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Numerical Investigation of the 3D Response of Masonry Skew Arches and Bridges

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Abstract

This paper investigates the behaviour up to collapse of brick-masonry skew arches and bridges using detailed mesoscale models. The adopted 3D modelling approach is based on an explicit representation of masonry bond employing separate descriptions for units and mortar joints, where material nonlinearity is accounted for using nonlinear interface elements. Computational efficiency is improved with the adoption of domain partitioning, where the analysed structure is decomposed into sub-domains that communicate at the partition boundaries enabling parallel computation. Numerical simulations have been performed on a range of realistic structures with the aim of identifying key behavioural characteristics leading to the development of a profound understanding of the complex 3D behaviour of masonry skew arches. This will eventually result in a realistic evaluation of the actual condition of existing masonry skew bridges, leading to an effective implementation of potential strengthening measures. Moreover, it can also contribute to the development of simplified practical analysis tools for the assessment of these complex structures.

Keywords: nonlinear analysis, 3D mesoscale modelling, masonry skew arches, masonry arch bridges.

1 Introduction

Masonry arch bridges represent a major portion of the UK's infrastructure for both railway and roadway traffic. In view of their deterioration, a significant amount of both experimental and numerical research has been carried out to date to improve

understanding of their complex behaviour. However, most of past research was directed towards the investigation of square bridges ignoring skew bridges.

Limited experimental research on skew arches [1] and bridges [2] revealed the development of complex 3D response and collapse mechanisms. To capture such complicated behaviour, 3D modelling approaches have been developed in recent years. Milani and Lourenço [3] developed a macro-scale homogenised strategy for 3D nonlinear analysis of skew arches and bridges. Papa et al. [4] put forward a 3D adaptive limit analysis procedure which can be used to predict the ultimate behaviour of skew arches also interacting with backfill. Zhang et al. [5, 6] adopted a 3D mesoscale modelling strategy [7] to perform extensive parametric studies on the behaviour of brickwork skew arches. The Discrete Element Method has been also used to develop 3D models to investigate the influence of skew angle [8] and construction method [9] on the performance of skew arches. A subsequent study [10] extended 3D discrete element models for skew arches including also the contribution of backfill materials.

These previous numerical investigations have highlighted the significance of two aspects regarding the modelling of skew arch bridges. Firstly, a discrete 3D modelling approach should be adopted for masonry to allow for the actual masonry bond. Secondly, due consideration should be given to the 3D modelling of the different bridge components and the realistic representation of their interaction. Both aspects are addressed in this paper as outlined in the following section.

2 Methods

To understand the complex 3D behaviour of masonry skew arch bridges, 3D analysis tools that can capture cracks and plastic deformations within the structure up to collapse are required. This can be achieved by accounting for the nonlinear behaviour of different bridge components, as well as their mutual interaction. In this paper, the 3D mesoscale approach developed by Macorini and Izzuddin [7] is used for the masonry components of masonry bridges. This approach uses 3D elastic solid elements to model masonry units and 2D zero-thickness nonlinear interface elements to model both mortar joints and potential fracture planes within bricks. More specifically, material nonlinearity in masonry is lumped within the interfaces using the cohesive-frictional material model developed by Minga et al. [11], whereas geometric nonlinearity is considered using a co-rotational approach for interface elements and using green strains for solid elements. Backfill is represented by adopting a continuous elastoplastic approach based on a modified Drucker-Prager yield criterion as described by Zhang et al. [12]. These two approaches are implemented within the nonlinear finite element program ADAPTIC [13].

Interaction between different bridge components is achieved using nonlinear interface elements at the physical interfaces between their domains, allowing for interfacial plastic separations and sliding. A mesh tying approach based on the mortar method, as outlined in Minga et al. [14], is adopted to allow for the connectivity

between non-conforming meshes at the physical interfaces between the arch barrel, backfill, and spandrel walls.

The adopted modelling strategy for skew arch bridges results in computationally demanding numerical models. This challenge is tackled by using a domain partitioning approach [15], where the bridge is divided into smaller partitions. Each partition can be analysed separately using an independent processor which allows for parallel computing, resulting in a significant improvement in the computational efficiency.

