A ROAD-MAP FOR THE ASSESSMENT OF MASONRY ARCH BRIDGES

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Abstract: *It is estimated that there are more than one million masonry arch bridge spans in the world, the vast majority of which are well over one hundred years old. Over the last 25 years there has been increased interest in their behaviour, and ongoing international research which has now reached a level of maturity that should enable a more rational approach to be taken to their assessment. This paper outlines the SMART (Sustainable Masonry Arch Resistance Technique) method of assessment, which has the potential to provide a logical assessment road-map. Each of the steps is presented. In particular, the relationship between the ultimate limit state (ULS) and the permissible limit state (PLS) is discussed. In this context the PLS is defined as the maximum loading that will not (of itself) cause deterioration of the bridge.*

1 INTRODUCTION

It is estimated that there are more than one million masonry arch bridge spans in the world, the majority of which are well over one hundred years old. Most are now carrying loads well in excess of those envisaged by their builders. The maintenance and assessment of these bridges is a constant concern for bridge owners. Over the last 25 years there has been a growing interest in obtaining a better understanding of their behaviour, and ongoing international research which has now reached a level of maturity that should enable a more rational approach to be taken to their assessment. The Sustainable Masonry Arch Resistance Technique (SMART) method has the potential to provide a logical road-map to their assessment [1], and is outlined in this paper.

2 THE SMART ASSESSMENT METHOD

Bridge assessment involves theoretical demonstration of the ability of a bridge to carry traffic up to a level of loading, speed and volume that is anticipated during the next operational period. In the UK, 5 levels of assessment are now often considered, using a range of techniques from the most basic (level 1) through to the most sophisticated and complex (level 5).
The SMART assessment method [1] attempts to incorporate all existing assessment procedures whilst allowing the flexibility to take in future developments by adopting a more holistic approach to the problem. The method is based on a broad approach that considers 8 steps which are presented in Table 1.

2.1 Step 1 - Bridge Classification

It is important at the outset to dispel the idea that all masonry arch bridges are of similar construction – nothing could be further from the truth. Different types of construction have evolved over centuries of trial and error and technological development. So before embarking upon any analysis the first four steps of the method should be used iteratively to identify a suitable classification for the bridge. This then indicates the level of analysis that should be used in the initial assessment. Each additional level of assessment may involve considerable time and cost, so all deliberations and conclusions should be carefully recorded. It is important to note that more sophisticated assessment methods do not always predict an enhanced carrying capacity compared with initial analyses. Central to these deliberations is the consideration of the geometry of the bridge and the interaction of all of the structural elements - including (where appropriate) the soil-structural interaction. These considerations are summarised in Table 2. (Note that in general the highest level of assessment indicated by any of the considerations listed would need to be selected.)

SMART - Step 1 **Bridge Classification**		
Classify bridge using archive and known foreseeable use during next operational period.		
SMART – Step 2 **Geometry and Construction**		
Initial – Level 1	Intermediate – Level 2/3	Enhanced – Level 4/5
Historical data/Archive Construction details Basic site checks Condition	Verification of initial survey plus some exploratory investigations.	Full geometrical and construction survey extending to the boundary of influence for the bridge.
SMART – Step 3 **Loading /Actions**		
Determine from statutory documents and owners intended use.	Ditto	Ditto
SMART – Step 4 **Materials**		
Identify all of the materials incorporated into the fabric of the bridge and categorise their condition and properties.	Determine the material properties of critical elements.	Determine the material properties of all the major elements of the bridge.
SMART - Step 5 **Analysis**		
Bridge owner's in-house/ bespoke method and/or 2D analysis using a 'rigid-block' and/or elastic idealisation.	2D analysis using a 'rigid-block' and/or elastic idealisation to determine the load capacity and internal stress ranges. Actual material properties should be used where available	Mechanism methods and FE/DE methods including sophisticated material and soil properties. Where appropriate 3D effects should be included. Actual material properties should be used where available.
SMART – Step 6 **ULS**		
Determine the ULS load carrying capacity based upon Step 4. Check modes of failure NOT included in the analytical modelling (e.g. ring separation).	Determine the ULS load carrying capacity based upon Step 4 (Level 2/3). Check modes of failure NOT included in the analytical modelling (e.g. ring separation)	Determine the ULS load carrying capacity based upon the Level 4/5 analysis which takes account of ALL modes of failure. Probabilistic methodology may be applied to the output. SN behaviour of structural elements should be considered.
SMART – Step 7 **PLS**		
Bridge owner's in-house/bespoke method may be used to determine the PLS or 'working load capacity'. For a range of bridges, a 'load factor' reduction of the ULS load carrying capacity may be appropriate.	Structural idealisation used to identify 'elastic' structural model to check stress ranges. Check adequacy against alternative failure modes. Deterministic philosophy to be used.	2D/3D analysis to investigate working load range. Actual properties to be used plus probabilistic methodology (in its simplest form this could be a parametric study).
SMART – Step 8 **Residual Life**		
Application of safety/condition factors. Recommend appropriate basic rehabilitation.	Ensure residual life by stress control. Recommend appropriate rehabilitation.	Ensure residual life Probabilistic consideration of stress control Recommend appropriate rehabilitation.

