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3D analysis of masonry arch bridges taking into account the spandrel walls

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1 INTRODUCTION

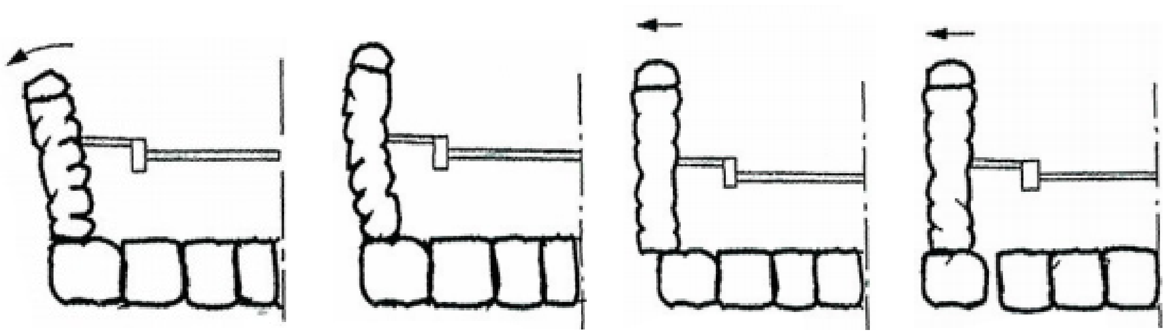
Significant portion of the European railway bridge stock is represented by masonry arch bridges even nowadays. Over the past century the axle loads and the train speeds have been continuously increased (Jensen 2008), while the structural elements of these bridges have been gone through severe deterioration (Brencich 2007). To determine the load bearing capacity of a masonry arch bridge, different techniques are used depending on the level of assessment (Jensen 2008). The simplified methods are typically empirical or based on the assumption of linear elastic structure (e.g., MEXE method). In the case of a detailed investigation, typically limit state analysis are used which are based on the principles of plasticity. In the case of special assessment, sophisticated methods based on Finite Element Method or Discrete Element Method (DEM) should be used.

The mechanical behavior of masonry arch bridges is extraordinary complex, characterized by nonlinearities due, e.g., to formation of cracks, to sliding of elements upon each other, to nonlinear behavior of the backfill. Complexity of the behavior is also caused by the interactions between the various structural components. For example, the backfill and the barrel interact with each other in multiple ways: the backfill means an extra self-weight load on the arch (causing an additional compression in the arch), it disperses the concentrated loads as they are transmitted to the barrel, but it also provides a passive earth pressure against the movement of the arch barrel. Various interactions are typical for the spandrel walls, which are in the main focus of this actual paper: spandrel walls may interact with the barrel, adding extra stiffness and load bearing capacity of the structure, but spandrel walls restrain the lateral movement of the backfill too. While certain phenomena can be reasonably studied by 2D models (such as barrel-backfill interactions), investigation of other phenomena requires 3D models (such as the behavior of spandrel walls).

The statistic research (Orbán 2004) showed that the occurrence of the structural problems connected to the spandrel walls is more common than the failure of the arch barrel caused by overloading. Still, until now researchers typically focused on the behavior of the arches and on the arch-soil interaction, while the behavior and mechanical role of the spandrel walls of the masonry bridges were less investigated. According to the visual inspection of bridge assessment engineers, the failure mechanisms of the spandrel walls can be grouped into four main group (Gibson 2014), as it can be seen in Figure 1.

While the tilting, bulging and sliding movements of the spandrel wall do not necessarily imply decrease in load bearing capacity and/or stiffness of the structure, the detachment of the spandrel wall (longitudinal crack of the arch barrel under the spandrel wall) causes the loss of structural integrity. In this case, the outer and the inner part of the bridge cannot work together. Recent guidelines (e.g., Jensen 2008) gives displacement and rotation limits to evaluate the condition of the spandrel walls.

The aim of this paper is to develop a numerical model able to capture the previously mentioned four failure mode of spandrel wall and able to demonstrate the beneficial role of the spandrel walls regarding the load bearing capacity and the structural stiffness of the masonry bridge.



