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Parametric Nonlinear Modelling of 3D Masonry Arch Bridges

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Abstract

Detailed modelling of masonry arch bridges presents unique computational challenges. Not only do such structures exhibit complex nonlinear behaviour, but they are also difficult to describe within a consistent 3D computational framework for high-fidelity simulations, due to the range of interactive components with varying geometric characteristics. This paper presents a novel parametric model design tool for the generation of detailed 3D FE meshes of realistic masonry viaducts. This tool has been developed according to a modular description as an add-on component within the Rhino – Grasshopper environment. The tool allows for modular complex bridge assemblages with independent definition of the key viaduct parts, including arch barrels, spandrel walls, piers as well as multi-layered fill. Moreover, new components (e.g. skewed arches, end-walls, abutments, complex geometry pier-variants) can be seamlessly introduced into the framework due to its modular nature. Notably, as all components are geometrically addressable, it is possible to further enhance the model generation tool by adding non-standard routines to create more complex geometry than that allowed by current parametric definitions (e.g. arch barrel and spandrel wall with varying thickness, piers with circular segments). The developed strategy enables also variable fidelity model generation, where different segments of the analysed viaduct can be represented by meso- and/or macro-scale masonry descriptions at different levels of detail. This approach further allows for consideration of initial damage in the brick/blockwork, which is a very common feature of many existing masonry bridges.

Keywords: masonry arch bridges; parametric modelling; Rhino-Grasshopper

1 Introduction

The advent of the 18th and 19th century industrial revolution and the subsequent economic growth promoted large scale construction of masonry viaducts in the UK and around Europe which are still in use at present. The age of these structures associated with the deterioration of the original masonry materials requires accurate assessment of their performance under ever increasing traffic loading.

Detailed modelling of masonry arch bridges presents unique computational challenges. Not only do such structures exhibit complex nonlinear behaviour, but they are also difficult to describe within a consistent 3D computational framework for high-fidelity simulations, due to the range of interactive components with varying geometric characteristics.

Some preliminary work on the utilisation of generative algorithms to create detailed parametric masonry models were presented in [1], where curved masonry walls were tiled in an automatic fashion trying to account for manufacturing constraints. Further refinement was presented by Cascini et al. [2] within the LiABlock_3D software designed for limit equilibrium analysis of masonry structures. A further refinement to the above method was put forward by Savalle et al. [3] utilising the parametric nature of Grasshopper for Rhino to automatically construct block assemblages.

This paper presents a novel parametric design tool for the generation of detailed 3D FE meshes for realistic masonry viaducts. This tool has been developed in accordance with a modular description as an add-on component within the Rhino – Grasshopper environment [4].

2 Methods

The proposed modelling strategy capitalises on prior work undertaken by the authors [5], where 3D nonlinear simulations were conducted using meso- and macro-scale masonry models implemented in ADAPTIC [6] to investigate the response up to collapse of a representative single span masonry bridge specimen.

In the macroscale modelling strategy (Figure 1), the masonry components of a viaduct are modelled using continuum 3D solid elements, the size of which is independent from the dimensions of units and mortar joints leading to computationally efficient 3D models. In general, while the reduction of the modelled material to a single constituent guarantees computational benefits, it requires calibration of the material parameters based upon physical experiments on large components, or the use of homogenisation techniques and the results from material tests on masonry constituents (e.g. bricks and mortar joints).

In the mesoscale description for masonry (Figure 2), on the other hand, the masonry material is modelled based on separate representations for brick units and mortar joints. More specifically, as elaborated in [7], elastic quadratic solid elements are used to describe units, and nonlinear quadratic interface elements to represent mortar joints and potential fracture surfaces within bricks. The material description for nonlinear interfaces employs a cohesive-frictional constitutive model [8], providing computationally robust solutions of the local nonlinear problem. A multi-surface yield criterion in the stress domain is adopted, while the degradation of strength and stiffness is captured through the evolution of an anisotropic damage tensor which is coupled with the plastic work.

