Historical stone arch bridges under horizontal debris flow impact

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ABSTRACT: Many historical arch bridges are situated in Mountain regions. Such historical bridges may be exposed to several natural hazards such as flash floods with dead wood and debris flows. For example, in the year 2000 a heavy debris flow destroyed an arch bridge in Log Pod Mangartom, Slovenia and only recently, in September 2008 an arch bridge was overflowed by a debris flow. A new launched research project at the University of Natural Resources and Applied Life Sciences, Vienna tries to combine advanced numerical models of debris flows with advanced models of historical masonry arch bridges under horizontal loads. The research project starts with separate finite element modelling of different structural elements of arch bridges such as spandrel walls, the arch itself, roadway slabs, pavements and foundations under single and distributed horizontal loads. Furthermore miniaturized tests are planned to investigate the behaviour of the overall bridge under debris flow impacts. The results will be used to combine the modelling of the different structural elements considering the interaction during a horizontal loading. Furthermore this bridge model will then be combined with debris flow simulation. Also earlier works considering horizontal ship impacts against historical arch bridges will be used control. The paper will present latest research results.

1 INTRODUCTION

1.1 Background

Bridges are a major part of the infrastructure system in developed countries. It has been estimated that in the USA about 600,000 bridges (Dunker 1993), in the UK about 150,000 bridges (Woodward et al. 1999), in Germany about 120,000 bridges (Der Prüfingenieur 2004) and in China more then 500,000 road bridges (Yan and Shao 2008) exist. Historical stone arch bridges still represent a major part of this multitude. It has been estimated that 60 % of all railway bridges and culverts in Europe are arch bridges (UIC 2005). Recent estimations regarding the number of historical railway natural stone arch bridges and culverts in Europe lie between 200,000 (UIC 2005) and 500,000 (Harvey et al. 2007). Also in some regions in Germany about one third of all road bridges are historical arch bridges (Bothe et al. 2004, Bartuschka 1995). Dawen & Jinxiang estimate that 70 % of all bridges in China are arch bridges.

The success of historical natural stone arch bridges - which are often more than 100 years old - is based on the excellent vertical load bearing behaviour (Proske et al. 2006) and the low cost of maintenance (Jackson 2004) - not only in mountainous regions. However, changes in loads or new types of loads (Hannawald et al. (2003) have measured 70 tonne trucks on German highways under regular traffic conditions and Pircher et al. have measured 100 tonne trucks) might endanger the safety of such historical structures. Obviously, bridges with an age of more than 100 years were not designed for motorcars since this mode of transportation has only been in existence for approximately 110 years. The increase of loads does not only include vertical loads but also horizontal loads in the longitudinal direction and perpendicular to the longitudinal direction of these bridges. For example, the weight of inland waterway ships in Germany has increased dramatically in the last decades, which also corresponds with increasing horizontal ship impact forces (Proske 2003).

Furthermore some loads from natural processes such as gravitational processes may not have been considered during the design process of the bridges. Especially in mountain regions this gravitational processes (debris flow impacts (Zhang 1993), rock falls (Erismann and Abele 2001) and flash floods (Eglit et al. 2007) including water born missiles or avalanches) can cause high horizontal impact loads.

1.2 Historical Events

In the year 2000, a debris flow destroyed two bridges in Log Pod Mangartom, Slovenia, one of them was a historical arch bridge. In October 2007 the historical arch bridge in Beniarbeig, Spain was destroyed by a flash flood. Similarly the Pöppelmann arch bridge in Grimma, Germany was destroyed in 2002, in 2007 a farm track and public footpath arch bridge over the River Devon collapsed.

Figure 1: Debris flow impact at the Lattenbach (Proske & Hübl, 2007)

Fig.1 shows an example of the historical arch bridge at the Lattenbach, before and after a debris flow event, where the bridge is nearly completely filled with debris.

Due to far too expensive solutions or not applicable methods for historical arch bridges it would be very useful if models were available to estimate the load bearing capacity of historical masonry arch bridges for horizontal loads perpendicular to the longitudinal direction.

Since intensive research was carried out for the development of models dealing with vertical loads for historical arch bridges, there is an unsurprising lack of models capable for horizontal impact forces against the superstructure. This might be mainly based on the assumption that horizontal loads are not of major concern for this bridge type due to the great death load of such bridges.

The goal of this investigation is the development of engineering models describing the behaviour of historical natural stone arch bridges under horizontal forces, mainly debris flow impacts, focused strongly on the behaviour of the superstructure and based on numerical simulations using discrete element models and finite element models.