The skew arches investigated within this paper are constructed based on the helicoidal (English) method, which is the most widely used construction method for skew arches in the UK. It is suitable for brickwork masonry due to the use of uniformly sized masonry units. The FE mesh for these arches is constructed using the aforementioned mesoscale modelling approach according to the geometric principles provided by Buck [16], making use of the mesoscale approach capability to model the actual masonry bond as shown in Figure 1.

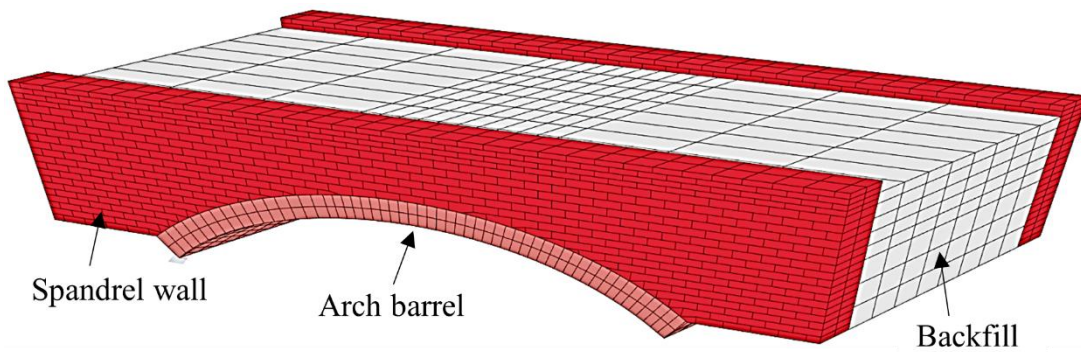
3 Results

Although skew arch bridges comprise several components, the arch barrel can be regarded as the main structural element. Therefore, the behaviour of the arch barrel is investigated first in this paper to understand the parameters governing its behaviour. To prove the ability of the adopted mesoscale approach to simulate skew arches, two experimental tests are considered. Firstly, a mesoscale model is validated against “Arch 3-2”, tested by Hodgson [2], which is a 45° skew arch with a span of 3000mm and width of 2510mm. The arch is composed of two rings, constructed using stretcher bond, with a thickness of 215mm. The specimen was tested up to collapse under a monotonic line load applied at 700mm offset from the south abutment. The developed 3D model enables an accurate prediction of the experimental crack pattern, as outlined in Figure 2 showing the contours of plastic work in tension in the interface elements of the mesoscale mesh. Moreover, the deformed shape of the model at failure, shown in Figure 3, agrees well with the experimental collapse mechanism, where both saw-toothed cracking and ring separation can be observed as reported in the experiment.

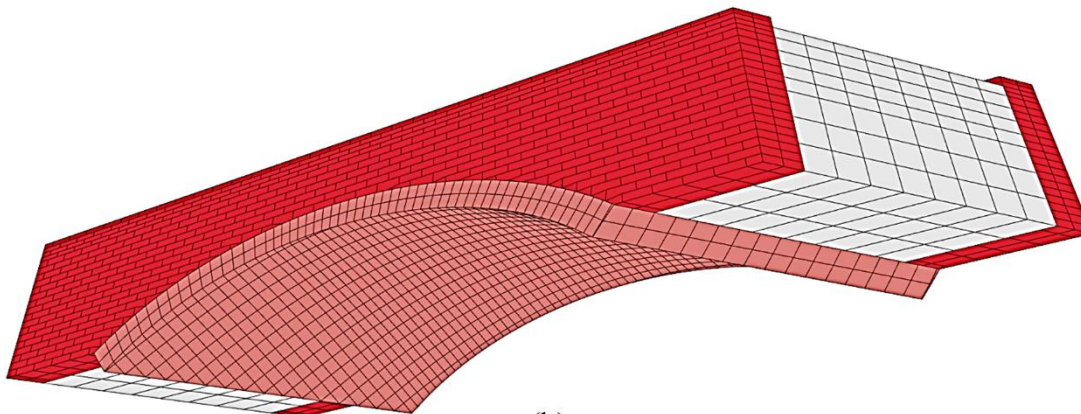
The second validation model is based on specimen “Skew2” tested by Wang [1]. This arch has the same characteristics of “Arch 3-2” except for having a width of 670mm, as well as having headers bonding. In this case, a concentrated load is applied at the arch mid-width at three-quarter span. Also in this case, the developed model captures the experimental five-hinge failure mechanism, as shown in Figure 4(a). Moreover, a good agreement is achieved between both the experimental and numerical load-displacement curves in terms of both strength and stiffness. This validated numerical model for specimen “Skew2” is then considered as a control specimen within a parametric study on skew arches to extend the understanding of their complex behaviour. The investigated parameters include different loading scenarios by varying either the configuration, the position, or the eccentricity of the applied loads. Moreover, geometric characteristics such as the arch width and rise-to-