Table 1 The SMART method

	Initial **Level 1**	**Intermediate** **Level 2/3**	**Advanced** **Level 4/5**
Span	< 6m	6m to 15m	> 15m
Shape/ **Topology**	Segmental Square	Elliptical 3 – centre	Skewed Multi-span Internal spandrel walls
Bridge Fabric	Granular/cohesive backfill Masonry in good condition	Granular/cohesive backfill Masonry in moderate condition	Granular/cohesive backfill Masonry in poor condition
Super-structure – Condition rating	Good	Moderate	Poor
Sub-structure Condition rating	Good	Moderate	Poor
Loading	Ambient	Change in regime	Change in regime

Table 2 Bridge Level of Assessment Classification

The process of determining the condition of the bridge is difficult and currently requires much experience and a fundamental understanding of the potentially complex behaviour of such structures. Table 3 presents a preliminary draft version of the condition rating for the bridge sub-structure. (Note that in general the most severe defect encountered would govern the ascribed condition rating.)

In using this table it is important to note that the limits which are suggested relate to deformations that have developed over many years and that if such deformations develop over a short period then it should be treated as a matter for concern and should be investigated immediately.			
Defect	**Good**	**Moderate**	**Poor**
Scour	No scour	Scour or weak founding material up to W/10 (W-width of abutment) or 1.5m (whichever is the lesser)	Scour or weak founding material for greater than W/10 or 1.5m (whichever is the lesser)
Differential settlement of piers/abutments	No differential settlement	Up to 50mm over a 2m gauge length	Greater than 50mm over a 2m gauge length
Pier/Abutment Vertically	1 in 200 or 25mm out of plumb	1 in 100 or 50mm out of plumb (whichever is the lesser)	Greater than 1 in 100 or 50mm out of plumb (whichever is the lesser)
Twist in plan of pier or abutment	1 in 200 or 25mm out of plan	1 in 100 or 50mm out of plan (whichever is the lesser)	Greater than 1 in 100 or 50mm out of plan (whichever is the lesser)
Movement of spandrel or wing wall relative to support	None	Up to 10mm	Greater than 10mm
Bulging of walls	None	Up to 10mm measured over a gauge length of 3m	Greater than 10mm measured over a gauge length of 3m
Tilting of walls	1 in 200	1 in 100	Greater than 1 in 100

Table 3 Substructure deformational defects and condition rating (including tentative values)

Eventually there will need be a similar table for the superstructure (though note that there is some overlap between what is regarded as 'substructure' and what is regarded as 'superstructure' in the case of a masonry arch bridge).

2.2 Step 2 - Geometry and Construction

The barrel may take various shapes including: semi-circular, parabolic, segmental, elliptical, gothic pointed and may comprise dressed stone, random rubble, brickwork or mass concrete. The backfill may be anything from ash and rubble through to mass concrete and may include internal spandrel walls.
It is very important to collect information that defines the boundary conditions of the bridge. The geometrical data and construction details should therefore include the embankments, etc. on the approaches to the bridge.
Any defects and/or historical deformation should be carefully recorded. This can be particularly important when they are to be rehabilitated before the next inspection. For example, re-pointing of the barrel will mask the intrados joint cracks – the pattern of which may be key to understanding the bridge behaviour and inform the bridge idealisation adopted in the analysis.

