Historical arch bridges under horizontal loads

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ABSTRACT: Arch bridges are designed to transfer vertical loads. For such loads these types of bridges show an extremely efficient load-bearing behaviour. In contrast, horizontal loads such as ice impact have destroyed many arch bridges. The authors have investigated horizontal ship impacts and debris flow impacts again historical stone arch bridges, which can reach dramatic impact forces. An example from Austria, where the debris flow has reached up to 10 m height, is shown. The impact forces are mainly taken from the piers (about 80%, depending on the height of the impact). Horizontal loads against the bridge arch are in most cases not considered, but for some load conditions it might be required, such as for debris flow. The paper gives examples for the consideration of such horizontal loads either to the piers or the arch.

1 INTRODUCTION

1.1 Problem

Historical bridges are still a major part of the infrastructure system in many countries. In some regions, for example in Zwickau, Saxony, Germany, 1/3 third of all the road bridges are natural stone arch bridges (Bothe et al. 2004). Bartuschka (1995) estimated that 32% of the 4,000 road bridges in Saxony are stone or concrete arch bridges. Schmitt (2004) estimates that about 1/3 of all railway bridges between 10 and 20 m span in Germany are historical arch bridges. The estimated number of arch bridges in other countries, such as in Great Britain shows comparable figures of between 20,000 and 40,000 (Orbán 2004, Melbourne et al. 2004, Murray 2004). A summary about the number of arch bridges in different countries can be found in Proske et al. 2006.

Information about the amount of historical arch bridges exposed to major horizontal loads is rather rare. The German federal waterway engineering and research institute in Karlsruhe, for example, maintains a list about bridges exposed to possible ship impacts but unfortunately not in general for horizontal loads. In addition, the owners of the bridges are different as well (federal state, community). These owners classifying bridges into endangered or safe categories have different guidelines for the evaluations including different considerations of horizontal forces. As a result, the number of potential to horizontal loads exposed arch bridges remains to be calculated. The first estimation of the number of historical bridges in Germany endangered by ships is said to be between 50 and 100 (Proske 2003).

The first author of this paper has investigated the event of ship impacts intensively (Proske 2003, Proske & Curbach 2006). His investigations have shown that such major horizontal loads can be observed, but they are only one type of horizontal loading. There are of course other types of horizontal forces, and these are described in this paper as well.

2 IMPACT FORCES

2.1 Classes of horizontal forces

Horizontal forces can be classified into different groups according to the causal agent:

- a) Impacts from technical transport systems or vehicles
- b) Natural mass movements (gravitational processes)
- c) Debris inside natural mass movements: wind / flood induced debris flow

Little information is available for the latter classification, as not much research has been carried out in this area.

2.2 Types of impacts

Horizontal forces already include assumptions about the characteristics of the impact. Socalled soft impacts permit the separated investigation of the hitting body and the struck body. This is not possible for hard impacts as the conservation of energy and conservation of momentum has to be considered. Fortunately many impacts can be considered as soft impacts. Soft impacts are defined as impacts where one body shows a much higher deformation capacity compared to the other body, which takes part in the collision. Under most conditions the hitting body, e.g. the colliding vehicle or the debris flow will show the greater amount of deformation. There are cases where this is not true. For example in fender systems against rock falls in the Alps. Therefore the unit required for their design is energy amount and the mitigation measures are designed by the required energy consumption. It is assumed that all events are soft impacts, where forces are used for the description of the impact. This assumption is demonstrated in figure 1. The left picture shows a ship after impact with a pier. The pier showed only little deformation but the ship experienced a deformation of about 50 cm. The right picture in figure 1 shows a railway wagon after impact with a roofing of a train platform. Also here the amount of plastic deformation is visible. Indeed the locomotive does not show high amounts of deformation, but in most accidents the locomotive does not derail nor hit piers. The important point for consideration is the fact that major plastic deformations in the hitting bodies limit the amount of forces, which can be activated during an impact. That is a reason why in many field the design impact forces fell over the last decades, even the weight of the hitting bodies increased.



Figure 1: Plastic deformations on a ship and a railway wagon.

2.3 Impacts by Ships

Arch bridges are heavily used to span transport routes such as roads, railway lines or waterways. Moving vehicles such as lorries, trains or boats use these routes. Ship impacts are first considered. A list of ship impacts against bridges can be found in Proske 2003. Figure 2 shows two examples, one from the year 2000 (left) and one from the year 1906 (right).

Ship impacts usually result in forces of a few MN, but may yield up to 20 or 30 MN. These major impact forces are not found on inland waterways, where historical arch bridges are situated. Here forces of about 10 MN are estimated. Lower values are possible depending on the size of the ship. It is noted that due to the difference in the structure inland waterway ships show different impact behaviour than ships on the sea. Meier-Dörnenberg 1984 (inland waterway ships)

and Woisin 1977 have carried out investigations in this area. A time-force-curvature for a ship impact is shown in figure 3 (above right).



Figure 2: Ship impact.

2.4 Impacts by trains

Impacts of trains are usually connected with the derailment of wagons. Examples are rare where locomotives are derailed. If a locomotive hits a body the forces are much higher comparing the hit of a wagon. In the codes of practice impact forces up to 10 MN can be found.

2.5 Impacts by automobiles

Design impact forces for cars and lorries are in the range of 1 MN but measurements show that values over 2.5 MN are common (Rackwitz 1997) and values of 32 MN have been detected by DaimlerChrysler on a road tanker (Wolf 2001). The maximum measured impact force depends heavily on the stiffness of the car elements. Usually the maximum is reached when the motor of a vehicle hits the wall. Figure 3 (above left) shows typical impact forces by cars. It is obvious that the impact duration is much shorter than during ship impacts. This might be of importance for the calculation of historical arch bridges because the duration of the force might cause same inertia of mass inside the bridge.

