MASONRY ARCH BRIDGES UNDER VERTICAL AND HORIZONTAL LOADING AND NUMERICAL MODELLING

A. Krawtschuk[1], O. Zeman[1], T. Zimmermann[1], J. Schellander[1] and A. Strauss[1]
[1] Institute of Structural Engineering, University of Natural Resources and Life Sciences, Vienna, Austria, alexander.krawtschuk@boku.ac.at

ABSTRACT

Arch bridges made from nature stone or masonry are the oldest structures which are still in use on lots of road and railway lines nowadays. With an average age of more than hundred years, these structures often are seen as historical important buildings. Most of them had been constructed during the great building period of roads and railways from the 1840ies to 1900. Lots of the considered nature stone bridges are constructed as circle or three centre curve, some of them also in a parabolic form or catenaries or cycloid. The height of the apex cover varies in a wide range. If masonry was appropriated, usually sand, chalkstone or clay bricks were used. For most bridges no observations of the material parameters are available, as a result the stone and the mortar strength are unknown. In order to determine useable material parameters for the recalculation of these arch bridges, usually material tests have to be performed. From the geology, it is known that the compressive strength of e.g. shale stone depends on the direction of the applied load. For masonry made out of bricks hardly any relationship of the loading direction can be found in the literature. In this article experimental test results of a series of tests concerning the determination of the uniaxial compressive strength under various loading directions are presented. The various load bearing behaviour depends on the manufacturing process which is also discussed in this article. Furthermore, the potential applications for evaluating the structural performance of existing arch bridges regarding the material parameters are estimated.

KEYWORDS: arch bridge, monitoring concepts, material testing, model update, life time assessment

INTRODUCTION

The genesis of the idea of arches is no longer verifiable, but the use of vaults as a form of bridging a space is likely to be several thousand years old. An important progress regarding arches could be mentioned in the Etruscan age. The Etruscans was a nation who lived before the Roman Empire in the middle of Italy. Some authors mention that the Etruscans developed arches with key stones, however they did not use any mortar for their constructions. Based on the broad arches of the Etruscans the Romans developed wide span structures with spans up to 36 m. In the Roman Empire the direction of the joints, the usage of mortar and the concept of pentagonal stones for avoiding plane connections to the surrounding masonry were enhanced. At the same time in an independent way arch bridges were also used and known in the Chinese Empire. These Chinese arch bridges were slender constructions, the thickness of the stones was much lower than at European arch bridges. With the upcoming cities and the increasing of trading, the needing of permanent bridges made from stone increased, too. In the renaissance, the usage of the types segment-arch and basket-arch was the standard shape. Thereby it was possible to achieve larger spans and better alignments as with a simple circular arch. In the industrial period of the 19th century, the boundary conditions for the construction of bridges altered significantly. With the upcoming railroads and an increase in moveable cargo, new transport routes were built and hence it was necessary to increase the spans and height of arch structures as well as the bearing capacity [1]. New materials (ferro concrete and later on reinforced concrete) enabled new structural shapes and wider spans and replaced the use of arch bridges.

ADVANTAGES AND DISADVANTAGES OF ARCH BRIDGES

Large parts of the population see arch bridges as an element instead of an interference with nature. Moreover arch bridges actually act as tourist attraction. However, this is a fact that arch bridges are constructed on many historic sites and they are already regarded as aesthetic. Other advantages of arch bridges, in addition to their indisputable beauty, are summarized by [2] and can be listed as follows:

- Limited deformations under traffic loads
- Usability and fatigue are irrelevant
- Application of uninterrupted rails based on limited deformations
- A high failure safety and robustness
- A high damage tolerance
- Early indication of malfunctioning
- A long lifetime and period of utilisation
- Arch bridges guarantee an undisturbed view for travellers
- The construction materials can be disposed reused as environmentally compatible material
- Excellent insertion into landscape

There are also disadvantages, according to [2]:

- Complex renaturation
- The clearance diagram under the bridge is not constant which can cause problems with traffic under the bridge
- Considerable reduction of the loading capacity by large support displacements

The consideration of advantages and disadvantages is always subjective, but it can be seen that the advantages outnumbers the disadvantages. Nevertheless these structures will be built new only in the rarest cases due to financial restrictions. The preservation of these structures can be seen as rational out of the reasons mentioned above.

