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ASSESSMENT, RELIABILITY AND MAINTENANCE OF MASONRY ARCH RAILWAY BRIDGES IN EUROPE

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Abstract. *The main purpose of this paper is to give an overview on the state of the art of inspection, assessment and maintenance of masonry arch railway bridges by the presentation of the results of an ongoing international research project run by the International Union of Railways (UIC) with the participation of 14 railway administrations.*

The survey has shown that the European railways partaking in the project possess more than 200,000 masonry arch bridges and culverts on their lines which is approximately 60%, a significant proportion, of their total bridge stock.

It has been shown that several methods are used by the railway administrations for the assessment and structural analysis of masonry arch bridges. As the correlation between assessment results and measurements on arches is very limited, further research targeted towards a better understanding of their structural behaviour is considered essential.

Several inspection methods have been used in recent years to investigate the condition or to determine the structure of masonry arch bridges. As well as the predominant use of visual inspections, and destructive investigation there is a tendency in recent years towards applying non-destructive testing techniques.

As many masonry arches belong to the civil engineering heritage of the railways their substitution or refurbishment requires careful consideration. It was concluded that maintenance policies and repair measures for masonry bridges should rely more on existing structural capacity and give preference to stabilization rather than substitution or replacement.

1 INTRODUCTION

Masonry arch bridges form an integral part of the European railway infrastructure. They are the oldest structure types in the railway bridge population with thousands still in service.

In order that European railways accommodate increased axle loads, train speeds and a greater volume of freight traffic, it is necessary to assess the load carrying capacity of existing masonry arch bridges. Assessment of masonry arch bridges is difficult as there is little knowledge or experience of design of these structures to modern standards, and much of the structure is hidden from view.

To provide confidence in the assessment result, reliable input parameters are required for the calculations. Accordingly effective inspection and measuring methods to establish the parameters are necessary. Several investigation procedures have been implemented in recent years for masonry arch bridges. As well as predominantly visual inspection and destructive testing there is a tendency towards using non-destructive testing techniques as much as possible.

The current condition of masonry arch bridges varies from good to very bad, although statistics show that there are a relatively large number of bridges in a medium or bad condition with a tendency for accelerated deterioration. Accordingly there is a potential doubt as to the adequacy of masonry bridges to withstand increased axle loads, train speeds and a greater volume of freight traffic.

Contrary to doubts masonry arch bridges are proving durability with life-cycle costs significantly more economical than for the majority of other structure types. In addition, they belong to the civil engineering heritage of the railways, and their substitution or refurbishment requires careful consideration with maintenance strategies adopted to promote solutions that preserve and restore these structures instead of their replacement.

2 AIM AND PROCEDURE OF SURVEY

A study group was set up in 2002 by the International Union of Railways (UIC) in order to establish information on the ‘state-of-the-art’ of masonry arch railway bridges. The work was initiated by the Hungarian Railways and during the preparatory stage 13 more railway organisations joined the project. Currently the following railway administrations are involved in the project: MAV /Hungary, task leader/, DB /Germany/, SNCF /France/, NR /UK/, ÖBB /Austria/, SBB /Switzerland/, JBV /Norway/, CD /Czech Republic/, REFER /Portugal/, RENFE /Spain/, RFI /Italy/, BS /Denmark/, JapanRail-RTRI /Japan/, PKP /Poland/.

The principle objective of the ’state-of-the-art’ phase of the project was to collect and summarise tools, literature, guidelines, experience and the best practice of the railways in the field of masonry arch bridges. The aim was to help bridge engineers, maintainers, designers and decision makers by promoting an effective exchange of information between railway administrations.

Questionnaires were drafted to establish and compare the different experiences and approaches of the railway administrations to the art of masonry arch bridge inspection, assessment and maintenance. The responses to the questionnaires and discussions at the symposia organised provided data to enable an overview on the masonry arch bridge stock on the European rail network to be made. Available documents and information on the subject have been summed up and fields have been identified where more attention should be focused in the future.

3 STATISTICS ON THE MASONRY ARCH RAILWAY BRIDGE POPULATION

A survey has been carried out to give an overview on the number, characteristics and condition of masonry arch railway bridges in the participating railway administrations. As the input for the statistics is incomplete or approximate in some areas, evaluation of the data has enabled only an overview on the current situation. Some figures of the statistics are summarised as follows:

3.1 Statistics on the number of masonry arch bridges

Statistics were compiled about the total masonry arch bridge population of the railways including culverts with a span not exceeding 2m. The highest figures are summarised in Table 1.

