CENTRIFUGE AND FINITE ELEMENT MODELLING OF PONTYPRIDD BRIDGE

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ABSTRACT

This paper describes the initial work undertaken on experimental and numerical modelling of historic structures. William Edwards’ bridge located at Pontypridd, Wales, and constructed in 1756 has been selected because of its unusual geometric complexity and historical importance. A series of centrifuge tests at 1/55⁰ scale is described and proposed to be used in calibrating a Finite Element model, which uses a macroscopic approach. A homogenisation technique is used to obtain equivalent materials, representing the behaviour of masonry and the various interfaces. This allows a very important reduction of the computational cost, making it possible to perform detailed analyses of complex structures such as bridges. Conclusions are drawn on the behaviour of masonry arch bridges and on the suitability of using Finite Element models in the assessment of three dimensional masonry arch structures.

Key words: Masonry arch bridges, Centrifuge Modelling, Finite Elements, Homogenisation, Pontypridd Bridge, Interfaces.
1. INTRODUCTION

In the last twenty years, understanding the behaviour of masonry arch bridges has been the aim of several studies (7). The main objective is to obtain more accurate and reliable methods of assessment, which simultaneously optimise economy, efficiency of the transport network, conservation of the heritage and safety.

The importance of the arch-soil interaction has been shown (2) and is currently considered in most methods of assessment. The spandrel walls have also proved to play an important role in the behaviour of masonry arch bridges but are usually ignored. In some cases (9), two-dimensional models consider indirectly the effect of the spandrel walls, by adjusting the stiffness of the backfill material. In a series of tests on redundant structures undertaken by the Transport Research Laboratory (TRL) (7), it was observed that spandrel wall separation occurred frequently and so it was assumed that the spandrel walls could be ignored in the analysis, being safe and not too conservative. However, it has been experimentally shown (3) that separated and non-separated spandrel walls played an important and very similar role in the strength of arch bridges. The three-dimensional behaviour of masonry arch bridges has also been shown experimentally (6). Finally, ring separation has been acknowledged (3) to be important and is since included in some models (3,1).

The main aim of this paper is to present a FE model based on a homogenisation technique, which considers all the important mechanisms that contribute to the behaviour of masonry arch bridges. To calibrate the model step-by-step a series of centrifuge tests have been conducted. Tests on masonry materials and interfaces have also been carried out for the validation of the various aspects of the numerical model.

2. EXPERIMENTAL PROGRAMM:

2.1. Centrifuge models:

Laboratory testing of small-scale models has the convenience and economy of building and testing models of reduced size. However, because gravity forces are essential in the behaviour and strength of masonry arch bridges (10), if model and prototype are built with the same materials, they would not be equivalent. For the models built with the same materials to be correct small-scale representations of prototype structures of real dimensions, centrifuge modelling is needed to simulate enhanced gravity conditions. Its application in modelling masonry arch bridges has been previously validated (11).

The centrifuge models of the series are based on Pontypridd Bridge (Fig. 1) (4) because of its unusual geometric complexity and historical importance. The use of centrifuge modelling at 1/55th scale allows economic results at failure to be obtained for a 42-m span bridge. The following models have been tested:
- **Ring only model**: the main interest of this model is to single out the effect of the soil and its interaction with the arch by combining its results with those from the tests with backfill.

- **Model with backfill and frictionless interface**: The main feature of this model is the inclusion of a double skin of PTFE film to eliminate any friction between the soil and arch extrados. In models tested at larger scales (2), significant shear stresses have been measured at the interface, along with normal pressures. However, as equivalent cells are not commercially available at the scale of this work, it was decided to estimate their effect by suppressing any shear stress in the arch extrados. This type of result is very useful for the calibration of any method not considering the arch-soil interface as a solid bond.

- **Models with backfill**: These models have standard soil-extrados friction but no structural spandrel walls. These results are important, since most of the numerical models presented up to the present are two-dimensional models. Two of these models were tested to verify the repeatability of the centrifuge tests at the required 55g. Satisfactory results were obtained.

- **Three-dimensional models**: Two models including structural spandrel walls have been tested, under central and eccentric knife-edge loading. The spandrel wall ends were restricted by the stiffness of a 5-mm thick neoprene sheet to simulate the effect of the wing walls. The eccentric load was intended to evaluate the behaviour of the structure under traffic load.

It has been argued (10) that high variability of strength in the mortar-stone bond has been responsible for the lack of repeatability in masonry arch bridge tests. To reduce this effect on the tests and because it is the mortar used in most historical constructions, lime mortar has been used in all the tests. All the models have only one ring of stone masonry to coincide with the prototype structure. This ensures that the problem of ring separation does not interfere with the results. To calibrate the proposed bridge modelling strategy with respect to ring separation, other experimental results from centrifuge tests should be used (11).