CONSTRUCTION OF ARCH BRIDGES

An arch is defined as a radial arrangement of stones or bricks, which should be built by an uneven number of stones and bricks respectively for ensuring that the keystone is placed directly in the middle of the arch, see Figure 1. The region between the arch itself and the deck is defined as backfill material, which can be carried out with quite different types. The backfill material can be made from unbound filling, grouted soil, structural components made from concrete or masonry, excavations for cut down the dead load or spandrel walls in longitudinal direction of the arch bridge. In former days often a reduction of dead load was achieved by the incorporation of excavations and openings in the backfill by using so called spare vaults. Since WW II constructions of this type became less important due to the high effort and the corresponding high personnel costs [1].

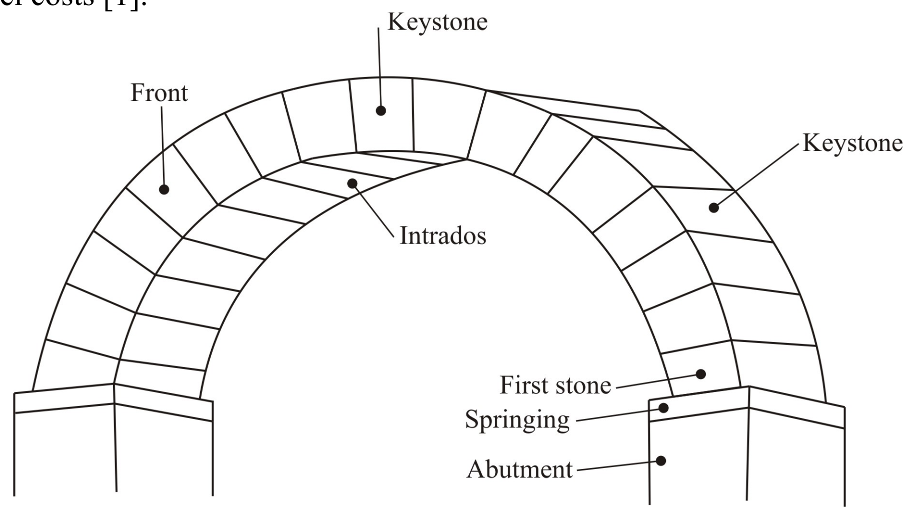


Figure 1: Definitions of arch bridges [1]

The static system and the bearing behaviour of an arch bridge are influenced by various boundary conditions. Figure 2 shows the influence of material, arch geometry and superstructure.

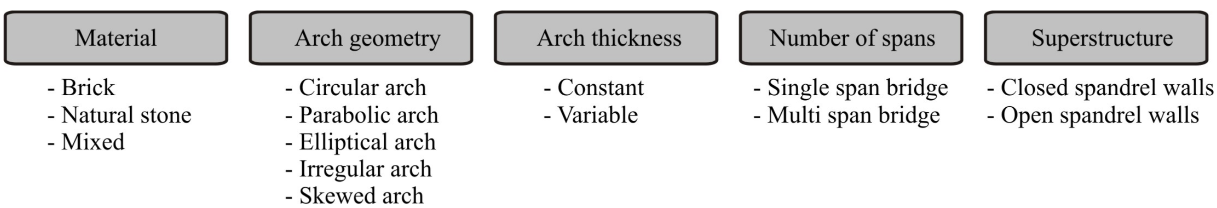


Figure 2: Influence parameters on an arch bridge [1]

CASE STUDY OBJECT

For the development of an adequate model which enables both the include of information from in-situ measurements and from calculation approaches, a case study object the so called "Rohrbach" masonry arch railway bridge is investigated, which is located within the municipality of Rohrbach by Mattersburg in the region of South-Eastern Austria. The bridge services the Mattersburg railway line of the Austrian Federal Railway called OEBB. The masonry arch bridge consists of 5 arches with a rise of approximately 2.0 m and a span of approximately 6.0 m. The bridge is connected to earthen dams via abutments on either ends of the bridge, see Figure 3.

Figure 3: Case study object Rohrbach bridge (5 arches)

The Rohrbach bridge was constructed between the years 1845 and 1847. The bridge was originally designed and constructed to support one set of rails for each direction of railway traffic, resulting in a total width of 8.85 meters [3]. The bridge, with its deep vault, can be seen in Figure 4a. After construction, only one set of rails was laid to handle traffic in both directions. This condition still exists but the rails are not positioned symmetrically in the centre. They are eccentrically positioned slightly to the southwest of the centre, see Figure 4b.