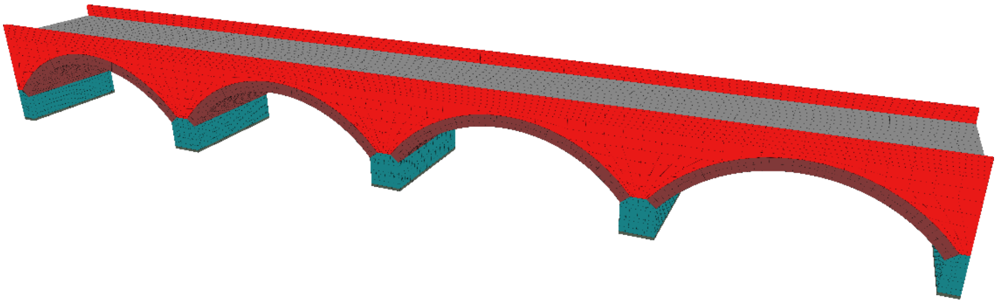

Figure 1. Macroscale model for a four-span segment of Foal Mead viaduct

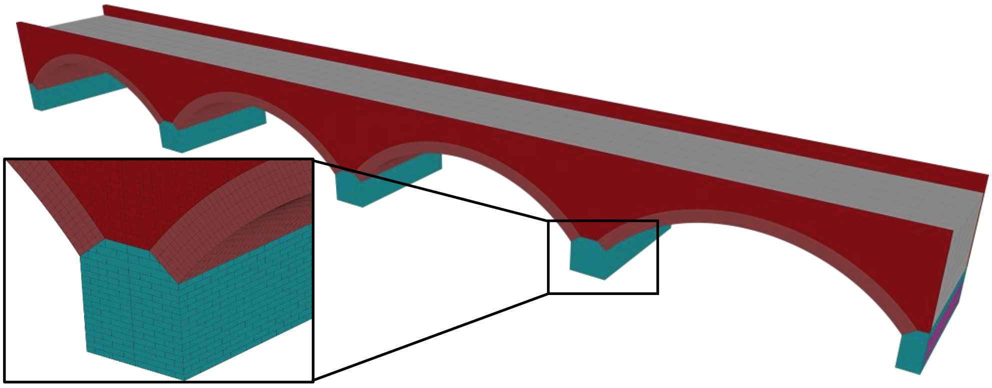

Figure 2. Mesoscale model for a four-span viaduct segment

To facilitate the devised generative algorithm in handling both model types simultaneously, a mesh tying strategy [9] based on the mortar method is employed. At the physical interfaces between the bridge components (e.g. arch, lateral walls and backfill), master and slave surfaces (Figure 3) are defined, where the slave surfaces are associated with the coarser mesh (backfill domain) which is typically connected to the adjacent finer mesh, representing a different (masonry) part of the bridge, by nonlinear interfaces to model potential sliding and separation at the physical interface.

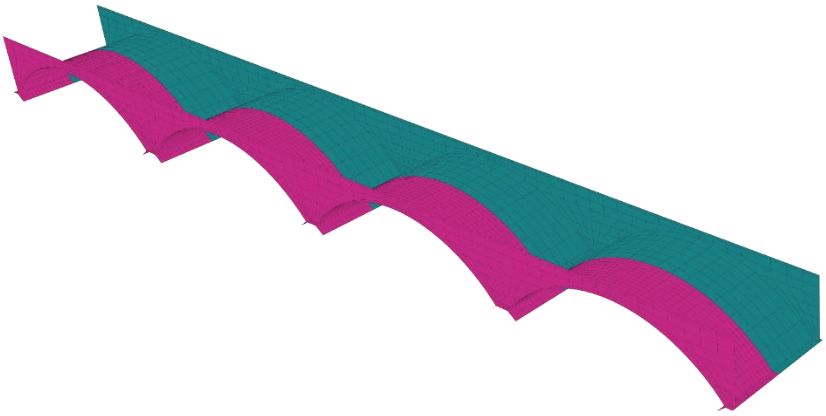

Figure 3. Master (cyan colour) and slave (magenta colour) surfaces for the mesh tying algorithm