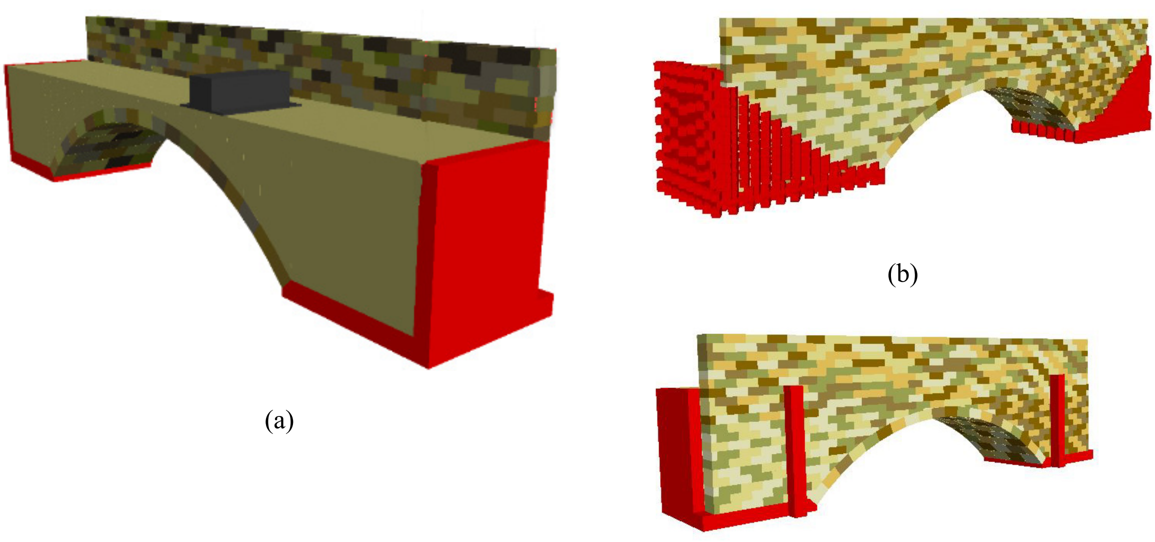
a) b) c) d)

Figure 1. Failure mechanisms of spandrel walls: tilting (a); bulging (b); sliding (c); detachment (d).

2 NUMERICAL MODEL DEVELOPMENT

In this work, the masonry arch bridge was analyzed with the help of a three-dimensional software, *3DEC 5.2* (Itasca 2016). Every stone of the arch barrel and the spandrel walls was represented by linear elastic discrete elements. The backfill appeared in the model as a single, deformable element, with Mohr-Coulomb failure criteria. The interface elements between the stone blocks and the backfill permit the interpenetration of the elements, while let the soil slide upon the stones. The ballast, the sleepers and other constructional elements were neglected in this study. The supporting effects of different type of wing walls were modelled with appropriate boundary conditions. The geometry of the developed model can be seen in Figure 2. Zero velocity boundary conditions in every direction was applied on the red elements in Figure 2.

The validation of the presented numerical model was done previously against the results of the experimental test made on Prestwood Bridge (UK) (see details (Forgács 2018)). During the parametric studies, the geometrical parameters of the arch barrel was chosen according to the geometry of Prestwood Bridge and was unchanged during the study. Various heights of backfill, and different spandrel wall thicknesses were analyzed and compared.



(a) (b) (c)

Figure 2. Geometry of the masonry arch bridge: (a) loading element at quarter span, wing walls parallel (b) and perpendicular (c) to the abutments.

At the beginning of each simulation only gravitational effects were applied and the structure was brought into equilibrium. After it, a displacement-controlled loading was started with a loading element at quarter span. The response of the structure was analyzed by load-displacement curves. Moreover, the lateral displacements of the spandrel at quarter span were recorded.