(a)

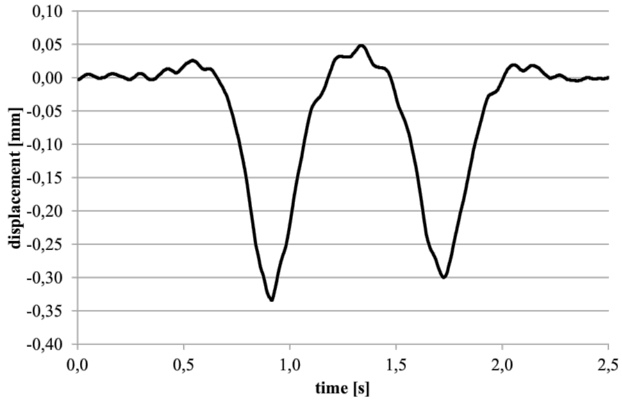
(b)

Figure 4: (a) vaults of the case study object, (b) rails on the case study object

As mentioned above the case study object was taken as an adequate structure for setting up a model for recalculation of the structure, if required due to load increases, deteriorations or damages of the structure. For setting up a recalculation model lots of different measurements were conducted. These measurement data are used for calibrating the boundary conditions of the calculation model and incorporates (a) in-situe measurements. For the determination of an appropriate material model for masonry (b) small scale laboratory tests were performed on drill cores made from bricks. In addition to these small scale laboratory tests, further research considers (c) a larger scale specimen of the bridge (size 1:2). The aim of all these research is to set up a reliable calculation model for existing arch structures.

IN-SITU MEASUREMENTS

Multiple in-situ destructive and non-destructive tests have been conducted on the mentioned structure. One of the already applied measurement methods was ground penetration radar [4], which is a non-destructive testing method allowing the investigation of the subsurface without the need for excavation or other destructive activity. This technique allows for the identification of interfaces between different elements or layers or material within the analysed area. By means of the results of these tests, an assumption of the backfill material could be made. Further testing on the bridge was conducted with laser vibrometer tests to determine the deformation of the bridge under service load. These tests were conducted during a 4-hour window between 10:00 and 14:00 in 03/12. It included a passage of 8 separate trains, which run hourly in each direction across the bridge, see Figure 5.



(a) (b)

Figure 5: (a) Test setup for laservibrometer measurements, (b) displacements measured at the top of the intrados caused by a crossing single railcar type 5047

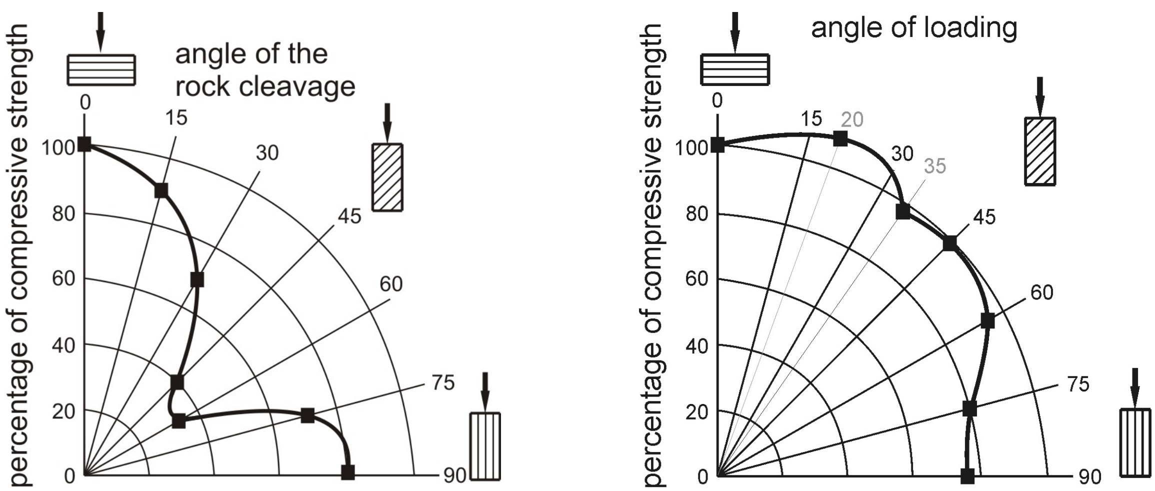
As another measurement principle on the arch itself and on intrados of the arch bridge displacement transducers (linear variable differential transformers LVDT) were arranged. The intersection of the steel bars enables the measurement system to record shear forces, which occur due to the loading of the bridge structure. Preliminary tests with this system were performed in 11/2011 and the main measurement campaign took place in 03/12 [5]. The measurement campaign with the proof loading provides the corresponding deformations and characteristics of the backfill material to defined loads which is a helpful database for the calibration an appropriate numerical model.

