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DRAFT REVIEW OF INDUSTRY GUIDANCE FOR MASONRY ARCH BRIDGES

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ABSTRACT

Masonry arch bridges were widely built up to the 1920s in Europe and the US and carry far heavier loads than they were designed for. Engineers and bridge managers have the responsibility of maintaining their bridge stock in safe condition and ensuring their continued use in the traffic network. Very little guidance and knowledge are however available on masonry arch bridges for practitioners around the world. In order to enable limited resources to be shared internationally, a draft review of national codes, guidelines, technical notes, books, etc. has been undertaken, that are accessible for the industry. Literature on inspection, analysis, maintenance, design and construction has been included from Europe, US, Canada and China. In order to address the lack of information and guidance on the subject, a strategic approach needs to be considered. Sharing limited resources, improving education and targeting needs are the first steps towards advancing the knowledge of masonry arch bridges internationally.

KEYWORDS: *masonry arch bridges, state of art, review, guidelines, codes of practice, strategic approach*

INTRODUCTION

Management of bridges includes a wide range of bridge types, materials and activities (Figure 1). While extensive knowledge and a large number of guidance documents are available for concrete and steel bridges, very little information is available on masonry arch bridges worldwide. As masonry bridges behave fundamentally differently from concrete and steel bridges and cannot be easily assessed using generic tools, bridge owners often struggle to maintain their masonry bridge stock.

Masonry arch bridges are represented to very different extents in the different continents. The largest concentration is found in Europe (Figure 2) (primarily in the UK, Italy, Spain and Portugal), built during the Roman era, industrial revolution and up to the 1920s. In Europe masonry bridges

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represent ca. 40% of bridges and reasonable information and guidelines are available for their assessment and maintenance. In the US masonry arch bridges represent less than 1% of the bridge stock, built during the industrial revolution and up to the 1920 with very few available guidance. The only country where masonry arch bridges are still widely built is China, with up to date design guidelines and construction knowledge.



Figure 1: a) Rialto, Venice, 1591, b) Mostar, Bosnia - Herzegovina, 15th c., c) St Angelo, Rome, 134, d) Pont du Gard, France, 1st c.

Due to the large number of masonry arch bridges in the road and rail network in Europe and being considered as part of historic heritage in the US, maintaining safe condition and continued service in the traffic network are critical issues.

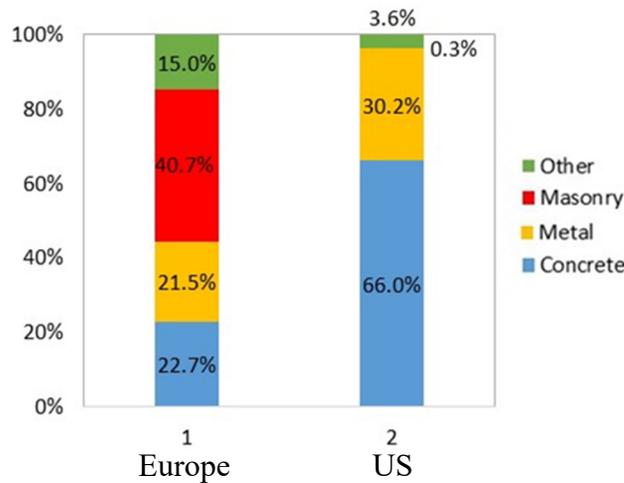


Figure 2: Comparative examples of bridge types in Europe and the US

The issue of limited resources and information on masonry arch bridge management are experienced around the world. As it is not possible to resolve the problems by any country individually, sharing resources is in the interest of the international bridge community. To identify a strategic approach, a Masonry Arch Bridges Workshop was organised during the 12th North American Masonry Conference, Denver, US in 2015. Great differences in available resources and needs were highlighted across the continents and the need for a strategic overview became apparent.

STATE OF THE ART

The current paper attempts to provide a review of available literature for engineers and bridge managers and focuses on guidelines, technical notes, books, etc. that are easily accessible for practitioners. Scientific publications (e.g. journal and conference papers) are not included in the review as they are largely written for the academic community and are not generally used by the industry. Apart from guidelines, a number of historic books are also included in the overview from around the 1900s as they can provide valuable background information on bridge design and construction (documents are available free of charge from Internet Archive [1] and other resources). The list is not, by any means expected to be exhaustive, but intended to serve as a first draft for further expansion. Language barriers are important issues and the list focuses on publications written in English, although some national codes written in other languages have also been included.