3 Results

In order to effectively model different arch bridges parametrically, each structural and non-structural part is treated as an independent entity that can be interfaced with. Currently, developed components include arch barrel (AB), backing/backfill (BKFL), spandrel wall (SW), and pier (PR). Each component can support both meso- and macro-scale models. Span construction as illustrated in Figure 4 is organized by sequentially attaching components together.

Any component except for the arch barrel can be removed from the generated span. The final bridge is constructed as a combination of several spans. Different components are in turn joined at the interfaces. Three connectivity strategies are allowed. If the interfaces of two adjacent components match perfectly, nodes at the boundary are merged (e.g. span-to-span interface of neighbouring backfill or pier sections). On the other hand, if potential separation between matching parts needs to be represented, a layer with nonlinear interfaces is generated between them (e.g. spandrel wall to backfill interface). The final option comes into play when there is no match between the mesh of adjoining components; in this case, the two parts are connected by mesh tying [9].

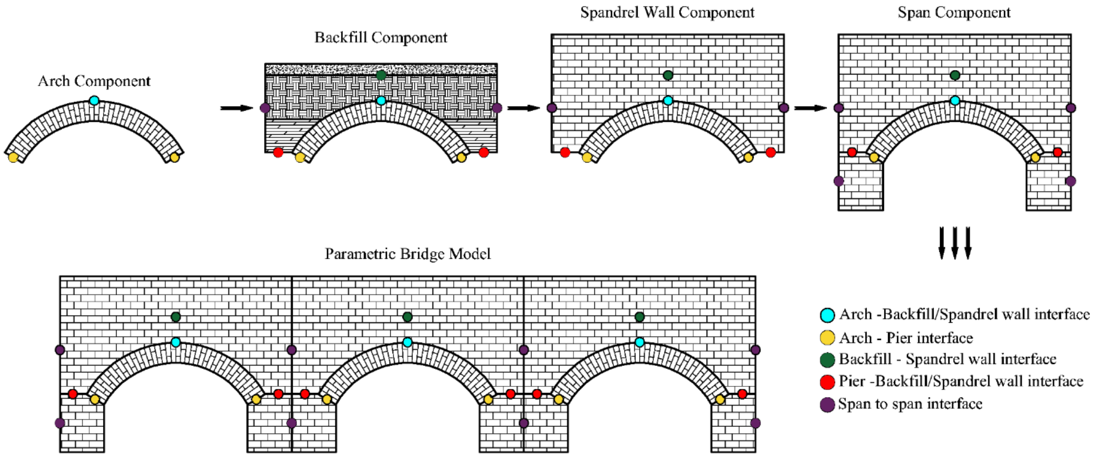

Figure 4. Modular design for the structural components

Detailed 3D modelling of large and complex structural systems such as realistic masonry viaducts can become impractical due to the large number of degrees of freedom (DOFs) associated with the model. To overcome such inherent drawback and improve computational efficiency, a domain decomposition approach earlier developed at Imperial College [10] is utilised.

According to this strategy, a large structure is divided into partitions (Figure 5), corresponding to subdomains of the original structure, and a “parent structure”, which is composed of dual super-elements. Each super-element consists of the boundary nodes of an individual partition and accounts for the two-way communication of the subdomain with the parent structure, which allows the parallelisation of the analysis. In previous research, this computational strategy was effectively used in mesoscale simulations of masonry components [11] including arches [12] and bridges [13], [14] leading to a significant reduction of the computing time.

A comprehensive investigation into the optimal partitioning have been carried out in the scope of the current work, where performance of different partitioning strategies (number and position of partitions) and hierarchies (multi-level partition network) have been compared for a typical masonry arch bridge application. The obtained results indicate that the midspan cross-section can serve as an optimal minimal bandwidth boundary for partitioning.

