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Mechanical role of spandrel walls on the capacity of masonry arch bridges

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Abstract. In the presented work the mechanical behavior of a masonry arch bridge of a single-track railway is analyzed numerically. The 3D discrete element model contains the arch barrel, the backfill and the spandrel walls as well. Every voussoir is represented by a discrete element, while the backfill is modelled as an elasto-plastic continuum. Between the elements zero-thickness nonlinear interfaces can be found where mechanical interaction can take place. Static analysis has been carried out to investigate the effects of spandrel walls on load bearing capacity and structural stiffness. Failure modes of spandrels due to the excessive lateral displacement of the backfill are identified.

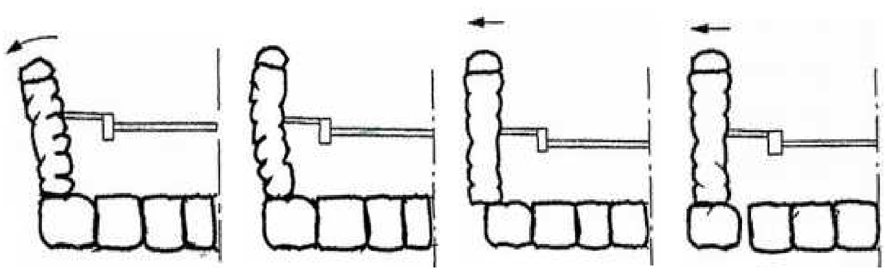
Keywords: masonry arch bridge, discrete element method, spandrel wall.

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 [1], while the structural elements of these bridges have been gone through severe deterioration [2]. Compared to the later developed bridge-construction techniques, the mechanical behaviour of the masonry arch bridges is not well understood. To determine the load bearing capacity of a masonry arch bridge, different techniques are used depending on the level of assessment [1]. The simplified methods are typically empirical or based on the assumption of linear elastic structure (e.g MEXE method). Detailed investigations require the use of rigid-block methods which 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 behaviour 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 phenomenas require 3D models (such as the behavior of spandrel walls).

The statistic research of Orbán [3] 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 engineers and 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 [4], as it can be seen in Fig. 1.:



a.) b.) c.) d.)

Fig. 1. Failure mechanisms of spandrel walls [4]: tilting (a.); bulging (b.); sliding (c.); spandrel wall detachment (d.)

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 [1]) 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.

2 Discrete Element method

In this work, the masonry arch bridge was analyzed with the help of a three-dimensional software (3DEC) [5] based on the discrete element method. The structural elements of the bridge (voussoirs of the arch barrel, elements of spandrel walls, backfill, etc.) were represented by polyhedral shape discrete elements. Between the discrete blocks zero-thickness interfaces (contacts) can be found, where mechanical interaction can take place. The contacts are elastic: forces are calculated with the help of relative displacements between the adjacent elements. Unrealistic interpenetration of elements can be avoided with high contact normal stiffness. The mechanical behaviour of a contact can be seen in Fig. 2.

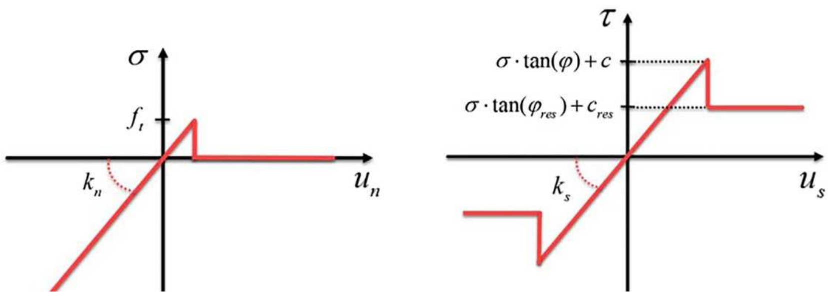


Fig. 2. – Mechanical behaviour of the contact: normal (left) and tangential direction (right)

Static problems are solved with the explicit time integration of Newtonian equation of motion, where artificial damping forces are introduced to get rid of the oscillations of the elastic system. Stable solution requires adequately small time-steps, which are automatically calculated according to the material and geometrical properties of the model. To ensure the deformability of the discrete elements, every element is sub-divided into tetrahedral finite elements. Beside the simplest linear elastic material model, numerous elasto-plastic constitutive law is implemented in the software.

