Assessment of Masonry Bridges with the Help of Combined NDT Methods

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Abstract. The structural behaviour of masonry arch bridges is complex and affected by several parameters. During their service life these bridges are subjected to a variety of environmental effects that may influence the characteristics of the elements and consequently their structural response. The description of the structural response therefore possesses large uncertainties owing to insufficient knowledge of geometrical and material characteristics and the static system within the masonry arch. The paper presents methods of inspection and testing for masonry arch railway bridges. An overview of a selection of available non-destructive, minor-destructive and monitoring methods is given and their efficacy to help analysis and assessment of masonry arch bridges is discussed. A methodology for the assessment of masonry arch railway bridges is shown where in-situ testing methods play a key role in determining input parameters. Some of the results of a testing programme are demonstrated where the efficiency of various non-destructive testing have been studied. It is shown that non-destructive investigation can provide valuable information on the condition of bridges and help verify basic input parameters for structural analysis and assessment.

Keywords: Masonry arch bridges · Non-destructive testing · Assessment

1 Introduction

Masonry arch bridges represent a major part of the railway infrastructure in Europe and throughout the world. Survey has shown [1] that the European railways 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. Many of arches belong to the civil engineering heritage of the railways, and maintenance policies for masonry arches should therefore require that careful consideration is given to options for their repair. A large proportion of arches show signs of deterioration, but in general they have stood the test of time much better than other types of bridges. The design of these structures was based on empirical rules and contemporary railway loads, which has resulted in

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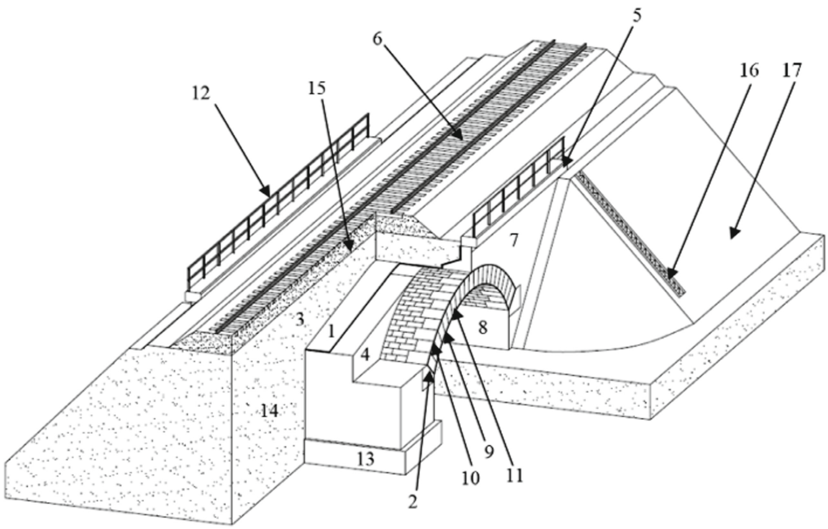
structures with an inherent ability to withstand greater loads and extreme weathering conditions. However, many masonry arches carry a load today that is radically different from that which existed when they were constructed. Accordingly there is a potential doubt as to the adequacy of masonry bridges to withstand the new loading effects.

In order to accommodating increased axle loads, train speeds and a greater volume of freight traffic for the railway companies, it is necessary to assess the load carrying capacity and serviceability of existing masonry arch bridges. Assessment of such bridges can however be difficult as there is little knowledge or experience available on their design, and much of the structure is inaccessible and hidden from view. The hidden parts, however, influence the structural behaviour and have a major effect on the load carrying capacity of these bridges [2]. Figure 1 describes the principal elements of a typical masonry arch railway bridge that were built in Hungary.

To provide confidence for the assessment result, reliable input parameters are required and effective inspection and measurement methods are necessary to establish or verify the input parameters. A range of inspection methods are currently used to investigate the condition or determine the composition of masonry arch bridges. As well as the predominant use of visual inspections and destructive investigation, there has been a tendency in recent years towards the use of non-destructive testing techniques to establish the necessary dimensional and material parameters [3].