2.3 Step 3 - Loading/Actions

Dead loads are essential to the stability of masonry arch bridges which may be considered at the ULS to be a gravity structure. Consequently, dead loads should be determined as accurately as is practicable.
The bridge owner will usually specify the loading regime, but the assessing engineer should always ensure that all relevant actions have been taken into account. It is also important that patterns of loading which are representative of those which will be applied to the bridge in service are considered (since the pattern of loading in relation to the shape of the arch governs stability.)

2.4 Step 4 - Materials

It is beyond the scope of this paper to consider the properties of all combinations of materials that might be found in masonry arch bridges. In masonry construction these materials include a wide variety of bricks and stone units, typically separated by bed and vertical joints comprising some type of mortar. The percentage of mortar in the masonry varies from zero in 'perfect' dressed stone to 40% for random rubble. In general the greater the percentage of mortar the lower the potential strength and stiffness of the masonry.
In addition, it is well known that material properties vary over time. This raises the issue of how best to characterise this. It would be ideal if an equation could be used to represent this as a continuous function but this is unlikely to be available for some time. A more pragmatic approach would be to use the worst credible properties (WCP), perhaps in conjunction with the probable credible properties (PCP) and best credible properties (BCP). It is likely that this will involve some field testing for all but the simplest of analyses.

2.5 Step 5 - Analysis

Masonry arch bridges are extremely complex 3-dimensional structures. The range of materials from which they were constructed together with the diversity of constructional detail means that great care and considerable experience is needed to develop a representational structural idealisation.

There are several methods of analysis currently available, which range from semi-empirical methods through to the latest non-linear finite and discrete element techniques. All these methods should carry a health warning in as much as they usually focus on the structural performance of the barrel because it is considered to be the most vulnerable element of the bridge. In fact, it is just one element of the entire structural system.
It is important when idealising a masonry arch bridge that all failure mechanisms are considered (especially when the adopted analytical method does not accommodate specific types of failure, e.g. ring-separation in multi-ring construction).

2.6 Steps 6 and 7 - ULS and Permissible Limit State (PLS)

The relationship between the ULS and PLS needs to be explained and where possible quantified. To date this has presented both researchers and assessing engineers with real difficulties as there does not appear to be firm advice based upon scientific evidence. Currently, half of the ULS capacity is taken as an acceptable working load in UK practice. This is based upon field tests undertaken by the TRL [2] in which it was observed that the barrel deflections departed from their initial ‘linear’ gradient (i.e. there was a change in the observed stiffness of the arch barrel) at about half of their respective ULS failure loads. These data should of course be viewed in the context of ‘whole bridge’ performance, i.e. since the tests included contributions from the spandrel walls, pre-existing defects, varying boundary conditions etc.
One of the most powerful arguments for the application of the plastic theorems to determine the ULS of masonry arch bridges is that the collapse mechanism is independent of the initial condition of the bridge and small geometrical changes in the shape of the arch barrel. i.e. plastic analysis is only reliant upon the bridge geometry, the weight of the respective bridge elements and the applied loading and the compressive strength of the constituent masonry.
The issue still exists as to the relationship between the ULS capacity determined from a quasi-static loading analysis and that which corresponds to the actual type of loading the structure experiences (i.e. a cyclic, rolling load, including the possibility of traction/braking forces). The possibility of incremental collapse, partial collapse, fatigue, material deterioration and long/short term settlement all need to be considered in the context of creating changes in the initial residual stress condition of the bridge and its designated load carrying capacity. In the context of plastic analysis, shakedown theorems reveal concepts and conclusions which are worth further consideration. For example, Heyman [3] highlights three powerful conclusions based upon fundamental shakedown theory. Firstly, it is the range of loading that influences incremental collapse (i.e. this is independent of dead load). Of course, the dead load of the bridge plays a very important role in determining the ULS carrying capacity but any load with a fixed value does not affect the difference between the