3 Numerical model development

In the presented work a masonry arch bridge of a single-track railway was considered. The geometry of the analyzed bridge was presented in Fig. 3. Only the half of the structure was modelled in order to decrease the computational costs. Every stone of the arch barrel and the spandrel walls was represented by linear elastic discrete elements, while the presence of the mortar could be taken into consideration with zero-thickness interface elements. In this way the developed model belongs to the group of simplified macro-models. 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.

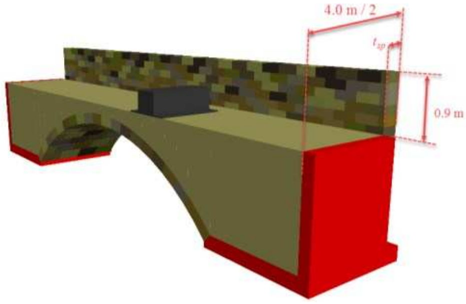


Fig. 3. Geometry of the masonry arch bridge

The validation of the presented numerical model was done previously against the results of the experimental test made on Prestwood Bridge (UK) (see details in [6]). During the parametric studies, the geometrical parameters of the arch barrel (Table 1.) 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.

Table 1. Geometrical properties of the arch barrel

Span s	**Rise** r	**Barrel thickness** t	**Number of courses** n_{block}	**Width of the arch** w	**Height of the backfill** $h_{backfill}$
6.550 m	1.428 m	0.220 m	20	4.00 m	[0.2; 0.6]m

The possibility of spandrel wall detachment was taken into consideration in a simplified manner. It is known, that during the detachment a longitudinal crack of the arch barrel appears under the spandrel wall. The crack can follow the laying pattern of the voussoirs (zig-zag pattern), or it can break through even the voussoirs as well. In the applied numerical technique, the voussoirs cannot break. Hence, the arch barrel was "pre-cut" with a vertical surface at the inner side of the spandrel wall. Material properties of mortar was assigned to this artificial surface. This assumption is on the safe side: if the detachment follows the laying pattern of the voussoirs in reality, then the surface of the sheared/cracked surface must be greater than the pre-cut surface of the numerical model. If the developing cracks follows a "straight line", the voussoirs have to break as well, while the pre-cut surface of the numerical model has the weaker properties of the mortar layer.The voussoirs and the elements of the spandrel walls were modelled with linear elastic material (Table 2.).

Table 2. Material properties of the stone elements

	Density	**Young's modulus**	**Poisson ratio**
Voussoirs and elements of the spandrel wall	2000 kg/m^3	15 GPa	0.3

The elastic and the Mohr-Coulumb parameters of the backfill material can be found in Table 3. Normal and shear stiffness were considered as a numerical parameter (to prevent element interpenetration), values were set to 35 GPa/m and 7 GPa/m (normal and shear direction, respectively). The friction angles and the parameters of mortar were obtained from literature [7] (Table 4.).

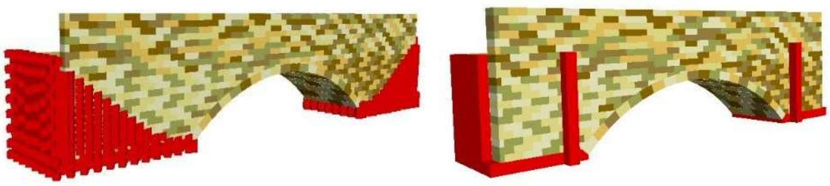
Table 3. Material properties of the backfill

	Density ρ	Young's Modulus E	Poisson ratio ν	Frictio-nal angle φ	Co-hesion c	Tensile strength f_t
Cohesive soil	2000 kg/m^3	300 MPa	0.3	37°	10 kPa	10 kPa

Table 4. Material properties of the interfaces

	Frictional angle φ	Cohesion c	Tensile strenght f_t
Voussoir-to-voussoir	30°	-	-
Voussoir-to-backfill	25°	-	-
Mortar (1:2:9)	38°	0.7 MPa	0.4 MPa

The supporting effects of different type of wing walls were modelled with appropriate boundary conditions: the red elements in Fig. 4 do not allow the lateral movement of spandrel wall.



a.) b.)

Fig. 4. Boundary conditions to different wing walls: a.) perpendicular to the abutment, b.) parallel to the abutment

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 (loading velocity: 2.5mm/s). The response of the structure was analyzed by load-displacement curves. Moreover, the lateral displacements of the spandrel at quarter span were recorded.

4 Results and discussion

All of the investigated bridges failed by the four-hinge mechanism of the arch barrel (Fig. 5). 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.