3 RESULTS AND DISCUSSION

All of the investigated bridges failed by the four-hinge mechanism of the arch barrel. As the loading was increased and the element pushed downward the backfill, the first crack appeared on the intrados right under the loading element. As the arch barrel swayed, the passive earth pressure started to mobilize on the other side of the structure. Meanwhile the vertically compressed soil layers compelled to move laterally, and it pushed the spandrel wall outwards. Comparing the differences between parallel and perpendicular wing walls it was observed that lateral displacement of the spandrel walls was smaller in the case of wing walls parallel to the abutments. In accordance with this, the load bearing capacity of the parallel wing wall models were typically ~5-10% greater. During the loading procedure, it was evident that the spandrel wall slid upon the arch barrel, and this movement was combined with a small forward rotation. As the thickness of the spandrel wall was increased the load bearing capacity increased in direct ratio. So far, mortar was not applied between the elements of the spandrel wall (dry-stacked wall). Finally, it was analyzed how the behavior changed if mortar was applied within the spandrel wall elements. In this case, the stiffness of the spandrel wall increased, while the structure failed with spandrel wall detachment. The phenomena can be explained as follows: with the use of mortar, differences in stiffness between the softer inner and the stiffer outer part of the bridge was increased. While the stiff spandrel wall was not able to deform, the softer inner part was not able to transmit the load to the spandrel walls, resulted in the detachment of the spandrel (longitudinal crack appeared at the pre-cut surface). After the detachment, the load bearing capacity can be calculated with reduced bridge width.

4 CONCLUSIONS

In the presented work a three-dimensional, discrete element numerical model was developed to analyze the interaction between the arch barrel, the backfill and the spandrel walls of a railway masonry arch bridge. The model was previously validated against the experimental test of Prestwood Bridge (UK). The results of the model can be summarized as follows:

- The model gives back those failure mechanisms of spandrel walls, which were observed and documented (Gibson 2012) earlier by bridge inspection engineers.
- Wing walls perpendicular to the abutments permit smaller lateral displacements of the spandrel walls compared to wing walls parallel to the abutments.
- The load bearing capacity of the masonry arch bridge is increasing with wider spandrel walls, and with the increase of the ratio of the spandrel wall/backfill's height ratio.
- On the other hand, as the relative stiffness of inner and outer part of the bridge is increasing, the occurrence of the spandrel wall detachment is increasing as well.

It is obvious that the occurrence of the wall detachment depends on the laying pattern of the elements, on the size of the voussoirs, and on the strength parameters of both the mortar layer and the voussoirs. These effects should be investigated in detail in the future.

REFERENCES

Brencich, A. & Morbiducci, R. 2007. Masonry Arches: Historical Rules and Modern Mechanics. *International Journal of Architectural Heritage*. 1:165-89.

Forgacs, T., Sarhosis, V. & Ádány, S. 2018. Discrete Element Modeling of skew masonry arch bridges taking into account arch ring-backfill interaction. *In: Milani G, Taliercio A, Garrity S, editors. 10th International Masonry Conference. Milan, Italy*.

Gibson, D.S. & Wilkins, A.G. 2012. Spandrel Walls - Managing the Risks. Mott MacDonald, Network Rail.

Itasca Consulting Group, Inc. 2016. *3DEC – Three-Dimensional Distinct Element Code, Ver. 5.2 Theory and Background Manual*. Minneapolis: Itasca.

Jensen, J.S., Casas, J.R., Karoumi, R., Plos, M., Cremona, C. & Melbourne, C. 2008. Guideline for load and resistance assessment of existing European railway bridges. *Fourth International Conference on Bridge Maintenance, Safety and Management (IABMAS 08). France*. p. pp 3658-65.

Orbán, Z. 2004. Assessment, reliability and maintenance of masonry arch railway bridges in Europe. *In: P. Roca CM, editor. ARCH 04: 4th International Conference on Arch Bridges. Barcelona, Spain*. p. 152-61.

Van der Pluijm, R. 1999. *Out-of-plane bending of masonry: behaviour and strength*. Doctoral thesis, TU Delft, Delft University of Technology, Technische Universiteit Eindhoven.