LABORATORY TESTS

For analysing the material properties of historical bricks, small scale laboratory tests were performed on drill cores. For natural stone it is known from geology that in case of anisotropic material properties the determination of the compressive strength is depending on the formation of the fracture cleavages. For e.g. a quarzphyllit stone, the influence of the loading direction to the rock cleavage can be determined as depicted in Figure 6a. It can be seen that under specific loading directions the failure is not caused by the compressive force but by the shear force. From various test results it is known that in case of cleavages the lowest strength can be developed under an angle of $\alpha = 45 \pm \varphi/2$.

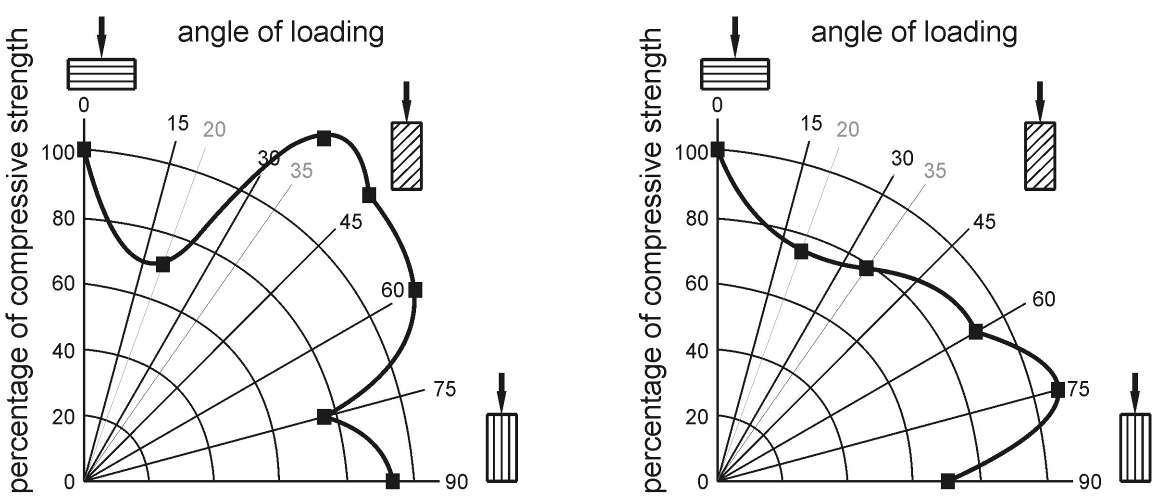
As a result of the different manufacturing process of bricks in former days when most of the existing arch bridges were constructed and the manufacturing procedure which is executed nowadays, the influence of the loading direction to the brick was studied. On the one hand two different brick types from the 19^{th} century and one brick type produced in 2012 were investigated. The loading direction was varied by drilling cores out of entire undamaged bricks in steps of 10° to 15°. The drill cores had a diameter and a height of 45 mm which leads to a ratio of height to diameter of 1:1. This aberration of the relevant testing code EN 772-1 [6] was accepted due to the fact that the size of the drill cores were limited the size of bricks. For each angle at least five samples were taken from different bricks and tested up to failure by a servo-hydraulic testing machine. The tests were performed deflection controlled which enables to record the displacement behaviour after the maximum load. The mean values of the determined compressive strengths from the conducted tests and the corresponding coefficients of variation are listed in, the test results.

For the modern bricks a correlation of the loading direction to the compressive strength was assumed due to the fact of the production process using an extruding press which leads to an orientation of the clay minerals. Figure 6b shows the influence of the loading direction and the drilling direction respectively on the measured uniaxial compressive strength. The assumption of the influence of the production process could be verified and it is shown that under a loading direction of 90° the compressive strength has just a value of 0.8 of the reference value which is fixed by an loading angle of zero degrees. In addition the fact that the compressive strength under an angle of ~35° is decreasing for the cleavages in Figure 6a is also valid for new bricks (Figure 6b). The appearance of the fracture for the new bricks shows at almost each loading directions the typical failure mode under uniaxial compressive force as it is also well known from testing concrete specimens as specified in Figure 8a.



