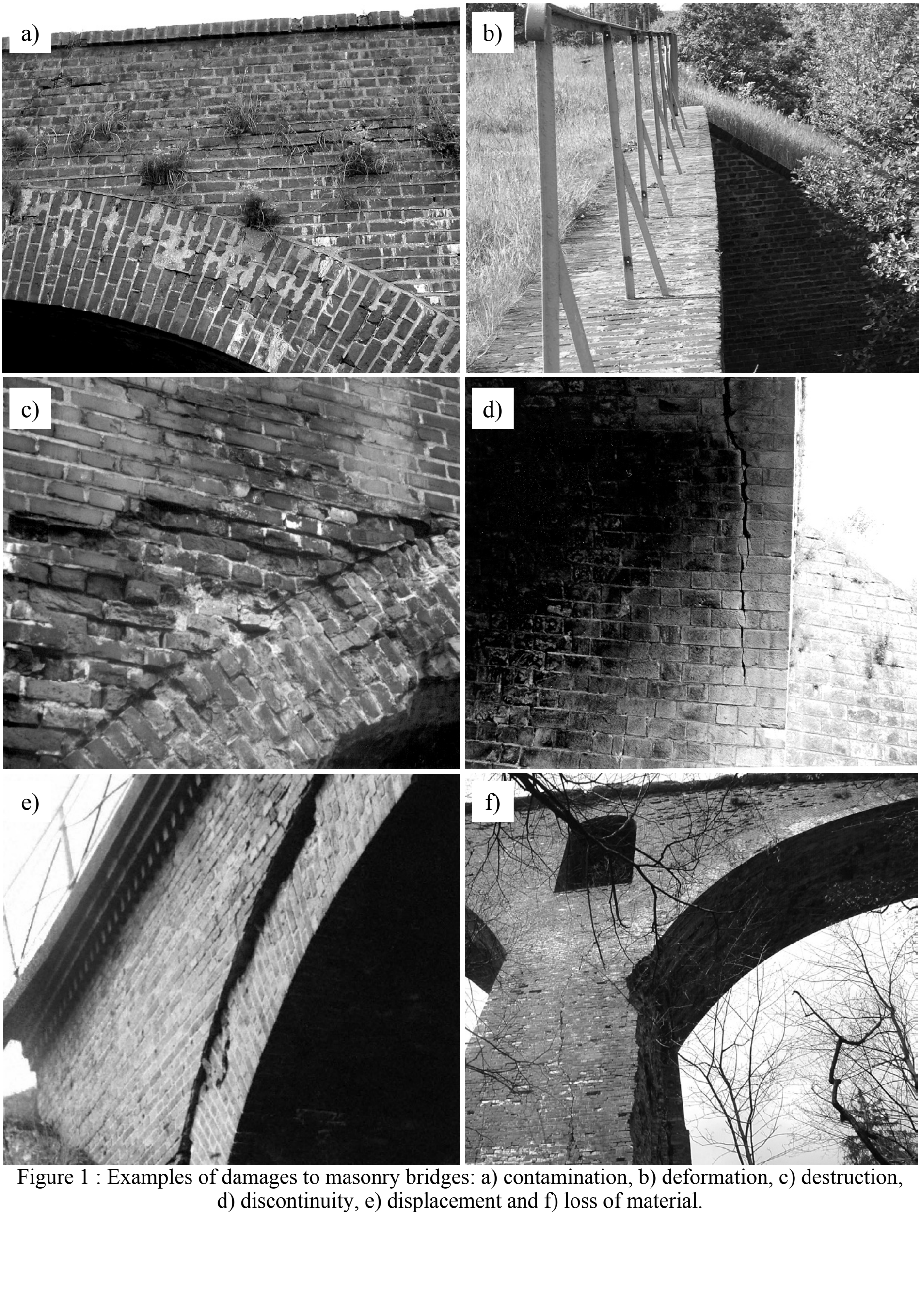

Figure 1 : Examples of damages to masonry bridges: a) contamination, b) deformation, c) destruction, d) discontinuity, e) displacement and f) loss of material.

Table 1 : Hierarchical classification of masonry bridge damages.

