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Numerical Modelling of Flat Arch Masonry Retaining Walls

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Abstract

A vast majority of arches can be found as bridges in railway and roadway systems, aqueducts, and roofs. However, employing arch action to resist lateral earth pressure has not been exploited broadly in the literature. A recent study has investigated the potential of utilizing flat arch unreinforced concrete block retaining wall to resist the lateral earth pressure and surcharge loading. The proposed retaining wall was constructed as a segmental circular flat arch. This novel concept was a success, with experimental stresses and deflections well below critical limits. Despite the success, the wall's deflection profile was unexpected, possibly due to loss of fixity at the abutments. Therefore, the authors were unable to numerically replicate their experimental measurements, preventing them from presenting a general response of this structural system. This paper investigates the possibility of explaining the experimental results as a result of abutment slippage. A 3-D finite element simplified micro model, verified using a thick-cylinder analysis, is used to numerically reproduce the experimental setup. The influence of grout stiffness and arch wall-abutment coefficient of friction on the loss of fixity is investigated. A detailed discussion on the influence of these factors and a renewed analysis of the experimental results is presented. The model confirmed the hypothesis of fixity loss as producing the experimental deflected shape. The development of this model makes possible a parametric analysis characterising the response of the structural system.

Keywords: masonry, concrete block, arch, retaining wall, finite element, micro model.

1 Introduction

Arches find typical application in bridges, aqueducts and roofs. However, arches have rarely been used as retaining walls. Kurukulasuriya and Shrive [1] investigated the behaviour of a concrete block masonry unreinforced flat arch retaining wall subject to lateral earth pressure and surcharge experimentally. The design was notable for purely resisting overturning and out-of-plane movement via arch action, without the need for anchors or a specially designed base. The simplicity and cost-effectiveness of this design make this an attractive option for low-rise (< 3 m) retaining structures, given successful experimental implementation and an accurate understanding of this system's structural response. Kurukulasuriya and Shrive's [1] novel approach proved successful – in the conducted experiment, no cracks were observed, and the maximum measured displacement was 2.5 mm – 1.3% of the wall's thickness.

Despite this success, the wall exhibited unexpected behaviour. The space between the vertical edges of the arch and its supporting walls were grouted in an effort to establish a fixed connection. The edge of the grouted side of the wall was found to displace 2 mm –the fixed end assumption was poor. Consequently, the stress analysis presented by Kurukulasuriya and Shrive [1] on the experimental wall, based on pinned and fixed boundary conditions does not reflect the stress state of the tested wall. Kurukulasuriya and Shrive [1] proposed that the grout providing the fixed end may have been weak and failed early, but did not produce an experimentally verified finite-element analysis based on this assumption. In this work, a 3D simplified finite element (FE) micromodel of this wall is created in Abaqus to investigate the validity of this explanation. The influence of grout stiffness and arch wall-abutment coefficient of friction on the loss of fixity is investigated. A detailed discussion on the influence of these factors and a renewed interpretation of the experimental results is presented. The stress profiles of the wall models which agree with the experimental observations are presented and the performance of the wall is judged anew from an improved perspective. Further, the development of an experimentally verified micro-model of this structural system will permit a parametric study characterizing the behaviour of this system for various geometries, boundary conditions, and material properties in future work. The complete definition of this system's structural response will permit industry uptake of this economically competitive structural solution in retaining wall construction.

2 Methods

Kurukulasuriya and Shrive [1] tested a 12-course, hollow concrete block arch retaining wall, of 7.6 m span and 2.4 m height. The wall had external dimensions of 8 m arc length, 1.08 m "rise" and 190 mm thickness, yielding a rise-to-span ratio of 0.135. The arch was connected to the confining walls by grouting the space between the arch and supporting walls [1]. One half of the wall was fully grouted, and the other half left hollow. More details on experimental characteristics are available in [1].