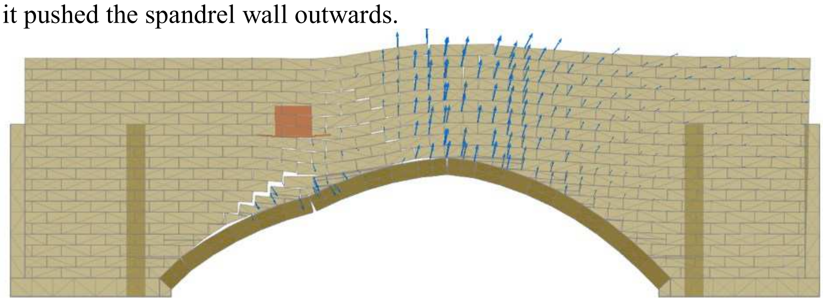
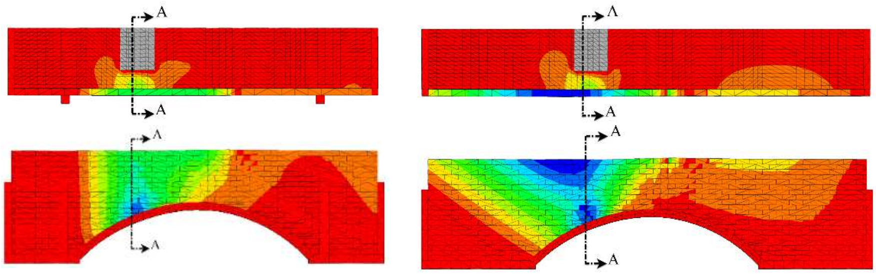


Fig. 5. Typical failure mechanism of the masonry bridge

Comparing the differences between parallel and perpendicular wing walls (Fig. 6) it can be seen that lateral displacement of the spandrel walls is 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 (Fig. 7a).



a.) b.)

Fig. 6. Lateral displacements of masonry arch bridges, wing wall parallel to the abutment (left), wing wall perpendicular to the abutment (right) (blue means the larger displacements)

Fig. 7b shows the distorted shape of spandrel wall. It is evident that the spandrel wall slided upon the arch barrel, and this movement was combined with a small forward rotation. Fig. 8. compares the load bearing capacity at different spandrel wall thickness: as the wall thickness increases the load bearing capacity increases in direct ratio.

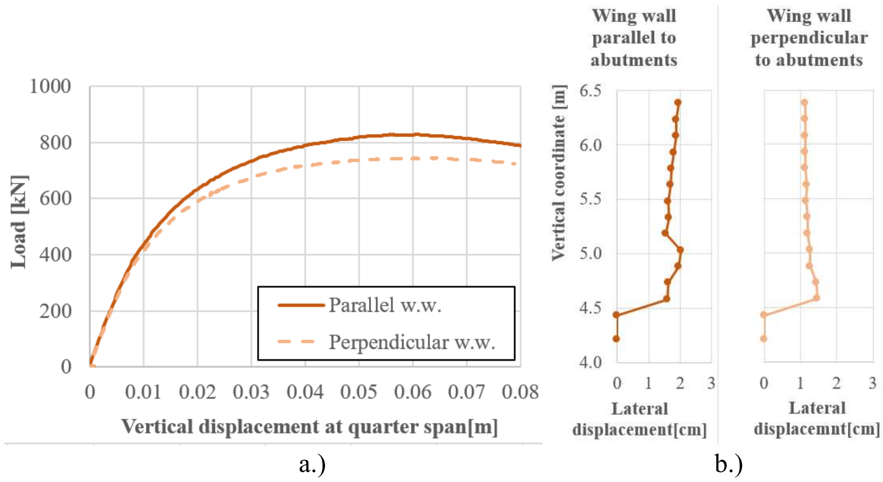


Fig. 7. Load-displacement curve of the bridge (left) and lateral displacements of the perpendicular and the parallel spandrel walls