Railway Administration	SNCF	RFI	NR	REFER	DB	RENFE	CD
Number of masonry arch bridges and culverts (A)	78000(E)	56888	17867	11746	35000(E)	No data	4858
Number of masonry arch bridges (B)	18060	No data	16500(E)	874	8653	3144	2391
% of total bridge population (C)	76.8	94.5	46.9	89.8	38.9	No data	18.9
% of bridge population with span>2m (D)	43.5	No data	No data	39.6	27.5	49.3	35.8
(A) Refers to the number of masonry arch bridges inclusive of culverts (arches with span≤2m). It has to be noted that many railway administrations do not register these structures as bridges and could provide only approximate data on their number. (B) Refers to the number of masonry arch bridges with span exceeding 2m. (C) Refers to the percentage of masonry arch bridges and culverts in the total bridge stock. (D) Refers to the percentage of masonry arch bridges in the bridge population with span exceeding 2m. (E) Only approximate value were available.							

Table 1: The highest figures on the number of masonry arches at various railway administrations (extract from the statistics)

The railways participating in the project possess more than 200,000 masonry arch bridges and culverts on their lines which is approximately 60%, a significant proportion, of their total bridge stock (details are seen on Figure 1e). It has to be noted however, that statistics on the total European masonry arch railway bridge stock may differ from these figures as those railway administrations are participating in the project that possess a relatively large number of arches.

3.2 Statistics on the span length, span number, shape, condition and age of arches

The statistics were calculated as representative values for the available data source involving all participating railways. The following conclusions could be drawn:

- Bridges and culverts with short spans represent the majority of masonry arch bridges (approximately 60% of bridge spans are under 2m and approximately 80% are under 5m; see Figure 1a).
- The majority of masonry arches at the railway administrations are single-span (approx. 85%; see Figure 1b).
- The shapes of masonry arches are generally not recorded by the railway administrations. The limited information has prevented any conclusions being drawn with regard to the shape of arches, except that semi-circular deep arches are the most common type.
- The vast majority of masonry arch bridges are in good and medium condition (approximately 85%) but there is significant proportion in a poor or very poor condition (approx. 15%; see Figure 1c).
- The majority of masonry arch bridges (approx. 70%) are between 100 and 150 years old. There is also a significant proportion (approx. 12%) of bridges more than 150 years old (see Figure 1d).