Europe

Most of the current guidelines and literature are published in Europe (Table 1). The majority of guidelines are from the UK and provide valuable resources on analysis, maintenance and some on design. There are also a number of historical books available from various countries on design and construction (e.g. [2,3,4,5,6,7]), but due to language barriers and limited accessibility these are currently of limited use for the wider engineering community.

Table 1: Literature published in Europe

	Inspection	Analysis	Maintenance	Design, construction
Europe				
Eurocode 6 [8] deals with masonry structures, but it does not provide any guidance on masonry arch bridges.				
The UIC document UIC Code 778-3R [9] is dealing with structural behavior, assessment and maintenance of masonry arch bridges.		x	x	
The EU funded Sustainable Bridges project [10] has put together a series of guidelines on inspection, assessment, monitoring, repair and strengthening of masonry arch bridges (freely available).		x	x	
UK				
CIRIA document C656 Masonry Arch Bridges: Condition Appraisal and Remedial Treatment [11] is currently probably the most extensive overarching document on masonry arch bridge, discussing materials, structural behaviour, inspection, assessment, monitoring, repair and strengthening.	x	x	x	
The Masonry Arch by Heyman [12] is probably the most widely accepted fundamental literature on the structural behavior and assessment of masonry arches and bridges.		x		

The Structural Masonry and Design of Masonry Structures by Hendry [13,14] deal mostly with masonry buildings, but provide highly valuable guidance on design and materials.			x	x
Masonry Arch Bridges: State of Art Review by Page [15] gives a comprehensive overview on assessment and maintenance.		x	x	
Assessment of masonry arch bridges has been widely carried out by the MEXE method [16] since the Second World War. There are however a number of more up to date assessment tools available specifically for masonry arch bridges [9,10,11] and referred to in the UK bridge assessment standard BD21/01 [17].		x		
The Inspection Manual for Highway Structures [18] is specifically written for bridge inspectors and contains some information on masonry defects and testing.			x	
The Design Manual for Roads and Bridges BD91/04 [19] is a brief, but only guideline available in Europe for the design of new masonry arch bridges.				x
The publication Brickwork Arch Bridges [20] provides useful practical advice on the construction, design and long-term performance of masonry arch bridges, as well as a case study for a new brickwork arch bridge build in 1992.				x
The Theory, Practice and Architecture of Bridges by Hann, <i>et. al.</i> (1843) [21], A Study of Voussoir Arch by Pippard (1951) [22] and the Manual of Civil Engineering by Rankine (1862) [23] are some of the early books providing detailed information on materials, structural behaviour, design and construction of masonry arch bridges.		x		x
Italy				
The national code CNR-DT 213/2015 Guidelines for the Assessment of Existing Road Masonry Arch Bridges by the Italian National Research Council [24] is the most extensive guidance available on condition assessment and analysis (in Italian).	x	x		

USA

In the US very little guidance is available on the maintenance of masonry arch bridges (Table 2). For design and analysis a large number of guidelines are available for buildings, but none for masonry arch bridges. Some useful technical notes have however been published for masonry arches in buildings, that are also relevant for masonry arch bridges. A number of high quality books are available from the 1900s on design, construction and use of materials for masonry arch bridges that can provide valuable background information for practitioners.

Table 2: Literature published in the U.S.