1-waterproofing 2- springing 3- fill 4- backing/haunching 5- edge beam 6- railway track 7- spandrel wall 8- abutment 9- intrados 10- extrados 11- arch stone 12- railing 13- foundation 14- backfill 15-ballast 16-inspection stairs 17-slope

Fig. 1. Elements of a typical Hungarian masonry arch railway bridge

2 Test Methods for Assessment

Assessment requires masonry strength and other mechanical properties as input parameters for the analysis.

The following list summarises testing methods that are frequently used on masonry arch bridges (see also [4] and [5]):

- Destructive Testing Methods:
  - Mechanical tests on cored samples,
  - Physical and chemical tests on cored samples,
  - Tests on soil, backfill properties.
- Slightly-Destructive and Non-Destructive Testing methods:
  - Boroscopy, endoscopy
  - Flat-jack test,
  - Hammering (sounding),
  - Surface measurements (Hardness, Schmidt hammer, penetration, pull-out tests),
  - Georadar,
  - Infrared thermography,
  - Sonic methods,
  - Conductivity measurements.
- Monitoring methods:
  - Crack monitoring,
  - Deflection and relative displacement measurements,
  - Dynamic tests,
  - Load tests (only in special cases recommended).

The reliability of an assessment depends on the validity of the parameters used in the analysis. There is, however, often insufficient information available on the actual parameters required for analysis and assessment of masonry arch bridges.

The geometry of a masonry arch bridge is not so simple as it appears at first glance. They rarely have accurate or sometimes any drawings at all of their construction or early repair details. The internal structure of arch bridges may be unknown from external appearance and may include features such as haunching at the supports, internal spandrel walls, ribs or the presence of a saddle over the arch barrel. The thickness of the barrel may be greater at the springing than at the crown that might not be visible at the edge of the barrel. The arch barrel thickness across a width may be reduced locally under the external spandrel walls or increased under the track. The material and geometry of backing or haunching and the way they are connected to the arch are often unknown and are rarely visible (see example in Fig. 2). Most masonry arches have a semi-circular arch shape, although compacted backfill and the presence of backing or haunching can reduce the working span and modify the shape of the actual load bearing arch. Piers were often constructed as a shell-type structure that has a solid masonry external layer filled with a lower grade material. Moreover, the type and quality of materials used for the abutment, barrel, spandrel and the fill above the arch can be highly variable.

It may, therefore, be difficult to determine the physical dimensions of the main structural elements of the arch. Inadequate knowledge of the geometry and materials used can make structural modelling difficult. Further complication is added by the possibility of the presence of hidden defects such as ring separation, voids in the granular backfill immediately above the extrados, areas of reduced density and stiffness in the fill and cracking in the arch ring. In such situations the application of NDT techniques have a good potential to provide valuable information regarding the structure and materials and help establish input parameters for numerical analysis.

Fig. 2. Left: Stone backing of brickwork arch (bridge under demolition, Hungary), Right: Haunching between piers (bridge under construction, Hungary)

3 Test Programme

The number of references and projects that have utilised NDT methods on masonry arches are limited and only a few calibration tests have been carried out. A test programme has therefore been carried out on Hungarian railway masonry bridges. The tests were aimed at developing an inspection system for masonry structures to explore the potentials of non-destructive testing methods. The following test methods were involved in the programme: Ground Penetrating Radar (GPR), infrared thermography and sonic methods combined with core drillings and endoscopy survey.

Non-destructive tests were carried out on the masonry abutments of the Rátót viaduct in Hungary using ground penetrating radar (GPR), seismic method and infrared thermography. Calibratory investigations were made with boroscopy in order to confirm and interpret data obtained by the NDT measurements. The viaduct was constructed in 1896 and consists of wrought iron truss superstructure with stone masonry abutments (Fig. 3). The viaduct is still in service but its reconstruction in the near future is considered necessary. The abutments are approx. 15 m high and 5 m wide. Originally, both abutments contained three internal arches from which only one arch at each abutment have remained visible. The others cannot be observed from outside the structure because they are fully covered by earth. According to the drawing the internal arch at the bottom of the abutment is 4,50 m wide while those at the top are 2,40 m wide. The abutments were constructed from large size stone blocks. There was no information on the internal structure of the abutments although it was presumed that there were loose rubble stones behind the outer stone layer.