span ratio have been investigated. Subsequently, the effect of masonry bond pattern on the skew arches' behaviour has also been explored.

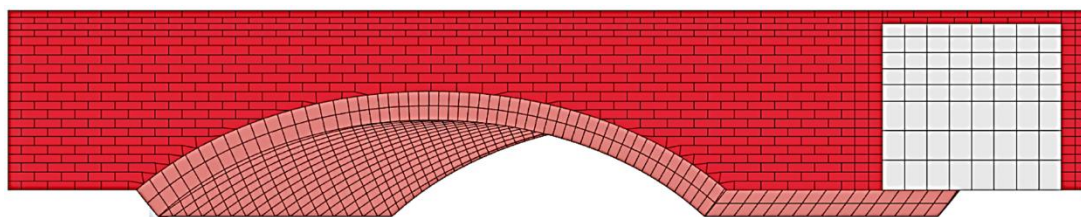
Finally, the skew arch models have been extended, as outlined in Figure 1, to include spandrel walls and backfill. Thereafter, a mesoscale model for “Bridge 3-3” tested by Hodgson [2] is used for validation, where further investigations on masonry skew bridges will be performed in future research to further explore their complex 3D behaviour.



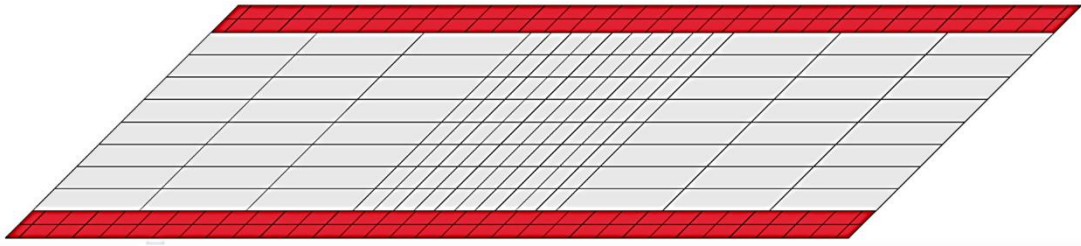
(a)



(b)

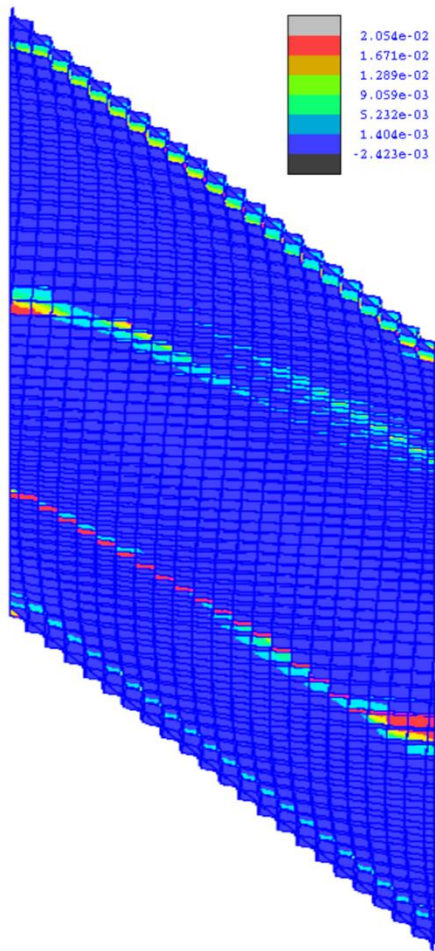


(c)