2 INNOVATIVE ASPECT AND GOALS

2.1 Innovative Aspects

The conservation of historical arch bridges is not only an issue of the preservation of cultural heritage but is also an economic issue since the number of historical bridges in developed countries is huge (Proske 2009). Compared to vertical load cases no models currently exist for horizontal loads perpendicular to the longitudinal direction. It is therefore required to develop new models dealing with these capacious horizontal loads which include all types of gravitational hazards like avalanches, debris flow, rock falls or flood borne missiles or impacts from modes of transportation. First works related to the development of debris flow design impact forces and the behaviour of arch bridges under such an impact have started already 2007 at the Institute of Alpine Mountain Risk Engineering at the University of Natural Resources and Applied Life Sciences, Vienna (see Fig.2)

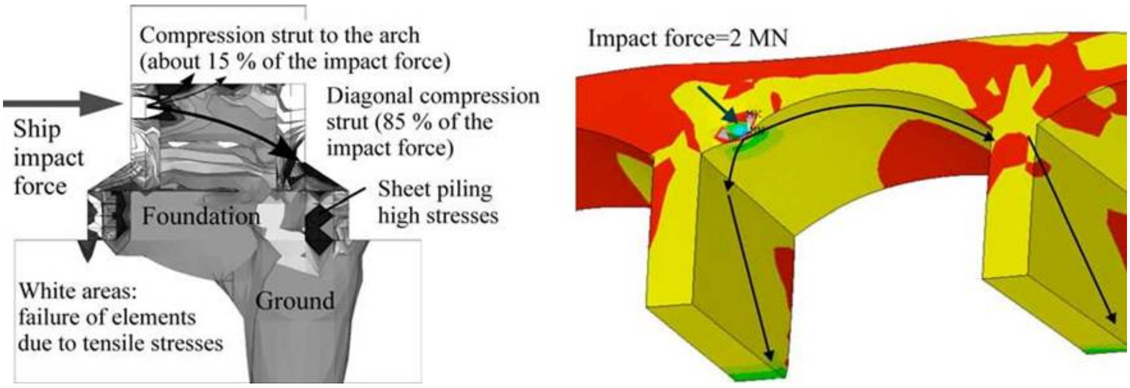

Figure 2 : Examples of the structural behaviour under impacts (left against the pier, right against the arch itself) (Proske and Hübl 2007)

This investigation and its results regarding debris flow impact will flow into the development of the new Austrian code of practice Ö-Norm 24801 for the design of structures exposed to debris flow impacts as well.

2.2 Goal

To develop load bearing behavior models of historical natural stone arch bridges under horizontal loads perpendicular to the longitudinal direction, a realistic model of debris flow against solid structures has to be implemented indifferent programs. Separate finite element modelling of different structural elements of arch bridges such as spandrel walls, the arch itself, roadway slabs, pavements and foundations under single and distributed horizontal loads are part of this investigation. Furthermore miniaturized tests are part of the project to investigate the behaviour of the overall bridge under debris flow impacts. The results will be used to combine the modelling of the different structural elements considering the interaction during a horizontal loading. Furthermore this bridge model will then be combined with debris flow simulation. Also earlier works considering horizontal ship impacts against historical arch bridges will be used.

Therefore three models of historical arch bridges are developed:

(1) Discrete element program model (PFC),

(2) Explicit finite difference program model (FLAC),

(3) Finite element program model (ANSYS, ATENA).

The first and second models are developed to simulate an overall debris flow impact scenario, whereas the third model is used to investigate details, such as single force against a spandrel wall, single force against parapets, friction at the arch, single impact force against the arch.

Results from the impact simulation against the superstructure should give an answer, whether the complete process can be separated into forces acting on the bridge. This reference force (force-time-function) will then be applied on the finite element models.

The numerical modelling will be accompanied by testing to permit validation of the models. The tests will be carried out as miniaturized tests (scale about 1:20…50). Already miniaturized tests of the impact of debris flows against debris flow barriers were already carried out at the Institute of Mountain Risk Engineering (Proske et al. 2008, Hübl & Holzinger 2003,Fig.3). Based on this experience, miniaturized arch bridges (span about 40 to 50 cm) will be constructed and investigated. Also single parts of the arch structure will be investigated in testing machines, such as behaviour of a pure arch under a horizontal load. Since the machine cannot be turned, force redirection mechanisms will be used to allow the application of a standard compression test machine from the University of Natural Resources and Applied Life Sciences, Vienna.