A 3D finite-element (FE) simplified micro-model [2] was implemented in Abaqus; this technique takes a repeating set of blocks and mortar as the fundamental unit. The model exclusively used linear eight-node 3D bricks (C3D8). A 20 mm global mesh was used; 10 mm was used for the grout at the abutment connection. To investigate potential stress redistribution caused by base sliding, a base was modelled, and interaction properties were defined between it and the bottom arch surface. Triangularly distributed lateral soil pressure was applied over the wall extrados, with a maximum of 0.046 MPa at the bottom. Unit–mortar elements were cemented via cohesive interaction with damage criteria. Normal behaviour was defined via Abaqus' "hard" contact. Maximum nominal stresses of 0.5 MPa and 0.3 MPa were taken to represent the cohesive normal and shear damage. Tangential behaviour was defined using the penalty friction formulation, with an isotropic frictional coefficient of 0.7 between the units and base. The Concrete Damage Plasticity model was used to capture the non-linear behaviour units and grout, with parameters chosen as validated in [3]. The base and the abutments were modelled as linear elastic steel. One half of the wall was fully grouted along the full height as shown in Figure 1.

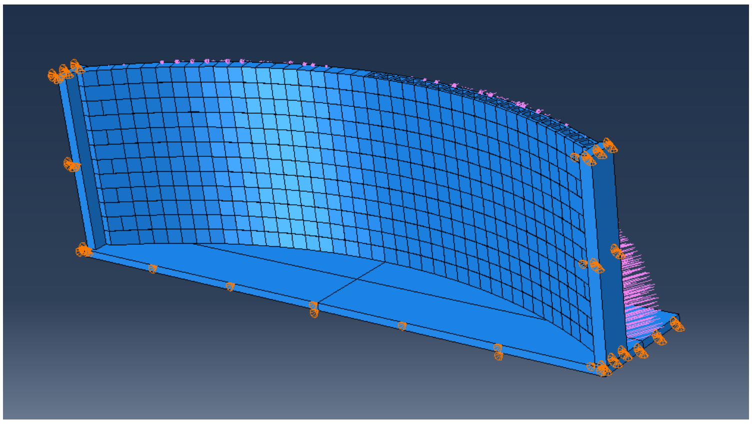

Figure 1: Assembly of the FE model

To replicate loss of connection between the arch and the grouted side confining wall, the coefficient of friction between the left abutment and the grout was varied from 0.7 to 0.1. Further, the elastic modulus was reduced to 10000 MPa, to investigate the influence weak connecting grout may have had on fixity loss. A model was also run assuming Mohr-Coulomb cohesion between the grout and wall. The cases considered are listed in Table 1.

Model	Friction coefficient	Cohesion	Elastic Modulus / MPa
I	0.7 [CSA S304-14]	Y	10000
II	0.1	N	15000
III	0.1	N	10000

Table 1: Variabilities in FE models

Numerical results were compared against experimental displacements and strains. The experimental instrumentation is shown in Figure 2. The wall centreline had circumferential and longitudinal strain gauges; the abutments only had circumferential gauges. Recorded strains were converted to stresses and compared to numerical stresses. Radial displacements were obtained via laser sensors.

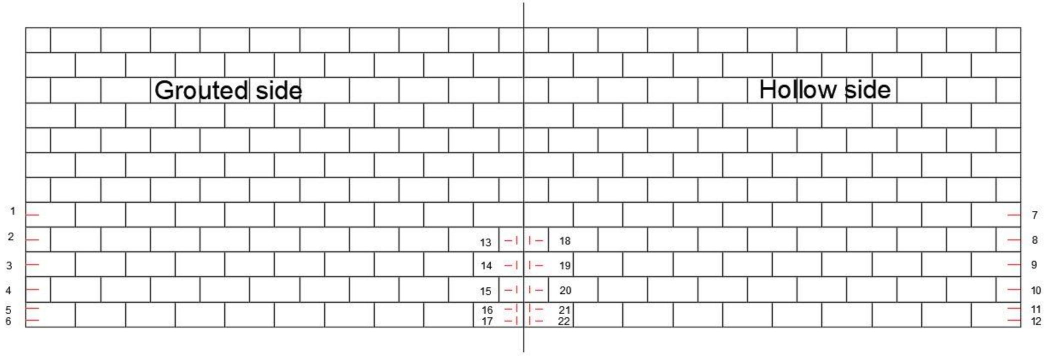

Figure 2: Experimental instrumentation used in [1].

3 Results

The numerical model was validated by analysing a fixed-fixed, baseless model, and comparing output axial stress at wall midspan and mid-height against stresses predicted from a thick-walled cylinder analysis, as per [4]. The strong agreement between both analyses is shown in Figure 3.