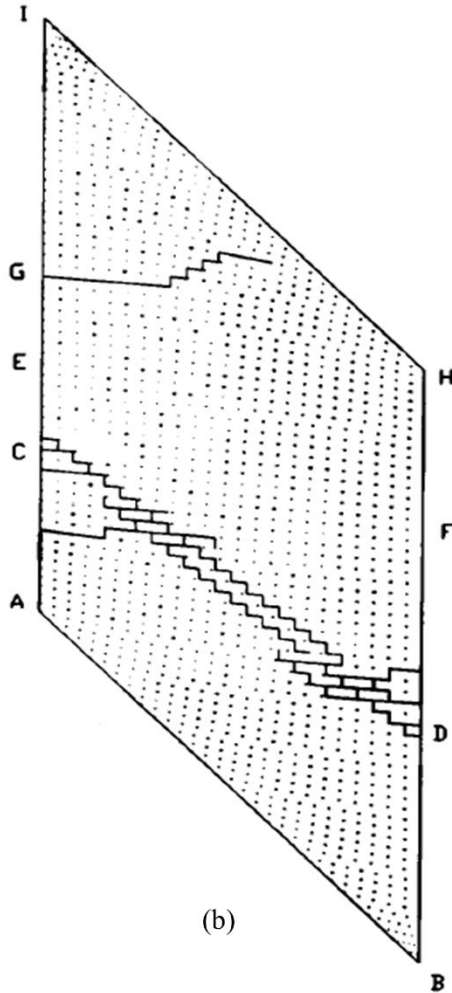


(d)

Figure 1: 3D Mesoscale representation for a skew masonry arch bridge, comprising arch barrel, backfill, and spandrel walls: (a) 3D top view; (b) 3D bottom view; (c) Front view; (d) Plan view



(a)



(b)

Figure 2: (a) Contours of plastic work developed in the interface elements due to tension W_{cr1} ; (b) Experimental crack pattern on the intrados of "Arch 3-2" [2]