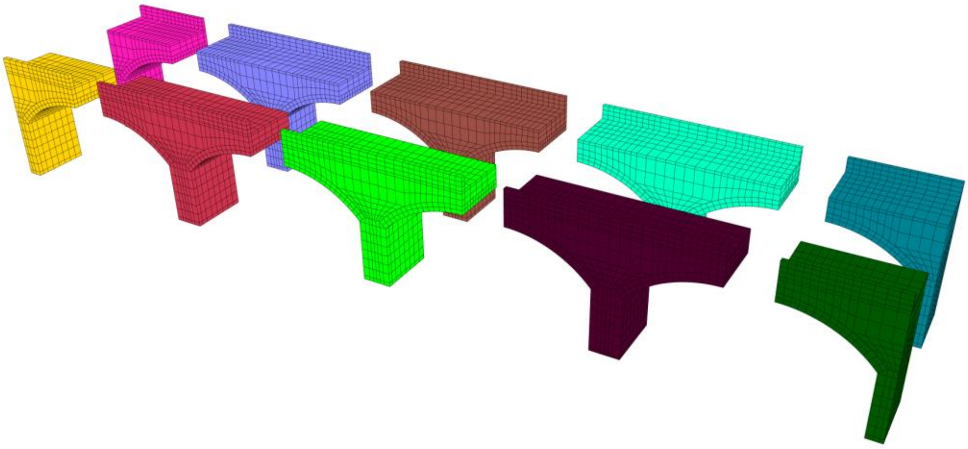

Figure 5. Possible partitioning strategy for a masonry viaduct

A further development has been aimed at reducing the computational burden when using mesoscale models for specific segments of a masonry viaduct. According to the proposed strategy, a small portion of a large viaduct corresponding to a single span or to an individual brick/block-masonry component (e.g. arch or spandrel wall) within a span is modelled using a detailed mesoscale description to capture local effects, while the rest of the structure is represented by an efficient macroscale model which significantly reduces the computational cost (Figure 6.a).

This new feature can be also adopted to take into account the effects of existing cracking in the brickwork (Figure 6.b-c). In this case, cracks are explicitly represented in a mesoscale mesh, where active nonlinear interfaces with negligible tensile strength and cohesion are introduced along the planes of cracking.

The described mixed strategy can be further enhanced in terms of computational efficiency by considering a coarse mesoscale mesh, where each individual element represents a composite assembly with different bricks and mortar joints. Recent developments by Panto et al. [15] have demonstrated the advantages of such an approach by reducing inaccuracies associated with more simplistic plasticity-based models.

4 Conclusions

This paper presents a novel software tool developed in Rhino – Grasshopper environment allowing for parametric generation of numerical FE models of masonry arch bridges both at meso- and macro-scale. The tool allows for modular definition of complex bridge assemblages with independent span definitions. It is based upon prior developments such as mesh-tying [9] and hierarchic partitioning [10], [16], where these techniques are seamlessly integrated into the parametric model generation.