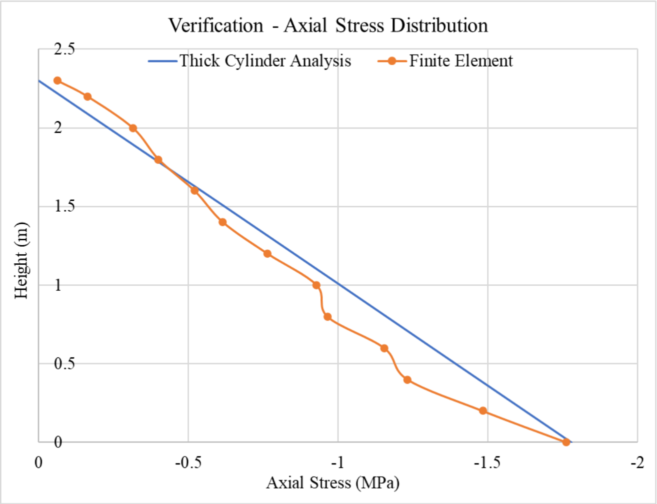

Figure 3: Numerical model verification.

Radial displacement at the top of the wall along the arc length is plotted for all models in Figure 4 and compared to experimental laser scan readings. Model I (with abutment cohesion) was effectively fixed; this deflection profile represents what should have been observed if fixity had been achieved experimentally. Models II and III (with only tangential friction at the grouted abutment) yielded a displacement profile more similar to the experimental observations, supporting the hypothesis that the experiment was characterized by loss of fixity. Displacement readings show similar slippage at the hollow end abutment, suggesting the experiment could be numerically replicated by appropriately adjusting the effective friction at each abutment. However, relaxing fixity at only the grouted abutment produced behaviour that more closely matched experimental observation. This finding is supported by experimental photographs of the arch-abutment connection from [4] (see Figure 5).

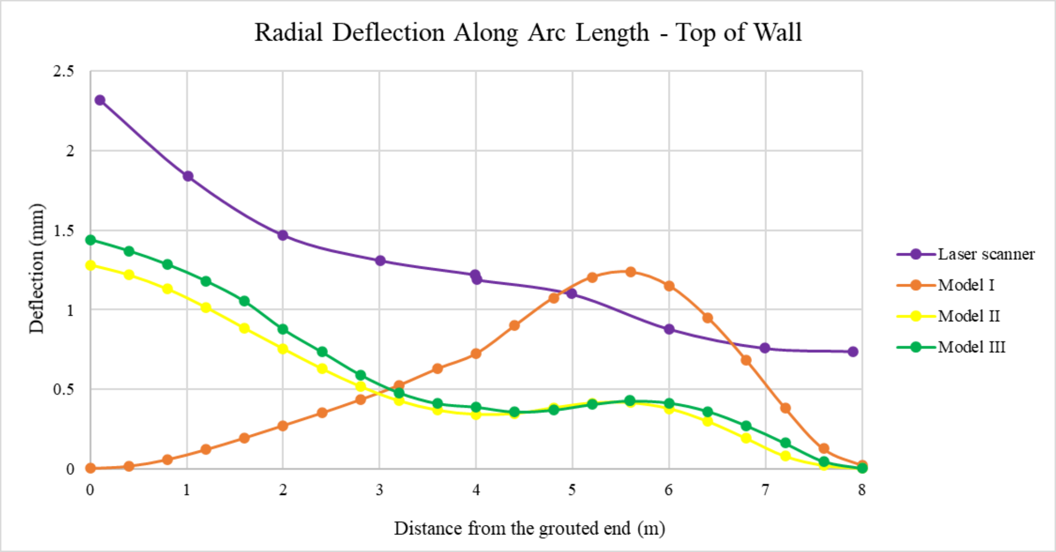

Figure 4: Radial deflection at the top of the wall.

Figure 5: Loss of bond experimentally observed [4].

This verified model suggests strain gauge readings on the hollow blocks may be unreliable. Consider Figures 6 and 7, where numerical stresses (S11, S33) on the grouted and hollow sides of the intrados centre are compared to experimental values back-calculated from strain gauges. Centre values were chosen to minimize the influence of boundary condition particularities. Experimental and numerical values agree well on the grouted side, but there is discrepancy on the hollow side, particularly towards the bottom. On the hollow side it is possible that strain gauge readings were influenced by local stiffness variations (e.g., placement of gauges on mortar-dense or aggregate-dense areas). This influence would be reduced on the grouted side due to the uniformity provided by the grouted cores – this is indeed observed in the plotted figures.