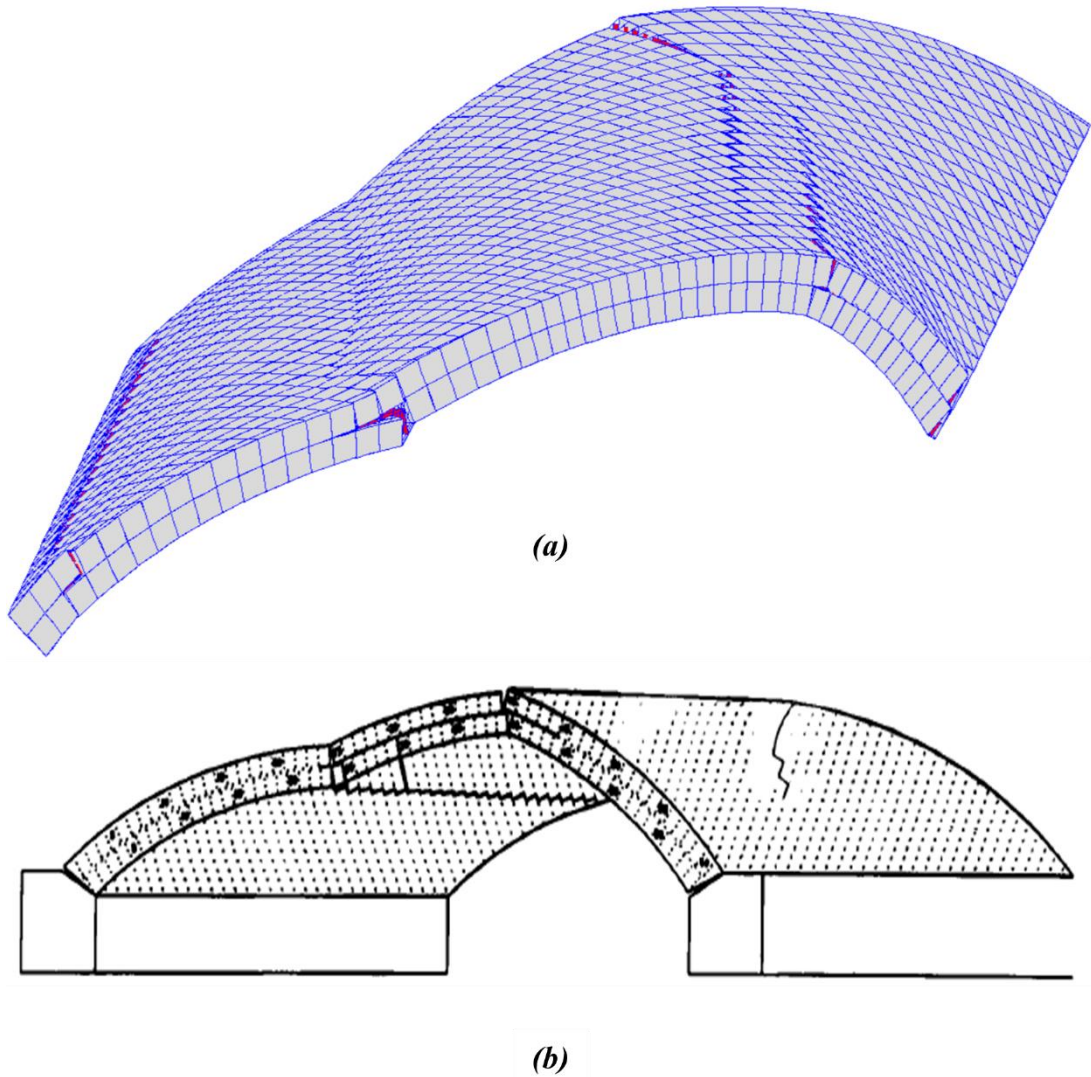


Figure 3: (a) Deformed shape at failure for the mesoscale numerical model of “Arch 3-2”; (b) Collapse mechanism of “Arch 3-2” [2]

4 Conclusions and Contributions

The parametric study has outlined some of the key characteristics of the response of masonry skew arches. Regarding the effect of load configuration, it was found that the load-displacement response under concentric patch loads and line loads is very similar in shape. However, the capacity of the arch under line loads is slightly less than that under patch loads. This can be related to the fact that the cracking pattern is more predetermined in the case of line loads compared to the case of patch loads. This observation has been shown to be valid for the different loading positions along the arch span, where consideration has been given to loads applied at mid, quarter, third, and eighth of the arch span. The study has shown that the most critical position is at quarter-span, whereas the least critical position is at mid-span. This observation agrees with the experimental observations reported in the literature (e.g. [1]). Since the

control specimen in this study has a small width, the effect of load eccentricity on the load capacity was unclear. The response under a concentric load or an eccentric load on either side was almost similar. However, this should not be the case for wider skew arches, where the effect of load eccentricity is expected to be more significant.

In terms of geometric considerations, the influence of different rise-to-span ratios (1:2, 1:4, and 1:8) on the load capacity has been considered first, as outlined in Figure 4. The results have shown that shallow arches have the highest load capacity, whereas deep arches have the lowest load capacity. Secondly, the influence of the arch width under a concentric loading at quarter-span has been explored by considering two additional arches of widths 1500mm and 3000mm, as outlined in Figure 5. The influence of the bond pattern and the defects in the circumferential mortar joints have also been studied. It has been found that the response of both stretcher and header bonds with strong circumferential joints is almost the same as that of soldier bond. Furthermore, the response of the header bond with weak circumferential joints is very close to that with strong joints. Unlike the header bond, the stretcher bond response varies significantly between the two cases of strong and weak joints.