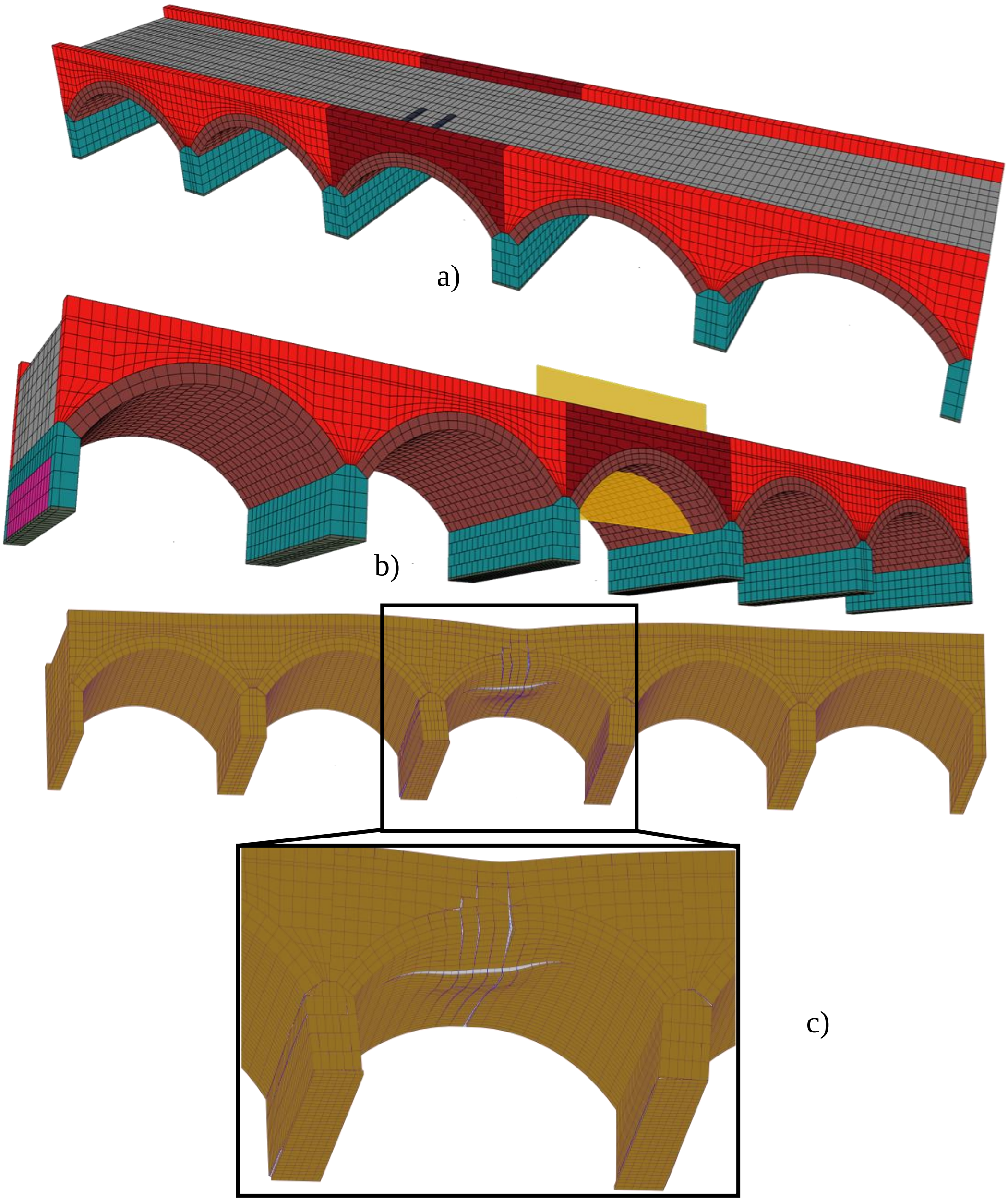

Figure 6. Damage application procedure a) Mixed relaxed FE model; b) Damage plane; c) Numerical results associated with pre-applied damage

New components allow for the parametric definition of arch barrels, spandrel walls, piers as well as multi-layered fill. Moreover, new components (e.g. skewed arches, end-walls, abutments, complex geometry pier-variants) can be seamlessly introduced into the framework, due to its modular nature.

This developed software component also allows for variable fidelity model generation, where different segments of the analysed structure can be easily switched between meso- and macro-scale models. This approach further enables the consideration of initial damage in the brick/block work of each masonry part of the analysed structure.

Future work includes extension of the components, a more detailed investigation of partitioning strategies to achieve automatic optimal subdivision as well as an in-depth investigation of the effects of pre-existing damage on the viaduct performance under different loading conditions.

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