	Inspection	Analysis	Maintenance	Design, construction
<p>The American Association of State Highway and Transportation Officials (AASHTO) Manual for Bridge Evaluation [25] mentions masonry arch bridge inspection and assessment only very briefly.</p> <p>Most inspection manuals issued by the various Departments of Transportations (DoT) also mention masonry arch bridges, but generally very briefly and mainly in terms of defect classification.</p> <p>The Pennsylvania DoT ‘Stone Arch Bridge Maintenance Manual’ [26] is a useful document dealing specifically with masonry arch bridge materials and repair.</p>	x	x		
<p>The American Railway Engineering and Maintenance-of-Way Association (AREMA) Bridge Inspection Handbook [27] mentions inspection of masonry arches also very briefly.</p>	x			
<p>The Masonry Society (TSM) [28] has published a number of standards for masonry structures and bridges, but do not include masonry arch bridges.</p>				
<p>The Brick Industry Association has published some brief, but useful technical notes for design and analysis of brick masonry arches [29,30,31] for buildings, but are also relevant to bridges.</p>		x		x
<p>The National Concrete Masonry Association has published a useful leaflet on masonry arches [32] for buildings, but are also relevant to bridges.</p>		x		x
<p>The Masonry Structures: Behavior and Design by Drysdale [33] deals with the design of masonry buildings, but has useful information on materials.</p>			x	
<p>A number of books were published around the 1900s for engineers and practitioners on masonry arch bridges, providing extensive information on materials, structural elements, structural behaviour, design and construction, for example:</p> <ul style="list-style-type: none"> - Trautwine: The Civil Engineer’s Pocket Book (1872) [34] - Baker: A Treatise on Masonry Construction [35] - Wheeler: Civil Engineering [36] - Howe: A Treatise on Arches [37], Masonry [38], Foundations [39] - Patton: Foundations [40] - Phillips: Masonry Construction [41] - Spalding: Masonry Structures [42] - Williams: Design of Masonry Structures and Foundations [43] - Leontovich: Frames and Arches - Condensed Solutions for Structural Analysis [44] 		x		x

Canada

Although little guidance is available in Canada on inspection, analysis and maintenance, masonry arches have been introduced into the masonry design standard as a first conscious effort towards addressing the lack of information and education on the topic (Table 3).

Table 3: Literature published in Canada

	Inspection	Analysis	Maintenance	Design, construction
The Canadian masonry design standard (CSA S304-14) [45] includes clauses, guidance and easy to use tables for the design of masonry arches for buildings, but also relevant to bridges.				x

China

No documents have been identified for masonry arch bridge inspection, analysis or maintenance in China at the time of writing, however China is one of the very few countries where detailed design codes and practical construction knowledge are still available (Table 4).

Table 4: Literature published in China

	Inspection	Analysis	Maintenance	Design, construction
The JTG D60-2004 [46] is a national design code for all bridge types in China, including masonry arch bridges.				x
The JTG D61-2005 [47] is a national design code for masonry arch highway bridges in China (in Chinese).				x
The TB10002.4-2005 [48] is a national design code for concrete and block masonry railway bridges in China (in Chinese).				x

DISCUSSION

Very limited guidance and literature has been identified on masonry arch bridges around the world. There is also very little training and education [49] and the topic is almost completely omitted in undergraduate courses in most countries. In order to address the lack of information, guidance and education on the subject, an overarching strategic approach needs to be considered on the international level.

Although masonry arch bridges receive little attention in the industry nowadays, they have proved to be highly resilient structures over the centuries with low maintenance and life-cycle costs, long life expectancy, low environmental impact [50] and are aesthetically appealing. They are limited to relatively short spans, slower to construct than other bridge types and perceived to be very

expensive to build (despite of the almost complete lack of factual information and case studies). As all bridge types, masonry bridges however also have their areas of potential application. While they are not suitable for long spans or locations where the speed of construction is of primary issue (e.g. railways), they can be well suited for rural locations, as highly resilient and highly sustainable structures and where aesthetics is a significant issue.

It is only through improved education and guidance that masonry bridges can be maintained as part of the transport infrastructure, their unique benefits recognized and their potentials utilized for the future.

CONCLUSIONS

Masonry arch bridges were widely built up to the 1920s in Europe and the US and carry far heavier loads than they were designed for. Engineers and bridge managers have the responsibility of maintaining their safe condition and ensuring their continued use within the traffic network, however very little guidance and knowledge are available on the subject.

As a first attempt to identify available resources, an initial review on national codes, guidelines, technical notes, books, etc. has been undertaken that are accessible for practitioners around the world. Most of the available guidelines and literature are from Europe and very little guidance is available in the Americas. A number of historical books from the 1900s are also highlighted as they can provide valuable resources on design and construction. China is one of the only countries where masonry bridges are still built and detailed design codes and practical construction knowledge are still available.

In order to address the lack of information, guidance and education on the subject, a strategic approach needs to be considered on an international level. Sharing limited resources, improving education and targeting needs are the first steps towards advancing the knowledge of masonry arch bridges internationally.

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