(a) (b)

Figure 6: Sensitivity of the loading direction to the compressive strength (a) cleavage stone, (b) new bricks

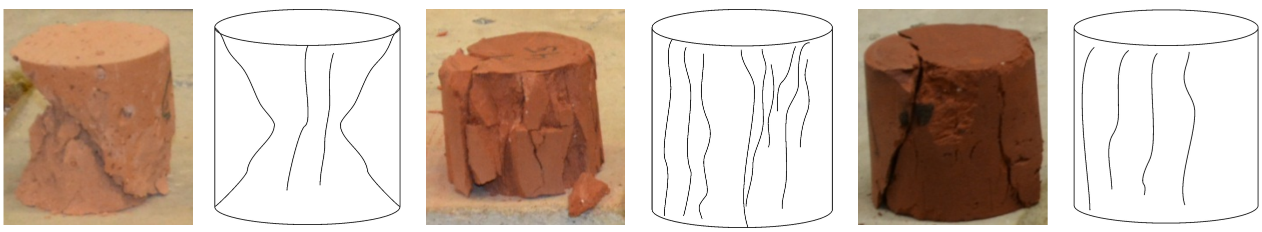


(a) (b)

Figure 7: Sensitivity of the loading direction to the compressive strength (a) historical bricks ChI, (b) historical bricks ChII

For the historical brick type I (Figure 7a) and type II (Figure 7b) a decreasing compressive strength could be determined with a loading angle of 20° for both types, but then the results differ significantly. For type I the compressive strength increases under these directions which represent the typical main directions of the shear stress in a uniaxial compression test.

As it can be seen in the scheme of a typical fracture in Figure 8b for type I, the cracks and hence the failure occurred in the direction of the load application. However, this fracture mode also occurred for the type II of the historical bricks as it is shown in Figure 8c, there was an obvious reduction of the compressive strength with increasing loading angle, but nevertheless there cannot be given reliable evidence if the loading direction influences to the compressive strength and therefore to the bearing capacity.
Due to the fact that the existing arch bridges made out of masonry which has been mentioned before are normally made out of historical bricks, the direction of the loading can be neglected for modelling these structures. Hence there is no significant influence on the material model.



(a) (b) (c)

Figure 8: Typical fracture modes for the different brick types (a) new bricks, (b) historical bricks ChI, (c) historical bricks ChII

In addition to the small scale laboratory tests with the drill cores, a 1:2 scale model of an arch of the case study object was built up. On this specimen laboratory tests with regards to vertical and horizontal loadings are going to be performed. In case of horizontal loading also small scale laboratory tests were performed, details can be found in [7]. The results of these tests are going to be used as input parameters for the laboratory tests which will be conducted in spring 2013.

MONITORING BASED MODELLING - MODEL UPDATE

In many cases it may be required to estimate the bearing capacity of existing arch bridges e.g. if the bridge is subjected by other traffic loads than the bridge was constructed for. In these cases an adequate model of the bridge has to be defined. The increasing loadings on existing bridges due to higher axial loads demand an assessment, a strengthening or a reconstruction of existing structures. In this contribution it shall be pointed out in which cases monitoring concepts and their application to existing structures can be used for determining the structural behaviour of arch bridges and how the reliability of static recalculations can be verified [8]. In addition in case of arch bridges made from natural stone or masonry the material parameters are mostly unknown.

The most important input factor of an adequate model is the available information about the expected structural behaviour, which can be achieved from experience, analytical approaches or numerical modelling. For an effective model the following requirements might to be met: (a) simulating the geometrical data of the structure, (b) consideration of time-dependent processes,

(c) model setup with an incorporation of measurement data which gives the possibility of modifying the material parameters by means of values from laboratory small and large scale tests and (d) an assessment of the bearing capacity (ULS), serviceability (SLS) and durability (DLS) in accordance to EN 1990 [9].