Fig. 3. The Rátót viaduct with stone masonry abutments

The objective of the non-destructive investigation was to determine the internal structure of the masonry abutment of the viaduct and to survey the condition of the stonework structure and the area behind the outer stone layer.

Figure 4 shows the horizontal test profiles on the abutment front wall and demonstrates an example of the radar test results. The first part of the demonstrated profile is exempt from anomalies except for the waves travelling directly from the transmitter to receiver. Until the yellow zone no significant reflections were perceivable within the outer part of the stone wall, which means that the outer stone layer is more or less homogenous. The thickness of this layer is about 50 cm but varies from stone to stone. Distinctively, the first and the last row of the rubble stone layer were constructed from thicker stones. The thickness variation of the abutment wall can clearly be seen on the radargram, but individual stones cannot be distinguished with the given resolution. The yellow zone represents the area behind the outer stone layer where strong reflections can be observed. The reflection from the boundary means that this area was built of a different material. The reflections within the area mean that this building material is highly inhomogeneous. There are profiles where the anomalies are more significant at the same depth than on other profiles. This suggests that the area behind the outer stone layer was filled with loose gravel stones rather than being a standard masonry. At the end of the yellow band, around a depth of 2 m, the profile reveals a weak anomaly. Beyond the yellow band, no significant reflections could be recorded.