static load factor λ_c and the shakedown factor λ_s. Secondly, the load factor for incremental collapse will be less than or equal to the static ULS collapse factor. This means that the load path to incremental collapse will lie everywhere within the static ULS collapse domain. This raises an interesting question regarding the safety/load factors that are used to determine safe working loads. The incremental collapse load will be less than or equal to the static collapse load, so applying a global load factor is inappropriate and could lead to diminished safety. Thirdly, the difference between λ_c and λ_s arises only from loads which would produce a positive elastic bending moment at a section where there is a negative hinge rotation, or which would produce a negative elastic bending moment at a section where there is a positive hinge rotation.

The PLS is defined as the maximum loading that will not (of itself) cause deterioration of the bridge. Consequently, it may for example be that crown loading is more significant than quarter span loading, which is often taken as the critical case for ULS loading.

Additionally, soil-structure interaction may be significantly different for each limit state. In the case of the PLS the consolidated soil state may be of most importance whilst at the ULS significant passive resistance might be mobilised. It is the interaction between the various elements of the bridge, all of which have different stiffnesses (and strengths), that requires careful consideration. For example, to mobilise significant passive backfill pressures the arch barrel would need to undergo significant movement to mobilise soil strains commensurate with large passive soil pressures on the extrados – or it may be that before this happens the comparative stiffness of the spandrel walls means that these attract load and thereby change the load path within the bridge. Furthermore seasonal changes in backfill moisture content can have significant effects on backfill strength. The ULS should be computed based on the worst case moisture conditions. However the PLS may be significantly influenced if moisture conditions are favourable for most of the operational life.

Smith et al. [4] divided the various contributions to bridge load capacity into six components, as listed in Table 4. While in that paper the designation SLS was used, in principle states up to SLS3 require no soil or arch displacement and could be considered to provide a lower bound to the PLS (assuming the masonry is not overstressed and liable to fatigue). A degree of load dispersal can also occur with minimal soil displacement; therefore SLS4 could also be used to provide a lower bound to the PLS.

Scenario	Simple description
SLS1	Load capacity of bare masonry arch only.
SLS2	Load capacity of arch including effect of backfill dead weight. No load dispersal.
SLS3	At rest horizontal earth pressures included as additional load on arch.
SLS4	Effect of load dispersal through backfill additionally considered.
SLS5	Effect of small displacement modifications to the horizontal earth pressures additionally considered.
ULS1	Effect of large displacement modifications to the horizontal earth pressures (mobilizing full soil strength) additionally considered.

Table 4: Soil-structure interaction scenarios (after [4]).

The case study bridge reported in [4] can be used to obtain an indication of the relative magnitudes of these states: SLS2 and SLS3 were approximately one third of the ULS while SLS4 was approximately one half of the ULS. (It should be noted that these results will change for different bridge geometries and were computed only for quarter span loading.) These magnitudes are significant and could provide sufficent calculated PLS capacity for many bridges which are large in comparison with normal service loading, for relatively little analysis cost. Further research is however required to cover a broader range of loading conditions and arch geometries.

It was also reported in [4] that, depending on soil strength and arch geometry, a factored ULS strength could be above or below an SLS load capacity. By extrapolation a factored ULS could also be more critical than a PLS. While that study involved the use of Eurocode 7 factors, it will be necessary to develop arch specific safety factors for ULS loading.

2.7 Step 8 - Residual Life

Having determined values for the PLS and ULS it only remains for the assessing engineer to consider the residual life of the bridge. This can potentially be done by the simple application of factors of safety. In the light of recent research, fatigue considerations might be considered. The application of a Miner's Rule type approach would give a 'feel' for the residual life of the bridge. This would be invaluable information, upon which the bridge owner could base bridge management decisions.

3 CONCLUSIONS

It is suggested that the SMART method can be used as a methodology by which the critical parameters affecting the load carrying capacity and service life of a bridge can be identified. The method involves an initial classification of the bridge and independent assessment of the ULS and PLS. At present there are practical difficulties which prevent its full application, but it does appear to offer a robust and rational way forward.

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5 REFERENCES

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