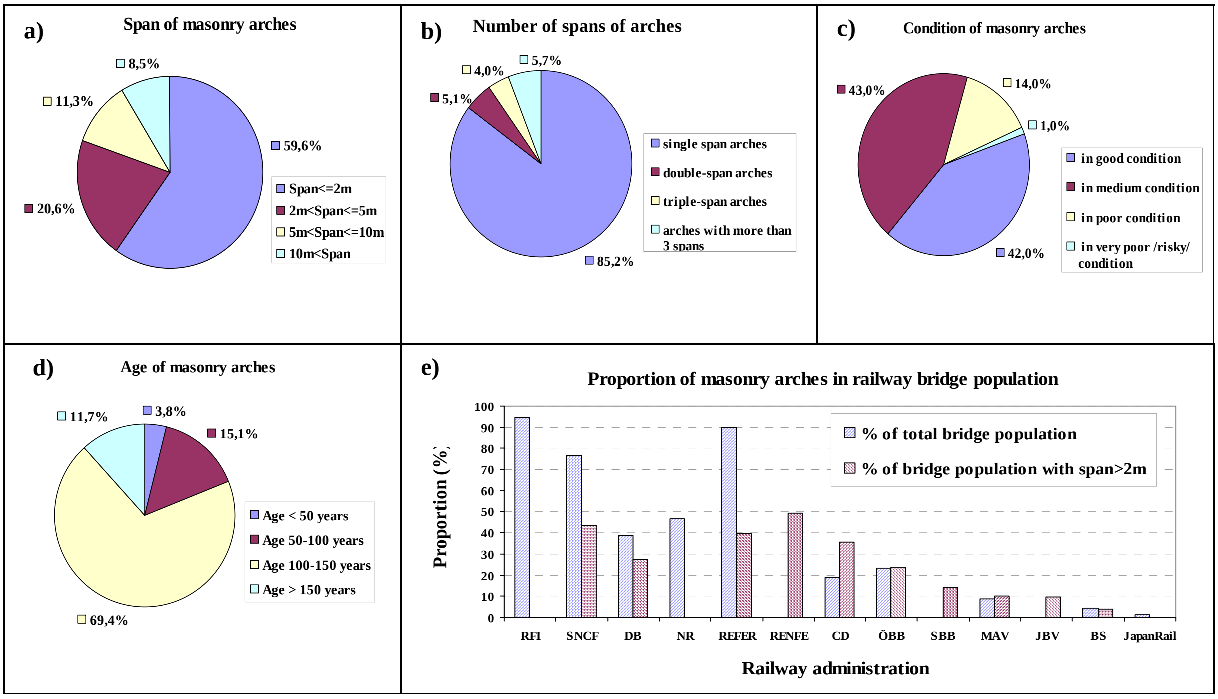

Figure 1: Statistical distribution of masonry arch bridges according to their
a) span length b) span number c) condition d) age.
/data were calculated as representative values for the European partaking railways/
e) Proportion of masonry arches at the bridge population of the railway administrations.

3.3 Main types of structural problems

Answers were provided by the representatives of the railways on the frequency of structural problems occurring on masonry arches. Each type of damage was given a mark according to the following classification key:

(1): Very frequent (occurrence > approx. 50% of bridges)
(2): Frequent (occurrence > approx. 25% of bridges)
(3): Occasional (occurrence > approx. 10% of bridges)
(4): Rarely (occurrence > approx. 5% of bridges)
(5): Exceptional (occurrence ≤ 5% of bridges)

The main damage types were ranked according to the average of marks given and listed in Table 2.

Rank	Type of damage[(A)]	Score[(B)]	Occurence
1.	Waterproofing damage[(C)]	2.1	frequent
2.	Material ageing	2.4	frequent
3.	Detachment, movement of wing walls	3.0	occasional
4.	Detachment, movement of spandrel walls	3.5	occasional
5.	Abutment, pier, foundation problems	4.0	rare
6.	Structural geometry problem	4.0	rare
7.	Other problems[(D)]	4.0	rare
8.	Cracking of vaults due to sagging, sliding	4.2	rare
9.	Edge beam damage	4.3	rare
10.	Degradation due to overloading	4.3	rare
11.	Deformation of barrel	4.4	rare
12.	Cracking of vaults due to overloading	4.5	rare
13.	Damage due to concentrated load on barrel	4.6	exceptional

[(A)] In many cases only the type of damage can be identified and the cause of the damage is unknown.
[(B)] Calculated as the average value of the marks given by the representatives of the railways for each damage types.
[(C)] Many arches have never been provided with a waterproofing system since the originally constructed. In these cases the responses referred to the seriousness of water penetration.
[(D)] Other types of structural problems considered: damage due to track maintenance, cladding to underside of the bridge, bridges struck by road vehicles, damage due to vegetation, consequences of incorrect rehabilitation, damage due to earthquakes, consequences of dynamic stabilisation of ballast, etc.

Table 2: Frequency of masonry arch bridge damages

- The above list confirms that the majority of defects of masonry arches result from insufficient or damaged waterproofing and material degradation due to ageing.
- Detachment or movements of wing walls and spandrel walls also show a relatively high occurrence rate.
- Pier and foundation damage also causes serious problems for some railway administrations.

- Cracking and degradation is only be attributed to overloading or concentrated loads in rare or exceptional cases.

4 CURRENT PRACTICE WITH THE ASSESSMENT OF ARCHES

Assessment of masonry arch railway bridges is a difficult task as there is no widely accepted and reliable structural assessment procedure. Structural behaviour of masonry arches depends on several parameters but there is little experience of the effect of changes in such parameters and masonry arches have internal elements that are extremely difficult to investigate.

Several methods are available for the assessment of masonry arch bridges. These include simple conservative methods (such as MEXE) and recently developed computerised methods (such as adaptations of the mechanism method and FEM systems). Besides their particular limitations, conservative methods often underestimate the load carrying capacity, which may result in uneconomical or unnecessary mitigation measures being taken to maintain or replace bridges. Conversely the use of sophisticated new methods is generally hindered by the difficulty in provision of input parameters or prolonged data processing.