The models (Fig. 2 and 3) were instrumented with displacement, pressure and load transducers. The main results obtained from the tests were the failure mechanism and load, deflections and normal pressures on the arch extrados. Under a monotonic knife-edge load at a quarter point, all models failed by the formation of 4-hinge mechanisms and tangential spandrel-arch separation occurred in the models with spandrel walls. Fig. 4 shows the contribution in terms of load and stiffness of each part of the structure. In the frictionless test, the transducer under the load failed during the test and so only the failure load was available (see Fig. 4). It can be seen that it did not have any effect on the failure load, but no conclusions can be drawn on its effect on the stiffness of the structure. The figure also shows that 40% of the strength of the bridge corresponds to the effect of the spandrel walls.
2.2. Material and interface tests

These tests were performed on small-scale samples under normal gravity conditions. The centrifuge was not employed, as the effects of gravity are not significant in these tests.

- Tests on constituents: Standard elastic and uniaxial compression and tension tests were performed on mortar and stone. In the case of the compression test on mortar, it was found that a triaxial test is better, due to the conditions of mortar in masonry under compression. An eccentric compression test on stone was performed to simulate the conditions of the stone in arch hinges.

- Masonry assemblies: triplets (3 x 1) and wallettes (5 x 3) were tested under uniaxial compressive stress, from which elastic and failure parameters were measured. These results, combined with those of the previous section enabled an experimental validation of the homogenisation technique to be used for the simulation of masonry.

It has been pointed out (11) that while a good simulation of the strength was achieved working with masonry at small-scale, more flexible results than in equi-

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**Figure 1. Geometric and material properties.**

<table>
<thead>
<tr>
<th>GEOMETRY (Prototype)</th>
<th>Segmental arch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profile</td>
<td></td>
</tr>
<tr>
<td>Radius (intrados)</td>
<td>27.08 m</td>
</tr>
<tr>
<td>Span (intrados)</td>
<td>42.73 m</td>
</tr>
<tr>
<td>Rise at centre span (intrados)</td>
<td>10.44 m</td>
</tr>
<tr>
<td>Arch thickness</td>
<td>0.76 m</td>
</tr>
<tr>
<td>External width</td>
<td>4.95 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MATERIALS (model)</th>
<th>Stone (sandstone)</th>
<th>Mortar</th>
<th>Masonry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compression strength</td>
<td>77 (97.34*)</td>
<td>1.38</td>
<td>33.80 MPa</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.15</td>
<td>0.064</td>
<td>0.17</td>
</tr>
<tr>
<td>Young's modulus (Sec 30%)</td>
<td>18235</td>
<td>1970</td>
<td>3104 MPa</td>
</tr>
<tr>
<td>Tensile strength (flexion test)</td>
<td>14.155</td>
<td>0.58</td>
<td>- MPa</td>
</tr>
<tr>
<td>Angle of friction</td>
<td>45</td>
<td>35</td>
<td>32 °</td>
</tr>
<tr>
<td>Cohesion</td>
<td>0.172</td>
<td>0.024</td>
<td>0.063 MPa</td>
</tr>
<tr>
<td>Masonry bond wrench strength</td>
<td>0.017</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: Eccentric loading  : Properties in a certain direction
valent full-scale tests were obtained. However, this does not influence the results of the numerical model, as the masonry modelling has been validated using the results of the assemblies, obtained at the same scale as the bridge models. This ensures that the numerical model properly simulates the experiments.

– Soil tests: Triaxial test to obtain the parameters for the Mohr-Coulomb yield criterion.

– Interfaces: Three tests on interfaces were undertaken:

– Masonry-soil in shear: Shear tests were performed at different normal stresses to obtain \( \phi \) and \( C \) at the interface. These results would be used for validating the homogenised simulation of the masonry-soil interface.

– Masonry-masonry in shear: Similarly, shear tests were performed to validate the homogenised simulation of the arch-spandrel wall interface and ring-ring interface.

– Bond wrench test: It is experimentally observed, that tension failure in masonry happens by de-bonding rather than by a tensile failure in mortar. The results of this test would then be used to check for tension failure in masonry in the direction of bed or head joints.

Despite the fact that the mortar-block has been considered to have properties with high variability (10), these tests showed a good uniformity. Fig. 1 shows the main results of the tests on materials and interfaces.
3. NUMERICAL MODEL

The homogenisation technique is used in two different situations: Firstly, the case when the pattern of joints is regular and the joints are small compared with the main dimensions of the structure and secondly, the case of the interface between two bodies with two different materials with widely different elastic properties.

3.1. Masonry modelling and calibration

Masonry is an anisotropic composite material, but at macroscopic level, under common loading and boundary conditions, it can be assumed to be a globally homogeneous material. As a result, detailed and expensive micromodels, where units and mortar are discretised separately, are not necessary and macromodels can be used. However, most macromodels are just adaptations of concrete models, which cannot consider either the anisotropy or the complex failure mechanisms of masonry. A two-step homogenisation technique (8) is used to create a macromodel that can take into account these factors with a reduced computational cost.