LEVEL I	LEVEL II	LEVEL III	LEVEL IV
Contamination	Backfill	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
	Masonry	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
	Protection	Inorganic	Aggressive
			Neutral
		Organic	Penetrating
			Superficial
Deformation	Backfill	Deflection	
	Masonry	Deflection	
		Slip	
		Swell	
	Protection	Deflection	
Destruction	Backfill	Modification of physical features	
	Brick/stone	Modification of chemical features	Calcium hydroxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Elastic modulus change
			Embrittlement increase
			Frost-resistance reduction
			Permeability increase
			Porosity increase
			Strength reduction
	Joint	Modification of chemical features	Calcium hydroxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Elastic modulus change
			Embrittlement increase
			Frost-resistance reduction
			Permeability increase
			Porosity increase
			Strength reduction
	Protection	Modification of chemical features	Calcium hydroxide reduction
			pH factor reduction
			Salt concentration increase
		Modification of physical features	Absorbability increase
			Adhesion reduction
			Embrittlement increase
			Fading
			Frost-resistance reduction
			Permeability increase
			Porosity increase
Discontinuity	Masonry	Crack	Irregular
			Longitudinal
			Skew
			Transverse
		Delamination	
		Fracture	Irregular
			Longitudinal
			Skew
			Transverse
	Protection	Crack	
		Delamination	
		Fracture	
Displacement	Excessive	Rotation	
		Translation	
Loss of material	Backfill		
	Brick/stone		
	Joint		
	Protection		

- *crack/fracture* – a discontinuity of the material perpendicular to the element surface; the following crack/fracture orientations can be distinguished:
    - *irregular* – forming a network of discontinuities without a dominating direction,
    - *longitudinal* – parallel (±10º) to the element longitudinal axis,
    - *skew* – oriented 10º-80º to the element longitudinal axis,
    - *transverse* – perpendicular (±10º) to the element longitudinal axis,
- *delamination* – a discontinuity of the structure material parallel to the element surface; including a ring separation in multi-ring arches,
- *fracture* – a discontinuity of the material perpendicular to the element surface ranging the whole cross-section, dividing it into separate parts,
- *rotation/translation* – rotational/translational displacement of the structure or its part without a deformation.

3 MECHANISMS OF DEGRADATION

In addition to the unambiguous classification of damage types, an important issue are degradation mechanisms causing damages. Taking into account the nature of the degradation mechanisms, the following main groups can be distinguished:

- *chemical mechanisms* – causing the degradation of bridge structures as a result of chemical reactions,
- *physical mechanisms* – deteriorating the condition of bridge structures by the influence of physical phenomena,
- *biological mechanisms* – deteriorating the condition of bridge structures by the influence of biological phenomena.

The most frequent chemical degradation mechanisms identified in masonry bridges can be defined as follows:

- *carbonation* – the mechanism whereby carbon dioxide from the atmosphere enters concrete and reacts with hydroxides to form carbonates and water; due to the consumption of these hydroxides the ph value is reduced below 9.0; the factors which increase the ability of concrete to carbonate are: low content of CaO, high diffusion constant of CO_2, high w/c factor, porosity of concrete and presence of mineral additives,
- *crystallization* – the formation of crystal phase of salts (mainly sulphates) present in the pores of the structural material; due to the volume increase of forming crystals, it leads to blowing up of the material manifesting as superficial losses,
- *leaching* – dissolution of soluble components (mainly $Ca(OH)_2$) from structural material by means of soft water; it is intensified by the presence of carbon dioxide; the mechanism manifests in the form of stalactites and efflorescence,
- *oil and fat influence* – the reaction of oils and/or fats with the calcium hydroxide in concrete; during this reaction calcium soaps are created, which are greasy substances of no binding features,
- *salt and acid actions* – chemical reactions mainly of sulphur, chlorine, nitrogen and magnesium compounds with the structural material; chemical compounds can react on a structure because of acid rain, polluted atmosphere, maritime climate, etc.

In the group of physical mechanisms, the following main processes causing the degradation of masonry bridges can be distinguished:

- *effect of high temperature* – a phenomenon caused by extremely high temperatures exceeding design values, for example by a fire on or under the bridge,
- *fatigue* – the mechanism causing the degradation of material by repeated cyclic loading; the process is mainly dependent on the number of load cycles, the level of stresses and the range of stress variation,
- *freeze-thaw action* – the process of cyclic transformations of water present within the structural material from liquid to solid phase and back, progressively blowing up the material,
- *modification of foundation conditions* – the mechanism of supports’ displacement which leads to changes in the global geometry of the structure and redistribution of internal

forces and stresses; it can be caused by the degradation of the ground or foundation due to floods, mining activity, seismic movements, changes in ground water level, etc.,
- *overloading* – the loads exceeding the designed load level; can be caused by very heavy traffic, floods, earthquakes, collisions, military or terrorist actions, etc.,
- *shrinkage* – reduction of concrete material volume during its hardening and drying; due to the imposed internal constraint of a shrinking element it leads to cracking; it can also be caused by improper concrete composition or bad curing of drying concrete,
- *water penetration* – the presence of water within the structure space incompatible with the project; usually caused by the inefficiency of a drainage or waterproofing system.