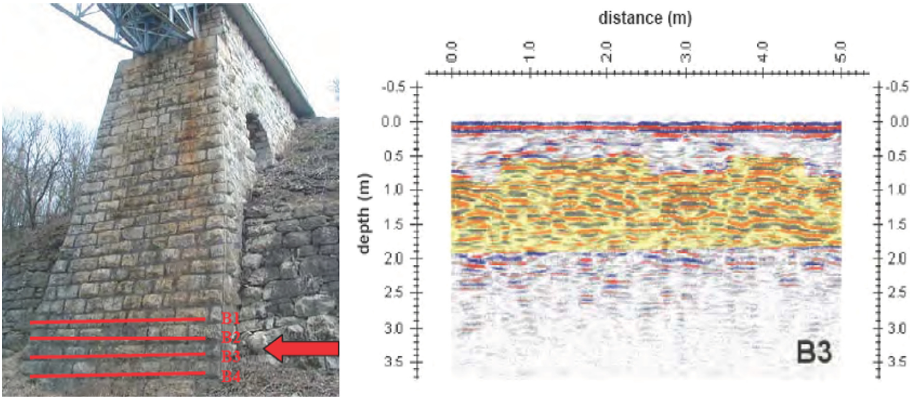


Fig. 4. Radar survey of the front wall of the stone abutment

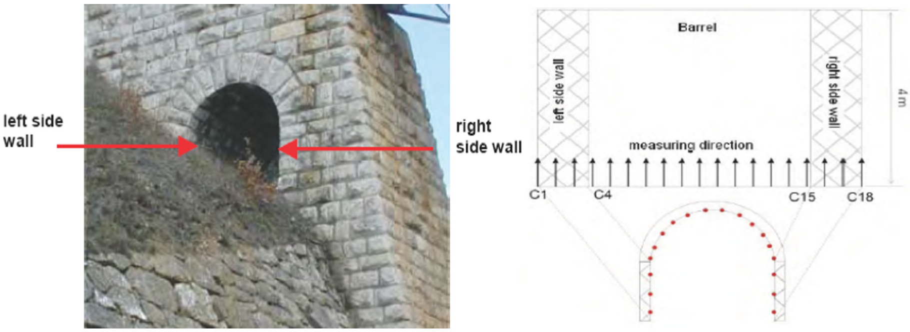


Fig. 5. Recorded radar sections on the internal arch

Figure 5 shows the location of the GPR recordings on the internal arch. The horizontal profiles are 4 m long and are spaced approximately 30 cm from each other. The numbering of the profiles starts at the left side wall, goes along the arch and ends at the bottom of the right side wall. The entire surface of the arch and the side walls is 400 cm × 520 cm. Examples of the recorded radargrams are shown in Fig. 6. The blue line on the demonstrated radargram marks the end of the outer stone layer which is about 50 cm thick. No observable reflections could be seen within this layer. The first and the last block of stones in this stone layer are thicker than others. The reflections recorded within the zone marked on the radargram with yellow band suggest that this area consists of loose gravel stones similarly to that have been observed from the recordings on the abutment. Behind this boundary, there is an approximately 0.5 m thick area that shows no reflections indicating a homogeneous material. The reflections measured on the left side wall received from the wall of a buried internal arch and the reflections on the right side wall received from the front wall of the abutment were marked by green line. The end of the radargrams of the right side wall contains strong reflections at around 2.5 m depth, indicating the outer surface of the abutment. Obviously there were no reflections received beyond this surface. From about 3.5–4 m depth in the left side wall, a bunch of weak reflections, marked by a yellow dotted line, was recorded. The reflections suggest the presence of the second internal arch that is filled up with soil.

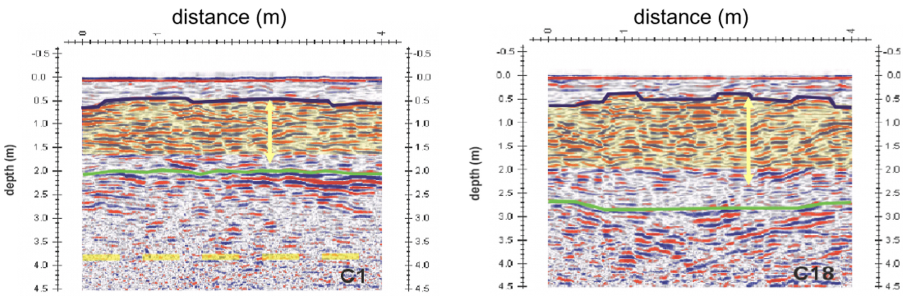


Fig. 6. Radargram of the internal arch (C1 and C18 sections)

Fig. 7. Boroscopy images. (Left) solid stone material (right) rubble stone material

Calibratory survey was carried out with the use of a boroscopy camera that was inserted into boreholes drilled in representative parts of the abutment. Digital recordings were made during the operation that allowed a detailed study of the internal parts of the structure in the boreholes. The objective of the survey was to help interpret the results of the radar measurements. The cores taken out from the drillings were utilised for testing the physical and mechanical properties of the stonework. In Fig. 7 the boroscopy images demonstrates the solid part (outer stone layer) and the internal gravel stone filling of the abutment wall at 50 cm depth measured from the surface.

These findings confirm the results of the radar survey. According to these measurements the outer stone layer is about 50 cm thick both at the abutment front wall and at the internal arch. More loose material was found behind the stone layer of the abutment front walls. Gravels behind the internal arch barrel are well embedded in mortar. These observations are in line with the range of reflections perceived by the radar survey.

A test programme has been performed with the use of infrared thermography on masonry arch bridges. The aim of the survey was to explore the application possibilities of this remote sensing method. The significance of research is confirmed by the fact that during the periodical inspection of masonry arch bridges, especially those with difficult or costly access, more and more importance must be given to remote sensing methods. The surface temperatures are represented on the thermal images by colours where lighter tones refer to higher temperature while darker tones refer to colder temperature (Examples are seen on Fig. 8). The procedure is capable to point at wet areas, crack, delamination near the surface of the masonry and presence of vegetation or other anomalies in the construction material that are invisible or hardly visible to the human eye. While infrared thermography can provide qualitative representation of moisture anomalies it can be combined with local measurements to obtain accurate data, based on the principle of electrical conductivity or impedance.