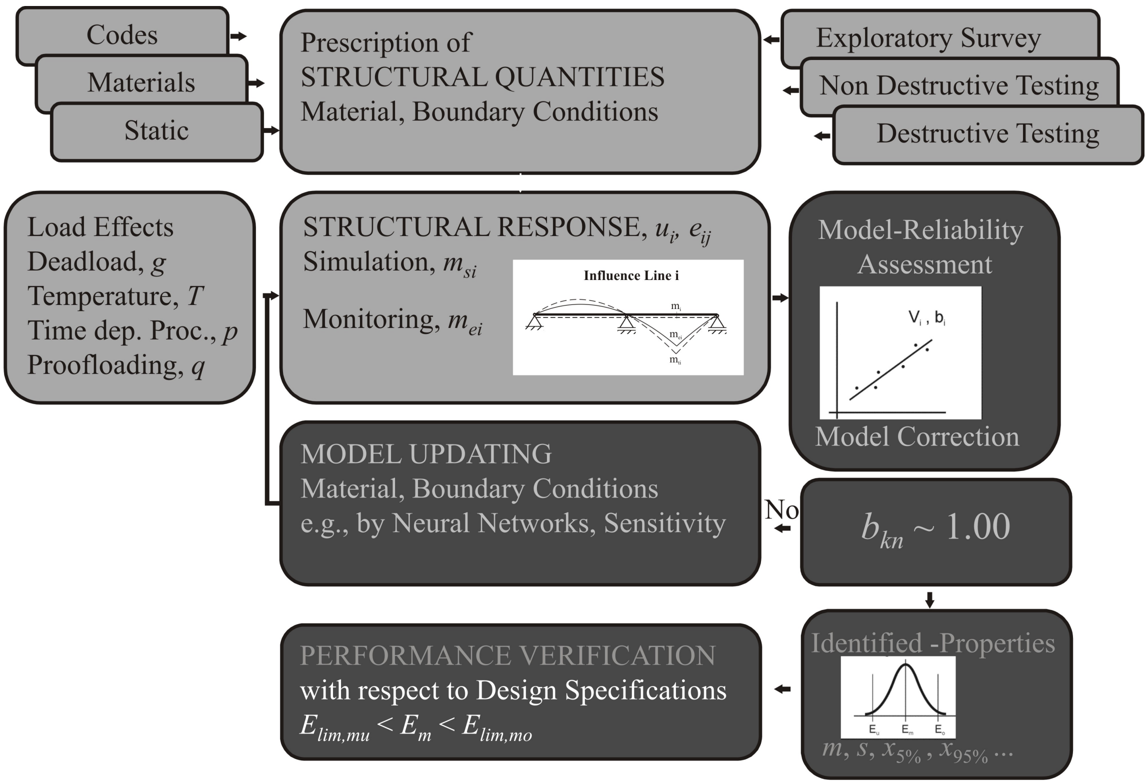


Figure 9: Scheme of the model updating process via monitoring data and structural characteristics

Figure 9 shows the scheme of model setup for a structural model. The problem itself consists of the influences of codes, static and material. Codes include the changing of load scenarios during the last century, the different subjected safety factors and the assessment procedure. The subject static includes the boundary conditions of the structure and its components, the dead load and various constraints (e.g. the backfill material or temperature influences). The material parameters are defined by original construction plans, destructive and non-destructive testing methods as well as laboratory tests for determining material parameters. An adequate model reproduces the structural behaviour by means of calculated data (e.g. calculated vertical displacements, strains or stresses) under various loading scenarios (e.g. traffic load according to the codes or proof loading campaigns if conducted). These simulated values can then be compared to monitoring data on the one hand and laboratory tests on the other hand to achieve a correlation function f (v_i, b_i). If the required correlation accuracy cannot be fulfilled, the modelling has to be recapped by means of the measurement data or changes in the material parameters or boundary conditions, which leads to a continuous model update process, see Figure 9.

For evaluating the performance of the case study object a finite element (FE) model was set up for recalculations of the existing arch structure to determine ULS and SLS. The model aims to compare the measured displacements obtained from in situ measurement campaign and material properties from laboratory tests to the calculated results. If the measured values v_i are in accordance with the calculated ones b_i, the structure can be estimated under various loading situations e.g. higher axle loads or extreme events like mudflow. In combination with an life cycle assessment the updated model can be used for the determination of remaining service life and serves as decision making tool. The FE-model was set up in SOFiSTiK with one exemplarily arch with a horizontally non-displaceable boundary condition for ensuring symmetry of the arch. In addition, below the springing's the horizontal and vertical non-displaceable supports were defined. In this FE-model it is possible to modify the material parameter to these values which were determined by testing and also the scatter of the modelling parameters can be incorporated which means stochastic parameters can be considered. As initial state, the material parameters were taken from the predefined masonry model according to EC 6 with a linear elastic material behaviour. After the conducted laboratory tests the material parameters can be modified to the experimentally determined ones. Figure 10 shows the FE-model of the case study object under a defined loading situation.

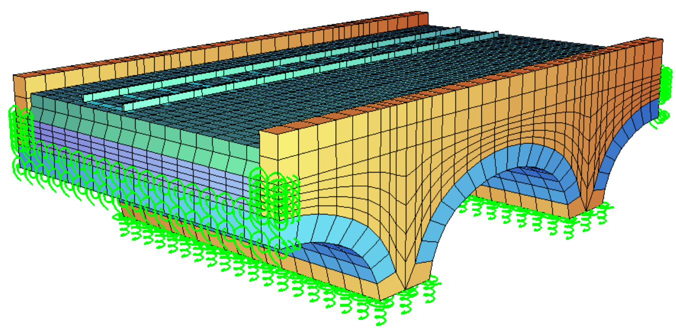


Figure 10: FE-model of the case study object

As a result of the conducted material tests for the presented FE-model of the existing structure, the compressive strength of the bricks can be assumed as non-correlating to the loading angle. The tests provide an average and a characteristic value for the compressive strength of the historical bricks as well as for the young's modulus. Based on the results of the non-destructive testing methods (ground penetration radar [4]), the characteristics of the backfill material and the bridge itself could be determined and also considered in the model setup. The model update process is still in progress.

CONCLUSION

In this contribution it is shown how on the base of adequate measurement data and surveying a FE-model of an existing masonry arch bridge can be set up for the evaluation process of the bearing capacity as well as to incorporate stochastic material properties. For being able to estimate the bearing capacity of an existing arch bridge, a model update process is presented and applied on a case study object. By means of this process it is also possible to incorporate data from experimental testing's into the calculations. For an increase of the accuracy and the practicability of the model on the one hand laboratory tests were and are going to be performed to determine the correlation of measured values on the real object and measured values on a scale model; and on the other hand small scale tests on specimens taken from bricks under variable angles. These variable angles determine the variable loading direction which occurs on existing structures. The results of these tests are presented and show a behaviour of the compressive strengths which highly depends on the type of bricks. The results are taken for adjusting the model in an adequate way.

ACKNOWLEDGEMENTS
The research concepts presented in this contribution are funded by the research projects ILATAS and NANUB supported by Eurostars and FFG grants. Additionally the support of the experimental investigations by the project CZ.1.07/2.3.00/30.0005 of Brno University of Technology is gratefully acknowledged. Also special thanks to the both companies Wienerberger AG and DOKA AG.

REFERENCES

1. Proske, D., van Gelder, P. (2009) „Safety of Historical Arch Bridges" Springer, Heidelberg, Germany.
2. Weber, W.K. (1999) „Die gewölbte Eisenbahnbrücke mit einer Öffnung". Dissertation. Technische Universität München, München.
3. Dengg, F., Mendlig, K. (2012) „Entwicklung von zerstörungsfreien Messsystemen für bestehende Brückentragwerke". Bachelorarbeit Universität für Bodenkultur Wien, Wien.
4. Seren, S., Hinterleitner, A., Toschnig, R. and Bayril, E. (2012), Geophysikalische Prospektion, Rohrbach ÖBB-Brücke
5. Krawtschuk, A., Zeman, O., Strauss, A., Scheidl C., Proske D. (2012) "Optimised monitoring concepts for historical masonry arch bridges" Proceedings of the 3rd International Symposium on Life-Cycle Civil Engineering, IALCCE 2012.
6. EN 772-1: *Methods of test for masonry units – part 1: Determination of compressive strength*, 2000.
7. Scheidl, C., Chiari, M., Kaitna, R., Müllegger, M., Krawtschuk, A., Zimmermann, T., Proske, D. (2013) „Analysing debris-flow impact models, based on a small scale modelling approach" *Surveys in Geophysics,* Springer, ISSN 0169-3298 Volume 34, Number 1, Surv Geophys 34:121-140.
8. Strauss, A., Frangopol, D.M., Bergmeister, K. (2010) "Assessment of Existing Structures Based on Identification" *Journal of Structural Engineernig*, ASCE, 136(1): 86-97.
9. Eurocode 0 – EN 1990 (2010), Basic of structural design, European Standard Organisation.