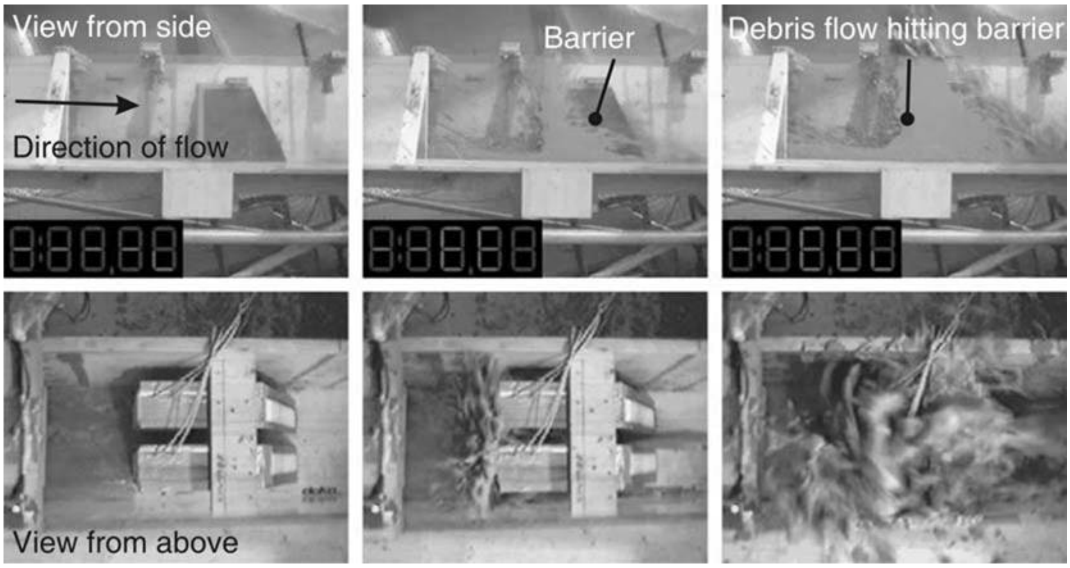

Figure 3 : Side view and view from above of the used debris flow impact measurement test set-up (Hübl & Holzinger 2003)

3 CALCULATIONS

3.1 Discrete element methods

Discrete element modeling can be done by usingPFC3D (Particle Flow Code 3D) which is used in analysis, testing and research in any field where the interaction of many discrete objects exhibiting large-strain and/or fracturing is required. By using the program PFC3D, materials can be modeled as either bonded (cemented) or granular assemblies of particles.

3.2 Finite element methods

The finite element method (FEM) is one of the most powerful computer methods for solving partial differential equations applied on complex shapes and with complex boundary conditions. A mesh made of a complex system of points is programmed containing material and structural properties defining the reaction of the structure to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a certain area.

Two types of analysis are commonly used: 2-D modelling and 3-D modelling. 2-D modelling allows the analysis to be run on a normal computer but tends to yield less accurate results whereas 3-D modelling shows more accurate results.

For this investigation two FEM programs are used:

(1) ANSYS

(2) ATENA

ANSYS is the leading finite element analysis package for numerically solving a wide variety of mechanical problems in 2D and 3D. By using ANSYS, the analysis can be done linear and non-linear, is applicable to static and dynamic structural analysis, heat transfer and fluid problems as well as acoustic and electromagnetic problems.

The ATENA program is determined for nonlinear finite element analysis of structures, offers tools specially designed for computer simulation of concrete and reinforced concrete structural behaviour. Moreover, structures from other materials, such as soils, metals etc. can be treated as well.

In the first step finite element methods are used to simulate the behaviour of historical natural stone arch bridges under an impact. Required data for the debris flow models are taken from the database of the Institute of Mountain Risk Engineering as well from the Austrian Railway Service (ÖBB).

The basic requirements for an appropriate assessment of stone arch bridges are:
(1) Choice of a realistic calculation model
(2) Consideration of geometrical and material nonlinearities
(3) Using applicable material models for masonry
(4) Adapted evidence based on the chosen material models.

Therefore, a simplified arch bridge model with various lengths (L), rising of the vault (r) and thickness of the stone arch (t) was chosen (Fig.4) – first by using a two-dimensional model – with the purpose to investigate the importance of geometrical properties to their structural performance and to demonstrate different results. Further models are in process and will be implemented in the FEM programs as well.

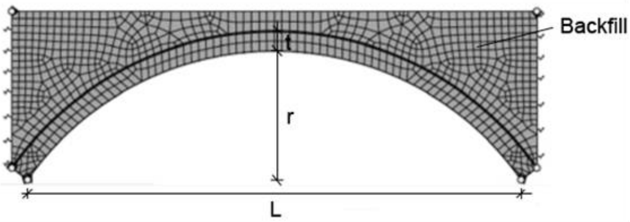

Figure 4 : FE model of a simplified arch bridge (Becke, 2005)

4 CONCLUSIONS

This research project launched by the University of Natural Resources and Applied Life Sciences, Vienna combines advanced numerical models of debris flows with advanced models of historical masonry arch bridges under horizontal loads. It started with the implementation of separate finite element modelling of different structural elements of arch bridges. Furthermore miniaturized tests will be done in 2010 to investigate the behaviour of the overall bridge under debris flow impacts. The results will be used to combine the modelling of the different structural elements considering the interaction during a horizontal loading and the bridge model will be combined with debris flow simulation.

Last but not least recommendation values for such bridge types should be given by this investigation that may include further formulas considering for example the adaptation of masonry stiffness or strength values.

5 AKNOWLEGEMENT

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