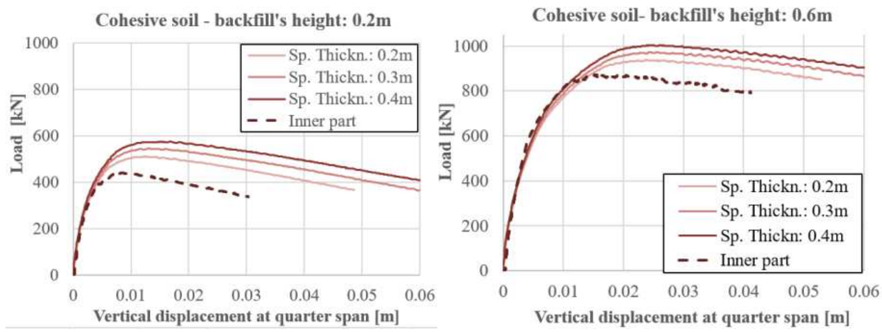


Fig. 8. – Effect of different spandrel wall thickness and backfill height

So far, mortar was not applied between the elements of the spandrel wall (dry-stacked wall). Finally, it was analyzed how the behaviour was changed if mortar was applied within the spandrel wall elements. Contrary to all expectations the load bearing capacity dropped down in this simulation (Fig. 9.). The phenomena can be explained as follows: with the use of mortar, differences in stiffness between the inner and outer part of the bridge is 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 the reduced bridge width.

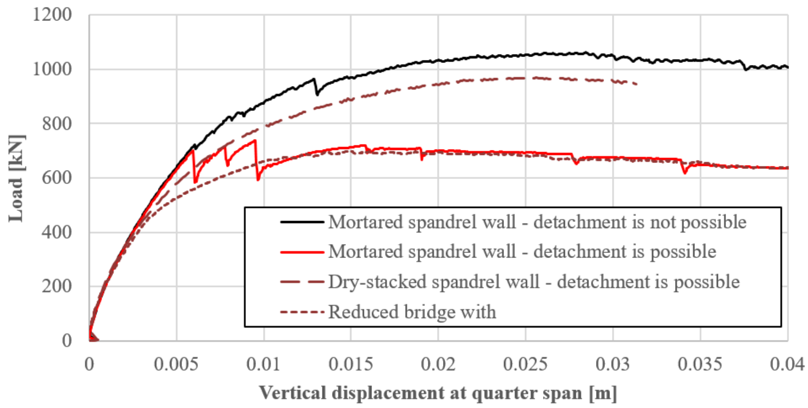


Fig. 9. Detachment of the spandrel walls

5 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 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 [4] 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 both of the mortar layer and the voussoirs. These effects should be investigated in detail in the future.

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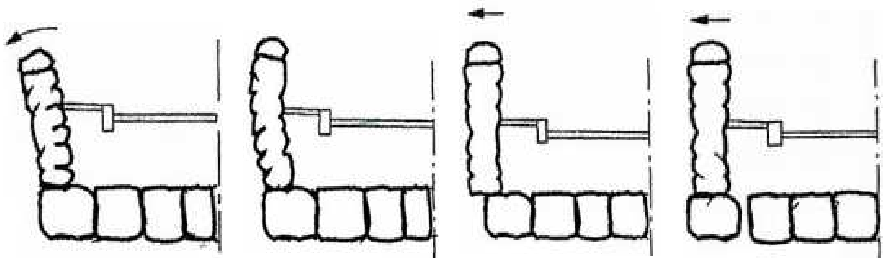

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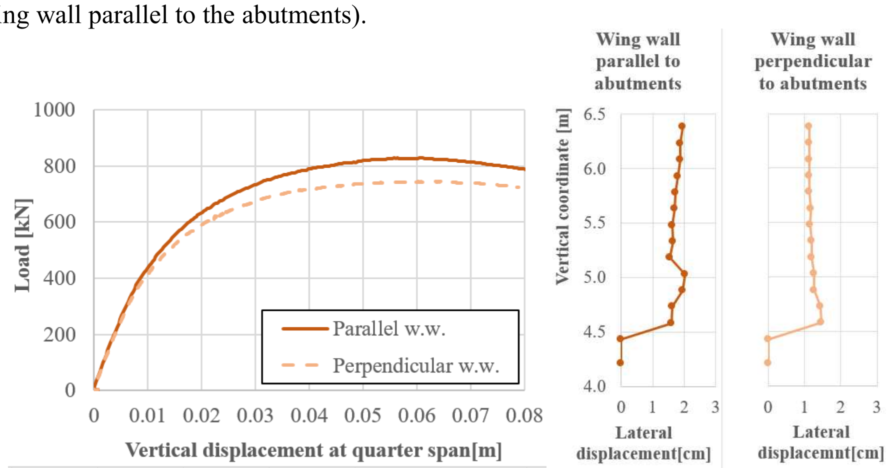

a.) b.)

Fig. 2. Load-displacement curve of the bridge (left) and lateral displacements of the perpendicular and the parallel spandrel walls

The presented study demonstrated that the developed numerical model gives back those failure mechanisms of spandrel walls, which were observed and documented [4] earlier by bridge inspection engineers and it can be applied to determine the load bearing capacity and the structural stiffness of masonry arch bridges.

References

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