4.1 Assessment of arches by the MEXE method

UIC Code 778-3R[1] gives guidelines for the use of the most widely applied approximate method, MEXE. Experience shows that in a large number of situations the method seriously underestimates the actual load-carrying capacity of the bridges. On the other hand in some other cases MEXE has been found to provide non-conservative results.

The method is generally used as a first sieve for the initial assessment and preliminary determination of load capacity.

According to the survey approximately half of the railway administrations partaking in the project use the MEXE method for the assessment of arches. Other railways use MEXE only in a very limited number of cases or not at all.

As MEXE can provide unreliable and highly conservative values for the load carrying capacity of masonry arches, some railway administrations proposed modifications to the method in order to achieve better conformity with their experience.

4.2 Structural analysis of arches using computerized techniques

The use of advanced computerised techniques in the analysis of masonry arch bridges is a relatively new concept. Several computational techniques have been developed for this purpose including 1D frame or 2D and 3D non-linear finite element (FE) models, discrete element-based (DE) models and combined finite element-discrete element models (FE/DE). These methods were developed to describe the complex nature of arch deformation, cracking processes and arch-backfill interaction phenomena.

Methods based on the lower bound mechanism or upper bound mechanism approaches are considered simple and promising tools for arch assessment, although they have been used only by a very few railway administrations until now.

Assessment of serviceability is becoming more and more important with increasing traffic volumes on masonry arches. There is however no suitable method for the serviceability assessment of masonry arches nor any criteria against which such an assessment could be made. Other shortcomings of existing methods are their inability to (or complicatedly) describe the effects of structural defects and strengthening intervention.

5 CURRENT PRACTICE WITH THE INSPECTION OF ARCHES

Several inspection methods have been used in recent years to investigate the condition or to determine the structure of masonry arch bridges. The most common method is still the pure visual inspection. Destructive testing is also used although there is a tendency in recent years towards using non-destructive testing techniques.

5.1 Destructive versus non-destructive testing methods

Most assessment procedures require the masonry strength and some other mechanical properties as the major input parameters for assessment. Destructive Testing (DT) of masonry bridges is therefore necessary in many instances, although it is noted that the results of most destructive tests are affected by significant uncertainties and they may provide only local information on some part of the structure, and cannot be directly extended to the whole bridge.

Semi-Destructive Testing (SDT) methods are based on in-situ localised measurements and considered as surface or small penetration techniques which can provide only qualitative information on the masonry condition and be used only for preliminary investigation.

While conventional DT methods focus mainly on the mechanical characteristics of the materials, Non-Destructive Testing (NDT) methods can provide an overall qualitative view on the arch condition. NDT methods on the one hand seem to be most promising tools for the inspection of masonry arch bridges but on the other hand need a great deal of further study and research. The number of references and projects that have utilised NDT methods on masonry arches is very low and only a few calibration tests have been carried out. Consequently correlation of NDT data with the mechanical properties of the structure is considered limited at present. Nevertheless NDT usually requires an expert with sufficient skills to carry out the measurements and interpret the results so that the significance of data is recognised and that data is not used inappropriately. This ‘strong reliance’ upon the non-engineer specialist is generally not acceptable to the railway administrations. There is thus a need for close collaboration between bridge engineers and NDT specialists.

5.2 Monitoring of masonry arches

Monitoring systems are occasionally installed on masonry arch railway bridges in order to follow the evolution of damage patterns such as cracks or deformations. The knowledge of this evolution can help preventing more serious damage or a total collapse of the structure. The method used for monitoring the extent of cracks and deformation movements, may also provide information that can be used to determine the root causes of the defects. These may be from visual inspection or electronic data collection.

5.3 Survey on the use of testing methods

Data and references have been collected from the railway administrations on the use of testing methods in the inspection and diagnosis of masonry arches. The main methods railway administrations have experience with, either by regular or experimental use, are summarised in Table 3.