Based on the averaging rule, a series of hypotheses in the unit-mortar bond and solid mechanics, and assuming that the masonry pattern is repeated sufficiently, the constitutive matrix for the equivalent material is obtained. Furthermore, the structural matrices, which relate the stresses in the equivalent material with the stresses in the masonry constituents, units, bed joints and head joints, can be determined (8).
The structural matrices allow a failure criterion to be imposed on the constituents. The failure criterion considered is Mohr-Coulomb with tension cut-off for each constituent. Additionally, shear failure is considered in the particular direction of the mortar bed and head joints, using the shear properties of the interface. Once failure is detected in either of the constituents, a crack in the appropriate orientation is generated and smeared in a further step of homogenisation. This means a third level in the process of homogenisation, in which the previously obtained equivalent masonry material is homogenised with a material simulating the crack. This gives another factor of anisotropy to the material. Standard elasto-plastic theory with an associated flow-rule is used to dissipate the extra stresses in the crack, due to tension or shear failure. The behaviour of the constituents after tensile or shear cracking is simulated by linear softening.

Experimental validation of this technique is carried out using results of tests on constituents and masonry assemblies, presented in section 2.2. The introduction of the Mohr-Coulomb shear failure criterion, coupled with the previous version of the program (5), allows a more realistic representation of masonry behaviour under compression, allowing simultaneously a correct simulation of elastic and failure stages.

3.2. Interface modelling and validation

Correct simulation of interfaces is a difficult problem, which has been considered using different numerical simulations. It is generally found that a large number of elements are needed to correctly capture the behaviour of interfaces or, when
standard joint elements are used, mesh dependency or ill conditioning of FE usually arise. To avoid this problem, without increasing the computational cost, an additional homogenisation technique is used by employing an equivalent element, which spans over the two materials. The main advantage of this method is that the thickness of the interface is eliminated in the constitutive relation and smeared into neighbouring materials, avoiding mesh dependency. Similar applications of this case of homogenisation can be found in the field of biomechanics (5).

The process to determine the constitutive relation and structural matrices for the equivalent interface element is similar to the approach for masonry. Shear and tensile failure are checked in the direction of the interface and when failure occurs, a subsequent crack is formed and smeared with the surrounding intact material, as explained before.

This technique is applied to the three interfaces, arch – soil, spandrel wall – arch and ring – ring in multi-ring arches. The validation of the simulation is performed for the three situations using experimental results, arch - soil in shear, arch - spandrel wall in tension (bond wrench test) and arch - spandrel wall in shear (masonry shear test).

In the case of multi-ring arches, the sequence of ring and joints would not be enough to be considered as periodic. As a result, the homogenisation technique as used for masonry (periodic media) cannot be applied and an interface-homogenised element should be used.

3.3. Bridge modelling and calibration

Combining the previous models a simulation of masonry arch bridges is presented. Each arch ring as well as the spandrel walls are simulated by using homogenised masonry materials. An elasto-plastic Mohr-Coulomb model is used for the soil and interface - homogenised elements are used in modelling the interfaces (see Fig. 5). The combination of this with the FE method, which allows consideration of complex geometries, has been implemented in STRUMAS, as a tool for modelling accurate but affordable simulations of masonry constructions. The proposed model can consider all the factors affecting the behaviour and strength of masonry arch bridges, i.e. soil-arch interaction, spandrel walls, spandrel walls separation and ring separation.

The model is being calibrated in a step-by-step basis, comparing its results with those of the centrifuge tests. Preliminary results show good agreement. The required model (Fig. 6) has 3,342 elements, or 1671 when loading with transversal symmetry is considered.

Continuum models of masonry arch structures are usually considered to depend on too many parameters, which are difficult to determine. In the case of FE mo-
delling it is also considered computationally too expensive. In the numerical model presented, all the input parameters not only have a physical meaning, but also a value is available from experimental tests. The only two parameters that need a better definition are the softening parameters, and the compressive strength of mortar under triaxial compression. Furthermore, it is proposed to combine the model presented with risk assessment techniques to take into account the variability of the experimental data and the variability and uncertainty of the geometrical and material properties of real structures. In terms of computational cost, the numerical techniques presented permit the simulation of complex problems.
with a reasonable number of elements. To date, there does not seem to exist any alternative to analyse the serviceability and adequacy of repair techniques as well as the final capacity of masonry arch structures.

4. CONCLUSIONS:

- A series of centrifuge tests has been presented to provide understanding on the way that different structural effects of masonry arch bridges contribute to its strength and stiffness. The validity of the series is only limited by the use of a single geometry and materials. Furthermore, completed with an extensive material testing, these results provide data for the calibration of the numerical model.

- A numerical modelling strategy based on a homogenisation technique, which permits the simulation of complex problems with a reasonable number of elements, has been presented.

- The simulation of a complex structure such as Pontypridd Bridge is possible using this technique.

5. ACKNOWLEDGEMENT:

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6. REFERENCES:


