

## INSPECTION AND LIFETIME ASSESSMENT FOR ARCH BRIDGES

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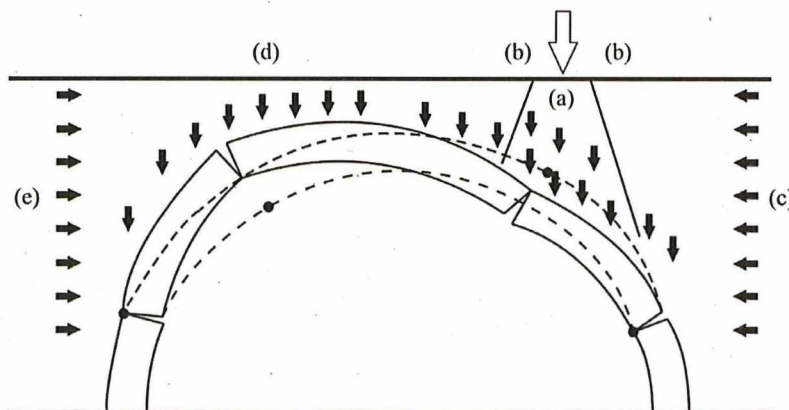
Arch bridges made from nature stone nowadays are the oldest structures which are still in use on road and railway lines. With an average age of more than hundred years, these structures often are seen as historical important buildings. Most of them had been constructed during the great building period of roads and railways from the 1840ies to 1900. Lots of the considered nature stone bridges are constructed as circle or three center curve, some of them also in a parabolic form or catenaries or cycloide. The height of the apex cover varies in a large range. If masonry was appropriated, usually sand, chalkstone or clay bricks were used. For most bridges no observations of the material parameter are available, as a result the stone and the mortar strengths are unknown. Under the usage of the German railway company, there are more than 8000 arch bridges yet, although at local roads there is an additional unknown number of them. In Austria, the railway network, especially along the southern railway line has around 1000 arch bridges in usage. In whole Europe, the stock of masonry railway bridges is estimated with around 70.000. In the course of route expansion plans in the past especially arch bridges have been replaced by new steel or reinforced concrete structures. Considerations of preservation, the budgetary situation of the rail and road operators, as well as a sustainable, resource efficient usage of resources and existing infrastructure are motivations to maintain and – if necessary – toughen up existing arch bridges. Therefore, the issues of sustainability, durability and serviceability become more important.

*Keywords: Arch bridge, railroad, FE modelling, monitoring system, life time assessment*

### INTRODUCTION – STATE OF THE ART

The oldest existing arch bridges were designed based on experience. Later graphical methods for the static were available and approximation formulas based on the arch thrust line to design major geometrical parameters such as span, arch shape and arch thickness at the apex and the abutments were developed. These simplifying estimations can also now be useful to perform the bearing capacity of existing arch bridges on the basis of their geometrical parameters. Especially for old arch bridges which were designed for different loads at their design and construction date, these methods can be used as an first estimation for the current bearing capacity or the future use of these buildings. The recalculation of these buildings under the valid load approach enables the assessment of the bearing capacity and the

suitability for an usage under nowadays valid load. Any necessary upgrading which considers the conservation of the existing structures both preserves the appearance of the arch bridges and saves costs. For the estimation of the bearing capacity as a result of a static recalculation, the knowledge of the construction and the material properties is required. If bridges are designed nowadays, e.g. made from reinforced concrete, steel or wood, these parameters are well known, In case of existing arch bridges made from stone, brick or rammed concrete, the material properties often cannot be identified, because too many factors which have an influence on the bearing capacity. The assessment of existing bridge structures can be used as a helpful method for the responsible organisations, e.g. road or railway maintenance companies, and the proper governments. In terms of the life cycle concept, the increasing axle loads, load restrictions, inspections, monitoring, maintenance measurements or even a replacement of the structures have to be considered. A conventional approach for the recalculation of arch bridges, the elasticity theory can provide results which differ significantly from the actual bearing capacity. Horizontal abutment displacements and weaknesses in the arch reduce the load. The involvement of the wing walls and the interaction with the surrounding soil influence the capacity significantly. Therefore the issue of structure-soil-interaction as depicted in Figure 1 is particularly essential for arch bridges; however, calculations on the basis of existing studies cannot be performed correctly. These interactions can be summarized as follows:



**Figure 1: Structure – Soil – Interaction in accordance to UIC Code 778-3 (2011)**

- (a) traffic load is distributed laterally over the depth, the distribution is dependent on the shear strength and stiffness of the backfill
- (b) dead load of the backfill acts as a destabilizing force on the arch on the side loaded by the traffic load
- (c) horizontal components on the loaded side of the arch as a result of the shear strength, stiffness, dead load of the backfill material and the traffic load
- (d) stabilizing effect of the dead load of the backfill on the unloaded side of the arch
- (e) horizontal components on the unloaded side of the arch as a result of the shear strength, stiffness, dead load of the backfill material and the traffic load

Practical considerations have shown that stone arches in combination with an appropriate structural state can have considerable reserves in their bearing capacity. Therefore they often



reach the standards which are recommended nowadays. If the age of the structure is taken as a safety indicator, existing arch bridges show the convenience and the robustness of arch structures. Current tools of structural design are quite manifold and take account both geometrically and physically non-linear structural properties. Nevertheless, because the structural behaviour of natural stone masonry is quite complex due to various influence factors, it has not been possible to set up an appropriate model for masonry which considers all decisive effects up to now. The codes for proofing the bearing capacity and the serviceability only allow an overhead assessment of the resistance values. Thus there is a noticeable gap between the possibilities of mechanical modelling and the available safety proofs. Current finite element programs serve a quite good approximation for modelling the material behaviour, as a result different models are implemented in these programs. In the calculation models, the spatial dimension of the arch structures is simplified to a cross section of one meter. The most important point for a correct modelling is to identify the relevant meter-stripe and to describe the loadings correctly, particularly single loads in the transversal direction of the arch.

The well-known graphical methods with thrust line have been followed by analytical methods, particularly since the development of computational calculations. By means of elasticity and plasticity theory, the models were enhanced, although there is still no satisfactory solution approach for the issue of the discontinuous joint. Since a few years, some FE-Programs can bear with discontinuous joints, but these models require an enormous calculation effort. Additionally, there is the possibility that these models give completely wrong results, as a result of unknown boundary conditions.

### **MONITORING BASED MODELLING**

Generally monitoring systems can be used for the assessment of structures, for specifying changes from an initial state to an actual state or for the detection of expected and critical processes as Strauss et al. (2009a) and Wendner et al. (2010) have pointed out. For setting up a monitoring system it is required to have information of the expected structural behaviour, which can be achieved from (a) experience, (b) analytical approach (c) numerical modelling and simulation. Nowadays numerical simulations are state of the art and they are not only the base of design, but also a fundamental element of the assessment of monitoring data. International and national standards as e.g. in Austria RVS 13.03.11 call for numerical and analytical models in order to maintenance and inspection strategies, for interpretation and measurement of data. Type and coverage of the required models (geometrical, physical, linear or non-linear, 2D or 3D) for the monitoring observations depends on the complexity of the structure and its members as Zilch et al. (2009) mentioned. In addition, there are a few requirements, which have to be fulfilled by each model: (a) the real structure has to be simulated by the model according to the problem type, (b) deterioration processes and other time-dependent processes have to be simulated, if the remaining life time is concerned, (c) the setup of the model must allow the incorporation of monitoring data (e.g. by simulation of the observed problem), (d) efficient model updating of the model parameter, boundary conditions and system stiffness information, (e) the final aim of each model is the time-dependent assessment of the serviceability, bearing capacity and durability (considering the Serviceability Limit State SLS, Ultimate Limit State ULS and Durability Limit State DLS in accordance to EN 1990) according to the codes and specifications and the structural requirements. Adequate specifications for modelling (e.g. linear vs. non-linear and 2D-modelling vs. 3D-modelling) can be achieved from the observation requirements and the aims

of the monitoring processes as Strauss et al. (2009b), Hoffmann (2008) and Zilch et al. (2009) have worked out. It has to be considered in setting up the model, how obtained data can become part of the model, which aims (a) to calibrate and optimise the model and (b) to make predictions of a structure's future bearing capacity and the remaining lifetime. These models can base on influence line concepts and correlation coefficient concepts, which permit the input of monitoring data into numerical analysis models.

## MODEL SETUP

In Figure 2 the scheme of the model setup for a structural model is depicted. The model itself is based on the description of the structural quantities, material properties and the boundary conditions. These structural information is influenced by two types of factors, firstly the given information (external) from codes, material and statics and secondly results from performed tests on the structure. These parameters are described in more detail below. The model reproduces the structural response by the selected simulation, furthermore the simulation is updated by monitoring data. The loads which are put on the structure result from the dead load, the traffic loads and a proof loading which shall be put on selected structures. From the updated model and the measured monitoring data, there can be calculated a model correction factor, which allows to compare the data from the calibrated model to the measured ones.

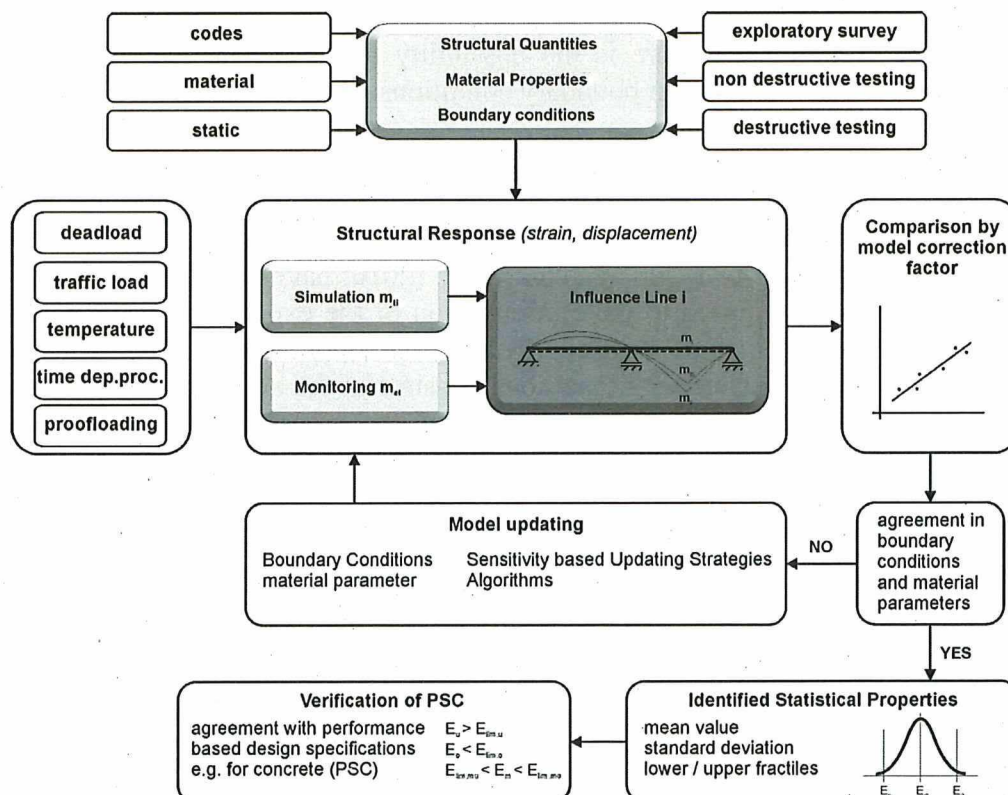


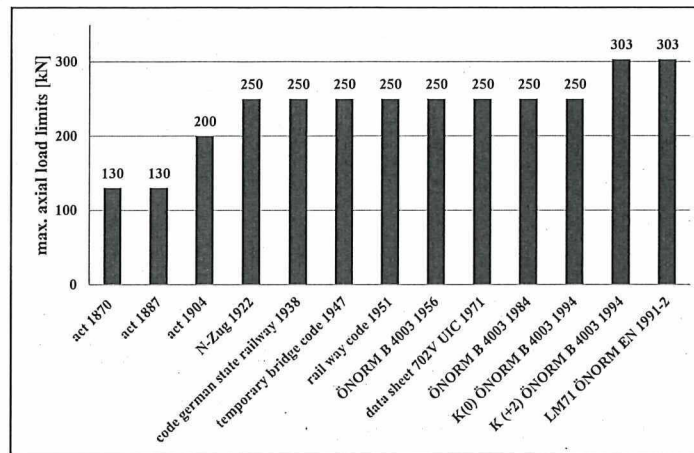
Figure 2: Scheme of model updating by monitoring data and structural characteristics

## CODES

The first regulations for loads on railway bridges in Austria were set up in 1870. As a result of the progressing development of the used materials and the increasing loads, these specifications have been modulated often as described in Simandl (2011). In Figure 3 there is



given an overview of the design axle load limits from 1870 up to now. The regulations came from the Austrian Department of Railway Affairs, from the German State Railway while WWII, from the Austrian Department of Traffic Affairs after WWII, from the Austrian Standard Institute and the last specification is a result of EC 1-2.



**Figure 3: Development of the design axial loads for railway bridges in Austria from 1870 up to now**

## MATERIAL

The bearing capacity of arch bridges contains lots of uncertainties. In addition to displacement of the abutments and the occurrence of cracks, the parameters of the used material considerably influence the condition of the structure. Arch bridges can be made of different materials, natural stone, masonry or compressed concrete, as discussed below. In case of natural stones or masonry, the strength of the material can vary in a large range. The strengths of historical bricks are much less than from bricks which are used nowadays, as described by Zimmermann & Strauss (2011). Another point which has to be considered is, that the mortar characteristics often are unknown and can vary, too. If the mortar becomes incoherent or the joints have not been filled up completely, the bearing capacity can behave unpredictable. Mortar strength is an important point to ensure the safety of the structure. Moreover, the material parameters of the back filling often differ from those of the external masonry, but in most of the cases there is no information of the used material

## TEST METHODS

### Non-destructive testing

By means of non-destructive testing methods lots of information in respect to arch bridges can be achieved, e.g. the shape of the abutment, thickness of the arch, constitution and dead load of the backfill. A few examples for non-destructive testing methods whose application is intended are listed below in accordance with Proske & van Gelder (2009)

- Georadar: This type of measurements is a non-destructive method for get information about the material properties, structural details and soil. The monitoring system is aimed to control the accuracy and the application of various measurement parameters (frequency, distance, etc.)
- 3D-Laserscanning is a non-destructive testing method for define structures geometrically and physically. By applying this procedure an admissible accuracy of damage detection is aimed by recorded frequencies and monitoring of the distances.

- Infrared Thermography
- Sonar methods
- Conductivity measurement
- Endoscopy
- Laser scanning
- Accelerometers
- Strain gages
- Linear Variable Differential Transformers (LVDT)
- Video scanning (optic measurement system)

### **Destructive testing**

In addition to the geometrical definitions for performing calculations it is essential to get specified information of the material parameter. These material properties can be achieved by material testing methods on test specimens. Examples are listed below.

- Drill cores: can be performed in norm or in small size, required samples are standardised e.g. in DIN EN 13791:2008
- Flat Jack: identification of the stress-strain curve and of masonry compressive strength

### **CASE STUDY AUSTRIAN NORTHERN RAILWAY LINE**

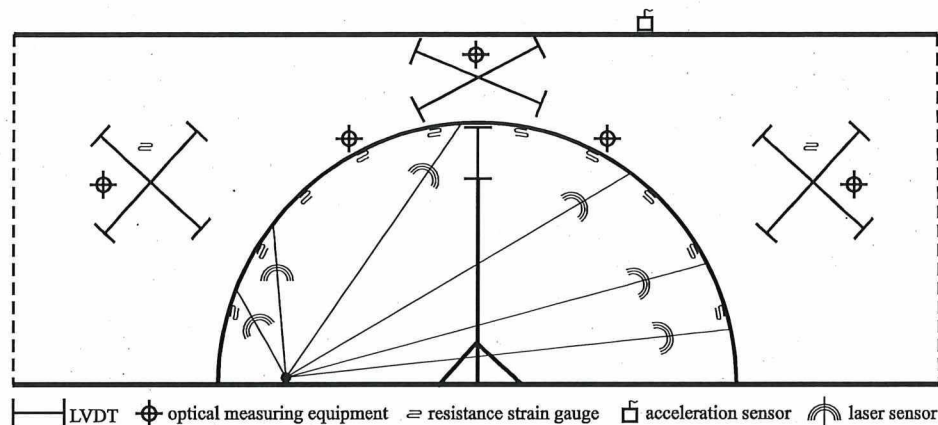
Section heading shall appear on the left, be fully capitalised and bold, and there shall be one line space above section headings. Section text shall appear in the line directly below a section heading. The use of subheadings shall be avoided. One line space should appear between paragraphs of a section. The Baltic-Adriatic axis (BAA) from Gdansk (PL) to Bologna (I) is one of the most important North-South transversal of Europe which connects upcoming regions of three new EU Member States (Poland, Czech Republic, Slovakia) with economical centres and agglomerations in Austria and Italy. In addition, it offers a connection to a few other priority axes of the trans-European transport network (TEN-V) and enables the relocation of transportation of cargo from road to railway lines as an important component of reaching the international climate aims.

The Austrian Northern Railway Line as part of the BAA is a double tracked main railway line, which has been electrified fully in the year 1978. The Northern Railway Line is a direct connection from Austria to the Czech Republic and was built in the 19<sup>th</sup> century as Kaiser Ferdinands Nordbahn from Vienna to Krakow (finished 1856). The railway line leaves Vienna at railway station Praterstern in the direction to Moravia. As described the line is part one of the most important European railway lines with international train service to Prague, Krakow, Warszawa, Berlin and Hamburg. The Austrian part of the Northern Railway Line contains several arch bridge structures. For instance, some of them are analysed below.



## FIELD CAMPAIGN

Based on the mentioned measuring methods an appropriate field campaign for an exemplary arch bridge has been developed. The application of the measurement systems at the considered arch bridge is illustrated in Figure 4. The field campaign is planned to be carried out in late 2011. The arch bridge will be equipped with the following measuring systems: Firstly, below the arc a laser sensor will be placed, which records the underside of the arch at several defined points. The non-contact laser sensors base on the so called laser distance measurement. The system e.g. is able to pick up changes in length or deflection of bridge structures by the included instrumentation. Due to a sampling rate of 20 Hz it is also possible to detect dynamic deformations.



**Figure 4: Field campaign illustrated for an exemplary arch bridge**

As another measurement principle in the arch itself and on the spandrel wall of the arch bridge Linear Variable Differential Transformers (LVDT) are arranged. In the arch the LVDT is passed vertically over a telescopic rod at the key of the arch. On the spandrel walls of the arch bridge the LVDTs are disposed on a proprietary system. Two steel bars with a diameter of 12 mm are fixed at one side with an angle on the front surface and on the other side they are kept by a pilot hole in other arranged angles. On the side of the loose mounting of the steel bars, the LVDT is 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 have been performed in 11/2011 (see Figure 5).



**Figure 5: Arrange of the measurement system for recording shear forces**



In further research work an optical measurement system is used, which works on a high-resolution video camera system. On the front side of the bridge structure a sampling panel (approx. 50 x 50 cm), which consists of a white background and a black dot, is mounted. Due to the high resolution of the video system (5 megapixels) and appropriate analysis logarithms, the individual images are superimposed. This aims to determine the deformations of the considered bridge structure visually under defined loading situations from the zero position in which only deadload is considered. By moving the sampling panels along the arch corresponding deflections can be recorded. In addition, the camera system provides valuable additional information, such as train type, number of axes, etc. to the values obtained with other systems. As method for the determination of the occurring deformations inside the arch and on the spandrel wall the usage of strain sensors and strain gages is proposed. These measurement systems will be mounted force-fitly on the masonry surface. The installation of the strain gages is done on an appropriate steel pipe or another adequate construction, which is anchored in the considered masonry. Depending on the length of the steel pipes, it is also possible to measure integral strains over a larger range. By this method an average strain over the arch bridge shall be determined, due to bypassing the influence of bricks and joints. A cross-shaped arrangement of the strain gages enables the determination of the corresponding shear strains as mentioned above.

For verification of the computational models which have been set up in the context of the research project and modified as a result of the measured deformations, additional data shall be provided by using accelerometers. This aims to define the eigenfrequencies of the structure as a method to describe the stiffness of the object in computational models. The measured eigenfrequencies are correlated with those of the computational model to test whether the model is similar to the real structural behavior.

### LINEAR AND NONLINEAR MODELS

As described above, the Austrian Northern Railway Line is one of the most important European railway lines (BAA). One of the considered arch bridge structures is located in a distance of ca. 80km from Vienna, the static system is a three-span natural stone arch bridge, see Figure 6. The modelling of the bridge was set up with the program SOFISTIK, Figure 7 shows a part of the geometric model of arch bridge „Bernhardsthal km 75.702“. The chief arch spans amount to 11.40m and the arch rise 3.80m. The lateral arch on either side spans amount 2.70m and the arch rise 1.40m. The used coordinate systems are both a Cartesian global and some local systems. The model consists of 17634 elements and 18788 nodes. In advance the material model is the Standard EC 2 (1992) Concrete Structures with country code 43 (Austria, reinforced concrete and prestressed with unbonded tendons). The first considered load case was set up in accordance to the load model UIC 71 from EC 1-2.



Figure 6: Arch bridge “Bernhardsthal“

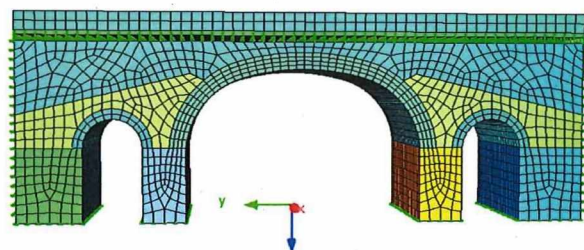
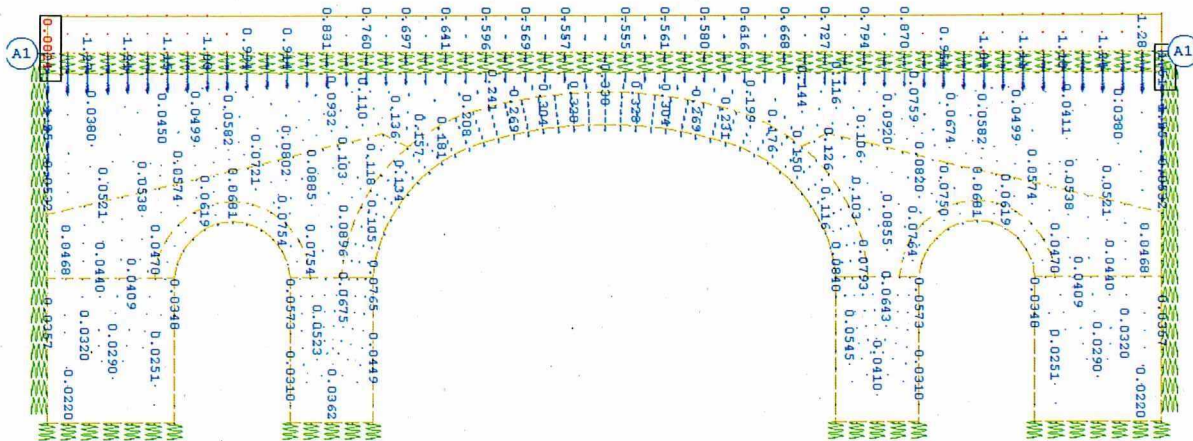


Figure 7: FE-Modelling of the arch bridge



The first obtained results from the SOFISTIK analysis are displacements in the local z-direction, as depicted in Figure 8.



**Figure 8: Calculated displacements [mm] in local z-direction (load case dead load)**

After the completion of the presented computational model the further steps of the investigation are the setup nonlinear finite element models of the considered arch bridge structure with the nonlinear analysis programs Atena and Ansys.

## MODEL UPDATING

Due to the fact that modelling and availability of monitoring data of the arch bridge discussed above is not finished yet, model updating is discussed on an established concept of a monitoring system on another existing bridge structure. The considered Marktwasser Bridge S33.24 is a jointless bridge structure, crossing the Danube River and is a three-span system. Design and structural behaviour of jointless structures not only depend on dead load and the applied traffic loads, but also on constraint loads which can be induced by temperature effects, earth pressure, creeping and shrinking processes. For considering the influence of these constraints, in total five different sensor systems which consist of strain gages, temperature sensors and extensometers were permanently installed as described in Strauss et al. (2011). The monitoring system aims to detect these influences in the superstructure and the reinforced earth dam behind the abutments. As a result of the different origin of the relevant load cases, the measuring instruments of the deck slab must enable to detect as well a constant and a linear distribution of the considered strains. Additionally temperature sensors were arranged for measuring constant temperatures and temperature gradients. Therefore a monitoring system of fibre optic sensor system of strain and temperature sensors was selected. As a further step for model updating, proof load tests have been performed on the lanes of the bridge in the most unfavourable configurations as shown in Strauss et al. (2011). Overall more than 35 load scenarios were put on the bridge structure and the structural response could be determined in the monitoring data. The FE-model of the S33.24 was set up with SOFISTIK, too. The abutments, the pillars and the deck slab were modelled by shell elements. The four lines of the drilling piles were discretised using beam elements with altogether 569,035 elements and 18,945 nodes as specified in Strauss et al. (2011). Geometrical data and the material properties were taken from the available statics and plans. For instance, the deck slab is made of concrete C30/37 and the piles of C20/30 according to EC2.

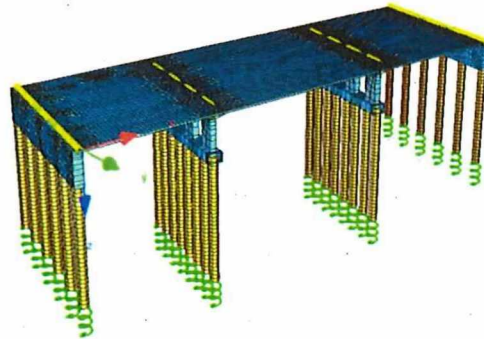


Figure 9:: Rendering of the SOFISTIK model of S33.24

The analysis of the measured data from the proof load scenarios has been performed by the concept of influence lines and areas. The comparison between simulated influence lines from the SOFISTIK model and the experimental gained influence lines from the proof loads shows in a first model deviations of 10% to 45%, see Figure 10(a) for Sensor  $d_{7u}$  on the bottom side of the deck slab and Figure 10(b) for sensor  $d_{9o}$  on the top side. The reasons for the deviations can be seen in an inadequate determination of points during the proof loading procedure or in deficient calibration of the monitoring system. For an appropriate calibration of the model, it is recommended to incorporate model correction factors for calibrating the calculated values to the measured data.

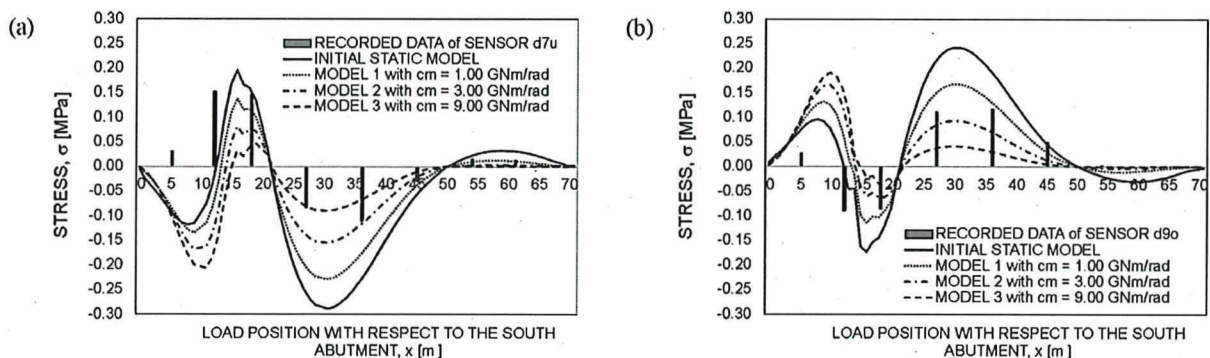


Figure 10: Influence lines extracted from the FE-model with respect to the measured values of the nine proof loading positions for the fibre optical sensors  $d_{7u}$  and  $d_{9o}$

## CONCLUSIONS AND PERSPECTIVES

The existing arch bridges in Austria and in Europe respectively often have an age of hundred or more years and have been put under preservation order. As a result of this and of budgetary restrictions, arch bridges have to be maintained, toughed up during their lifetime and in addition they must be assessed considering new load scenarios according to the codes. The recalculation of these structures is quite difficulty, due to the lack of initial plans and adequate data of material parameters. As described above, the interaction between the single components of arch bridges (soil, masonry, backfill) is afflicted to many uncertainties. Thus from the point of view both of the responsible official corporations and of pure research, it is necessary to design well operating concepts for estimating the load bearing behaviour of existing arch bridges. Intention of research incorporate measured data into modelling for update the models in terms of the various unknown influence parameters and to be able to make an efficient assessment of the bearing capacity of existing arch bridges.



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## REFERENCES

- Hoffmann, S. "System identification by directly measured influence lines - A user orientated approach for global damage identification at reinforced concrete bridges". Dissertation, Universität für Bodenkultur Wien: 149, 2008
- Proske, D. and van Gelder, P.: "Safety of Historical Arch Bridges", Springer-Verlag, Heidelberg, 2009
- Simandl, T. "Nutzungsdauer von Eisenbahnbrücken", Dissertation, Technische Universität Wien: 25-39, 2011
- Strauss, A., Bergmeister, K., Wendner, R. and Hoffmann, S. "System- und Schadensidentifikation von Betonstrukturen". Betonkalender 2009. K. Bergmeister, F. Fingerloos and J. D. Wörner. Berlin, Ernst und Sohn. 2: 55-125, 2009a
- Strauss, A., Hoffmann, S., Wendner, R. and Bergmeister, K. "Structural assessment and reliability analysis for existing engineering structures, applications for real structures." Structure and Infrastructure Engineering 5(4): 277-286, 2009b
- Strauss, A., Wendner, R. and Bergmeister, K. "Monitoring and influence lines based performance indicators". ICASP 11. Zurich, Switzerland, 2011
- RVS. "RVS Merkblatt „Monitoring von Brücken und anderen Ingenieurbauwerken“: Überwachung, Kontrolle und Prüfung von Kunstbauten - Straßenbrücken. RVS 13.03.11
- UIC Code 778-3, Recommendations for the inspection, assessment and maintenance of masonry arch bridges, April 2011
- Wendner, R., Strauss, A., Bergmeister, K. and Frangopol, D. M. "Monitoring Based Evaluation of Design Criteria for Concrete Frame Bridges". IABSE Symposium 2010. Venice, Italy, IABSE, AIPC, IVBH. Report Vol. 97: 7, 2010
- Zilch, K., Weiher, H. and Gläser, C. "Monitoring im Betonbau". Betonkalender 2009. K. Bergmeister, F. Fingerloos and J. D. Wörner. Berlin, Ernst und Sohn. 2, 2009
- Zimmermann, T. and Strauss, A.: Masonry and Earthquakes: Material properties, Experimental testing and Design approaches. In: Moustafa, A. (Ed): Earthquake Research and Analysis / Book 4, ISBN 979-953-307-680-4, Intech, 2011.