Testing Methods		**Percentage of railways having experience with the method**	
Destructive Testing Methods	Mechanical tests on large diameter cored samples (ϕ150-200 mm) or small diameter cored samples (ϕ50-100 mm)	62%	Average: 52%
	Physical and chemical tests on cored samples	62%	
	Tests on soil, backfill properties	31%	
Semi-Destructive Testing Methods	Boroscopy	38%	Average: 33%
	Flat-jack test	23%	
	Hammering (sounding)	23%	
	Surface measurements (Hardness, Schmidt hammer, penetration, pull-out tests)	46%	
Non-Destructive Testing Methods	Georadar	15%	Average: 21%
	Infrared thermography	23%	
	Sonic methods	31%	
	Conductivity measurements	15%	
Monitoring Methods	Crack monitoring	62%	Average: 44%
	Deflection and relative displacement measurements	38%	
	Dynamic tests	31%	
	Proof load test	46%	

Table 3: The most frequently used testing methods of masonry arches

5.4 Particular problems

- Although it is considered essential, only a few railway administrations have taken steps towards developing an explanatory catalogue which helps bridge assessors to evaluate the seriousness of damage they may find on arches.
- There no consistent methods are available for the inspection of non-accessible structural zones such as foundations, piers or behind cladding to tenanted arches. Assessment of these parts therefore often relies only on data from existing bridge files or pure assumptions.

6 CURRENT PRACTICE WITH THE MAINTENANCE AND REPAIR OF ARCHES

The aim of the survey was to summarise and evaluate the maintenance and repair solutions available for masonry arches in the participating railway administrations. Table 4 showes the most frequently used methods and indicates the percentage of railway administrations who have experience with each method.

Methods for the restoration of waterproofing and drainage	Percentage of railways having experience*
Drainpipes placed through the barrel, restoration of drainpipes	58%
Concrete saddle over the arch with bonded waterproofing	42%
Unbonded waterproofing on extrados	33%
Injection of barrel by cement based materials or microcement	25%
Injection of gel behind the barrel from intrados	17%
Methods for the restoration and strengthening of arch barrels	
Injection of arch barrel	83%
RC shotcrete lining under the arch	58%
Concrete saddle over the arch	42%
Stitching of cracks and low pressure grouting	33%
Supporting barrel with steel rings	25%
Methods for the restoration and strengthening of abutments, piers and foundations	
Underpinning through the abutment	67%
Scour protection (jacketing, sheetpiling, rock armour around pier)	50%
Stitching and grouting of abutment cracks	42%
Installation of props or invert slab	33%
Injection of soil under foundations	33%
Methods for the restoration of 3D integrity of arches	
Tie rods and patrass plates	67%
Tying spandrel walls to new saddle on barrel	17%
Load dispensing concrete slab over the arch	25%
Shotcrete lining under the arch and tying spandrels back to the lining	8%
* Refers to the percentage of railway administrations in the project who regularly use and have experience with the given repair or strengthening method.	

Table 4: The most frequently used repair and strengthening methods of masonry arches

7 CONCLUSIONS

- The 'State-of-the-art Study'[2] phase of the project has established the methods and practices used by the participating railway administrations for inspection, assessment, maintenance and management of masonry arch bridges. It has pointed to the necessity of further research and identified fields where railway bridge engineers are lacking information and appropriate solutions.
- There is a need for simple, reliable and *user-friendly assessment methods* to be developed and established in practice.
- Attention should be given to the *serviceability and durability criteria* in assessment as well as to the description and modelling of defects and strengthening interventions.
- In order to minimise damage to the structure destructive test methods should be complemented and replaced by NDT methods wherever possible. There is a need therefore to *increase the reliability of NDT measurements* and to gain consistent results for arch assessment.

- Although there are a large variety of types of damage that occur to masonry bridges there are no consistent descriptions of such defects. There is thus a requirement for a *Damage Catalogue* to be developed to provide the necessary consistent terminology and to illustrate the extent of the damage according to the type of defect.
- Maintenance policies and repair measures for masonry bridges should rely more on existing structural capacity and give preference to stabilisation rather than substitution or replacement.
- There is a need for *repair guides* to identify solutions according to the type of defect and cause. These repairs guides should be based on case studies and the experience of the railway administrations in implementing various types of repair.
- The survey has identified the necessity of an Information System&Database to be a reservoir for existing knowledge of management processes and data applicable to masonry arches and to provide a platform to enable the railway administrations to consult and share information.

8 FURTHER RESEARCH

The project continues with a follow-up phase in 2004-2006 with the following main work packages:

- WP1: Development of assessment tools for masonry arch bridges,
- WP2: Optimised inspection and monitoring of masonry arch bridges,
- WP3: Optimised maintenance and life-cycle management of masonry arch bridges,
- WP4: Interactive Information System&Database for masonry arch bridges.

The early demonstration version of the Database containing further information on the project is already on the Internet at the following web site: www.orisoft.pmmf.hu/masonry.

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