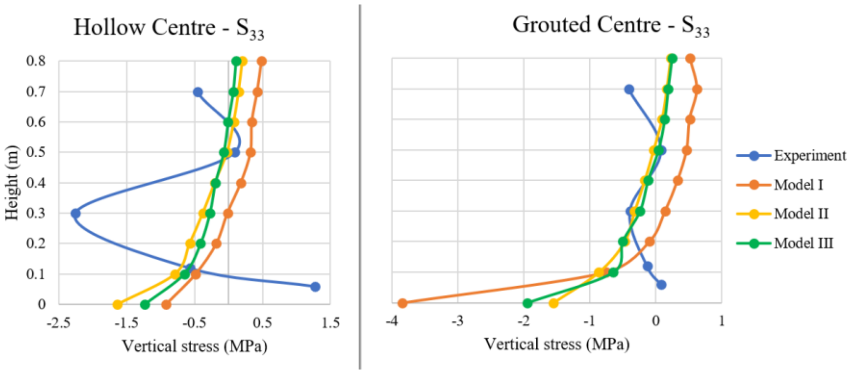

Figure 6: S33 plotted on hollow and grouted sides of intrados centre.

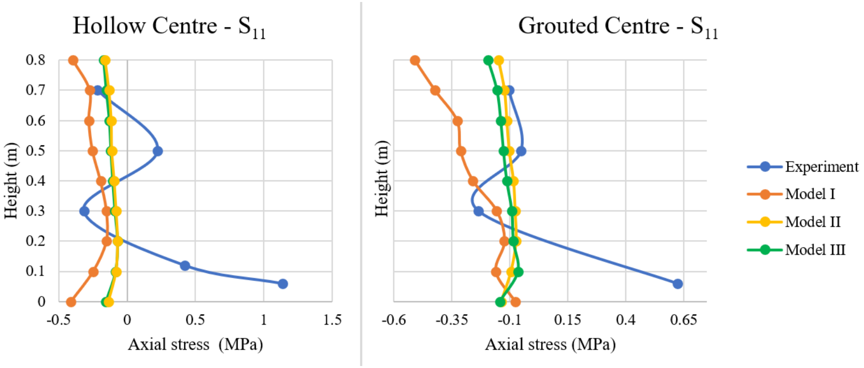

Figure 7: S11 plotted on hollow and grouted sides of intrados centre.

4 Conclusions and Contributions

Kurkulusuriya and Shrive [1] investigated a novel, flat masonry arch retaining wall system experimentally and found incredibly low experimentally measured stresses/deflections. However, they were unable to numerically replicate their experimental measurements, preventing them from presenting a general response of this structural system. In this work it was hypothesized that the experimental findings could be explained by a loss of fixity at the abutments. A 3D finite-element micro-model was developed to investigate the influence fixity loss would have had on the wall's response. After verifying the model against a theoretical thick cylinder analysis, the grouted abutment was changed from being perfectly bonded to frictional; this definition of abutment restraint ultimately reproduced the trend of experimental displacement measurements. The numerical model with the identified experimental boundary conditions was then used to investigate the accuracy of strain gauge readings; hollow-side strain gauges at the centre of the wall's intrados were found to be particularly inaccurate.

Much further work can be based on the presented results. Rationally explaining the experimental observations and the development of a verified numerical model for this system permit a more useful discussion of the system's structural qualities. This model will be used to conduct a parametric study of the various factors influencing the behaviour of this system (relative geometry, boundary conditions, material strength). Such a parametric study will provide guidance on development of design criteria and encourage increased uptake of this efficient and creative structural system.

Acknowledgements

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References

[1] M.C. Kurukulasuriya, N.G. Shrive, “Flat Arch Masonry Retaining Wall”, Journal of the International Masonry Society, 33(3), 64-74, 2021.

[2] P.B. Lourenco, “Computations on Historic Masonry Structures”, Progress in Structural Engineering and Materials, 4 (3), 301-319, 2002. doi:10.1002/pse.120

[3] A. Ahmed, G. Iskander, M. Bogoslavov, A. Isfeld, N.G. Shrive, “Examining the Mode of Failure of Slender Concrete Block Walls”, in Proceedings of the 14th Canadian Masonry Symposium, Montreal, Canada, 2021.

[4] M.C. Kurukulasuriya, “Flat Arch Masonry Retaining Wall”, MSc thesis, The University of Calgary, 2020.