Biological degradation mechanisms form the smallest yet important group of processes diminishing the condition of masonry bridges. The following main processes can be listed:
- *accumulation of contamination* – the mechanism of organic and non-organic contaminants increase caused by environmental and/or human activity,
- *living organism activity* – the mechanism caused by living organisms like bacteria, fungi, mosses, plants or animals acting by means of chemical reactions (mainly oxidation and reduction) or by mechanical influences.

All the described degradation mechanisms can also be categorised regarding the duration of the degradation process. The following groups can be distinguished:
- *incidental mechanisms* – the degradation process is very short (duration even below a second), e.g. overloading by collisions or earthquakes,
- *short-term mechanisms* – the process lasts several minutes or hours, e.g. the influence of extreme temperature, foundation displacement because of scour during a flood,
- *long-term mechanisms* – the majority of chemical, physical and biological processes.

There is no simple way of defining the relationships between damages and degradation mechanisms, because on the one hand almost each damage can be caused by a few mechanisms, and on the other hand one mechanism can cause a number of damages to the structure. An attempt to describe the relationships between the main types of damages and basic degradation mechanisms – based on the analysis of many practical cases – is presented in Table 2.

Table 2 : Degradation mechanisms in relation to damages to masonry bridges.

Degradation mechanism	Damage type					
	contamination	deformation	destruction	discontinuity	displacement	loss of material
Physical						
Effect of high temperature	•	•	•	•		•
Fatigue		•	•	•		•
Freeze-thaw actions		•	•	•	•	•
Modification of foundation conditions		•		•	•	
Overloading		•	•	•	•	•
Shrinkage			•	•		
Water penetration	•		•			•
Chemical						
Carbonation			•			
Crystallization	•	•	•	•		•
Leaching	•		•			•
Salt and acid actions	•		•	•		•
Biological						
Accumulation of contamination	•		•			
Living organisms activities	•	•	•	•	•	•

4 TESTING METHODS

The identification of the masonry bridge damages and degradation mechanisms is based on the results of testing methods. In order to assess effectively a bridge condition, one needs instruments that allow damages to be located as well as identifying their extent and intensity. All testing methods can be divided into two main groups:

- *Non-Destructive Testing (NDT) methods* – techniques of testing without disturbance of the structure,
- *Minor Destructive Testing (MDT) methods* – techniques of testing with negligible disturbance of the structure (e.g. small specimens cut out from the structure).

Minor destructive techniques mostly require taking specimens from a structure and their testing in a lab. The results of MDT methods are usually more precise and give more information on the tested structure when compared with NDT techniques. Non-destructive methods sometimes require expensive electronic tools, but they do not require specimens taken from the structure and can be used directly in the field. The results of NDT methods can be obtained promptly and are usually sufficient for the identification of damages and the assessment of the bridge technical condition.

The range of application of the most popular NDT and MDT methods in identifying the main types of masonry bridge damages is presented in Table 3. The description of the techniques can be found in Bień and Kamiński (2004) and Helmerich and Niederleithinger (2006).

Table 3 : Application of testing methods for the identification of masonry bridge damages.

Testing method		Damage type					
		contamination	deformation	destruction	discontinuity	displacement	loss of material
NDT	Basic methods						
	Visual inspection	●	●	●	●	●	●
	Direct geometric measurement		●		●	●	●
	Sclerometric test			●			
	Acoustic and stress wave methods						
	Acoustic emission measurement			●	●		
	Impact-echo test			●	●		●
	Parallel seismic method			●	●		●
	Ultrasonic-echo test			●	●		●
	Electrical and electromagnetical methods						
	Electrical conductivity measurement			●	●		●
	Ground penetrating radar test			●	●		●
	Thermal heat transfer methods						
	Pulse-phase thermography	●		●	●		●
	Transient thermography	●		●	●		●
	Proof load tests						
	Dynamic test			●	●		●
	Static test			●			●
MDT	Boroscopy	●		●	●		●
	Flat-jack test			●			
	Pull-out test			●			
	Specimen test – chemical	●		●			
	Specimen test – mechanical			●			

5 CONCLUSIONS

The proposed classification of damages, degradation mechanisms and testing methods form a complementary system of bridge condition assessment. For each system component, a unified basic terminology is also proposed. The system enables bridge owners a consistent identification and description of damages as well as creating a basis for a comparable rating of a bridge condition. Categorized testing techniques in relation to damage classification are necessary to identify and verify each individual damage. The combination of degradation mechanisms in correlation with damage classification is required for the development of future maintenance strategies and for a reliable foresight of the bridge infrastructure lifetime.

The presented proposal – based on the experience of many countries – can be considered as a part of international discussion concerning common methodology of bridge condition assessment and forecasting.

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