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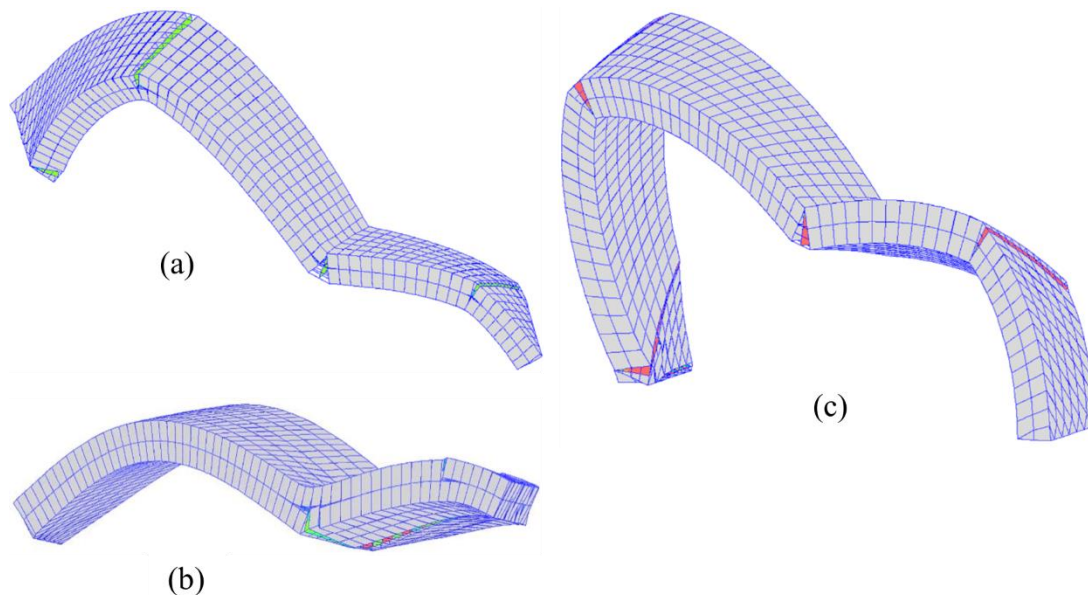


Figure 4: The influence of arch rise-to-span ratio on the behaviour of skew arches: (a) Rise-to-span ratio 1:4; (b) Rise-to-span ratio 1:8; (c) Rise-to-span ratio 1:2

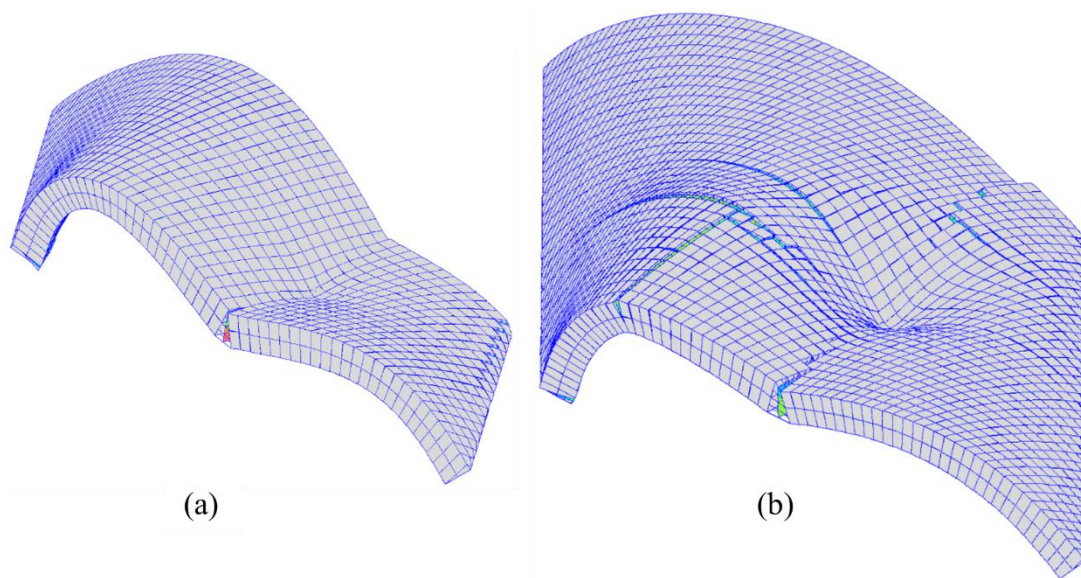


Figure 5: The influence of arch width on the behaviour of skew arches: (a) 1500mm width arch; (b) 3000mm width arch

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