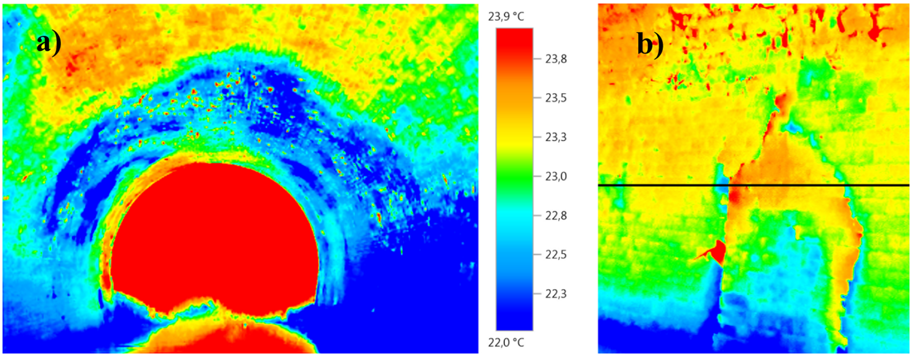


Fig. 8. (a) Infrared thermographyc image of a brick arch bridge. Dark blue colours refer to wet areas. (b) Infrared thermographyc image of a delaminated surface.

4 Selection of Test Methods

As a large variety of methods is available the choice of the most appropriate method for a specific problem can be rather complex. Masonry arch bridges are highly variable in their geometry and construction. Different test methods will be appropriate to different structures and not all techniques will work in all situations. Figure 9 gives recommendation for the use of test methods according to various purposes of inspection.

Type of method	Name of method	Purpose of measurement									
		Determination of construction materials	Testing mechanical properties	Testing physical or chemical properties	Survey of geometry (arch shape)	Survey of hidden geometry and features	Survey of defects	Validation of models	Overall view on bridge condition	Condition monitoring	Evaluation of the effects of repairs or strengthening
NDT METHODS	Sonic methods	3	3	3		2	2		2	3	2
	Georadar	3	3	2		2	2		2	3	2
	Infrared thermography	2	3	3		3	2		2	3	3
	Conductivity measurements	3	3	2		3	3		2	3	3
SDT METHODS	Coring and analysis of small diameter cores	1	1	1		2	3		3	3	1
	Boroscopy	1	3	3		1	2		3	3	1
	Flat-jack test		2					2	3	3	3
	Schmidt hammer rebound test	3	2				3		3		
	Penetration test on mortars	2	2	3			3		3	3	3
	Pull-out test	2	2	3					3		3
MONITORING METHODS	Hammer tapping	3	3	3		3	2		2	2	3
	Acoustic emission						1		2	2	2
	Crack monitoring						3	3	3	2	3
	Laser profiling				1		2	3	2	2	
	Moisture monitoring		3	2		3	2		3	3	2
	Monitoring deformations and movements				3		2	2	3	2	2
	Dynamic monitoring (vibration test)						3	2	2	2	2

1: Recommended
2: Recommended as supplementary application together with other methods
3: Recommended only in special cases or experimentally
Left blank: Not recommended

Fig. 9. Recommendation for the application of NDT, SDT and monitoring methods for various purposes of inspection [6]

5 Conclusions

To establish reliable input data for the assessment of masonry arch bridges the application of effective inspection and measuring methods are needed. In order to minimise damage to the structure destructive testing methods should be complemented and replaced by NDT methods wherever possible. Unlike conventional destructive testing NDT methods can provide mainly an overall qualitative information on the condition of the structure.

The results of the performed test programme have confirmed that NDT is a promising tool in confirming unknown geometrical data and finding hidden characteristics of masonry structures such as the presence of internal voids, flaws, layering condition, mapping of non-homogeneity, moisture variations, etc. which may otherwise be detected only by destructive or other complicated tests. However a great deal of further research is needed to increase the reliability of the interpretation of NDT results. The combined use of the test methods can highly increase the potential for a more reliable interpretation.

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