2.6 Impact forces by debris flow and rock fall

Bridges not only cross traffic routes they also cross the deepest lines in the surroundings. Such lines are under certain conditions, which can be found in mountain regions, exposed to mass movements. Such mass movements might include the natural movement of debris flow, rocks, landslide, floods or avalanches (channel processes).

Debris flows are extremely mobile, highly concentrated mixtures of poorly sorted sediment in water (Pierson 1986). The material incorporated is inherently complex, varying from claysized solids to boulders of several meters of diameter. Due to their high density (exceeding that of water by more than a factor of two) and their high mobility, debris flows represent a serious hazard for people, settlements, and infrastructure in mountainous regions. The front of a debris flow can reach velocities up to 30 m/s (e.g. Costa 1984, Rickenmann 1999) and peak discharges tens of times greater than for floods occurring in the same catchment area (e.g. Pierson 1986; Hungr et al. 2001). It is difficult to quantify annual economic losses due to such phenomena, however, only in the year 2005 more than 80 million Euro were spent in Austria for protection measures against torrential hazards (including floods and debris flow) (WLV 2006).

The impact forces by debris flow are classified as dynamic pressure and impact force of boulders (fig. 3 bottom). Such impact force of boulders might reach up to several hundred MN. A major stone boulder (1,500 tons) found in Kreuzerbach in Austria, could have an impact force of up to 400 MN. Zhang (1993) described the failure of a railway bridge by a single boulder impact with 50 MN. The failure caused about 150 casualties. In addition Zhang (1993) measured an impact with 3 MN. Measurements by the authors have shown forces up to 1 MN (Kaitna et al. 2007). Deng (1996) investigated impact forces by debris flow with lower values.



Figure 4 shows an arch bridge before and after a debris flow. The bridge is easily visible in the left picture but in the right picture only the top of the bridge is visible.

Figure 3: Typical force-time-function for impacts (above left: car and bus, above right: ship impact, bottom left: viscous debris flow, bottom right: single bolder in debris flow)



Figure 4: Debris flow impact (on the right picture only a small part of the bridge is visible).

2.7 Impact forces by avalanches

Voellmy first investigated avalanches and their impact forces in 1955. Usually according to hazard zone mapping in Austria or Switzerland, avalanche impact forces are considered with approximately 10 kN/m². Some measurements gave values up to 150 kN/m².

2.8 Impact forces by flooding

Flooding involves several horizontal forces. At first the higher water level yields higher water pressure. Additionally the speed of the water increases and erosion might occur. Figure 5 shows the flooding of the Pöppelmann Bridge in Grimma, Germany. On the left picture it is seen that the water is overtopping the bridge. On the right picture parts of the historical stone arch bridge are shown. The damage caused by erosion is clearly visible. The bridge was blasted afterwards.

Arch bridges are of major importance to flood considerations since this type of bridge might increase the area flooded due to is limited cross section. This becomes clear in figure 6, where a diagram for water level versus water discharge is shown. There are two lines in the diagram: The bottom line (connoted to the triangle) shows the water level if there was no arch bridge present. The top line shows the water level including the bridge in the model. The sudden rise of the water level can be seen at a discharge of approximately 2,000 m³/s. The triangle shows the difference to the maximum water level during the last major flooding in 1954 (1.7 m). Recapitulating, the existence of the bridge caused another 2.1 m. After the flooding in 2002, the arch bridge was heavily criticized as the cause of flooding of major parts of the city.



Figure 5: Overflow of the Pöppelmann Bridge (left) and bridge after flooding.



Figure 6: River depth versus discharge at the Grimma's Pöppelmann-Bridge

2.9 Impact forces by debris flow inside mass movements

Even impact forces by debris flow inside mass movements can be considered. Figure 7 gives a good impression of debris in water at the inlet of an arch bridge during a flooding.

2.10 Impact forces by ice

Also ice loading or ice impact can cause significant forces. Historically many bridge failures were caused by ice impacts. Ice loading depends strongly on the climatically conditions of the location of historical stone arch bridges. In Canada for example, major research has been carried out about ice loadings but the number of arch bridges is rather limited. On the other hand in Great Britain ice loading is not of major importance (Rail & Safety Standard Board 2004) but the number of arch bridges might be considerably higher. In general, the American Association

"Standard Specifications for Highway Bridges" (AASHTO, 1993) gives some recommendations for the calculation of ice loads. The value of the ice load might rise up to several MN.



Figure 7: Debris during flooding 2002 in front of a concrete arch bridge (Dresden)

2.11 Horizontal forces by earthquakes

Horizontal acceleration by earthquakes might cause horizontal forces too. Again, such conditions depend very strongly on the geographic location of the bridge. Rota (2004) has shown some examples of sidewall failures caused by earthquakes, where the walls just overturned. There are several technical solutions for that problem possible. In contrast to all other horizontal loads (may be except the horizontal forces from the deck load), the forces might cause tension at some structural elements, whereas all other loads first cause compression of the hit structural element, which then might also yield some tensile forces due to the force flow inside the structure.

2.12 Horizontal forces from road deck

Last but not least horizontal forces can arise from traffic load above the deck. For example railways might derail and cause an impact on elements of the sidewall. Especially for road bridges about 100 kN have to be considered.

3 RESISTANCE

3.1 Introduction

Several elements of arch bridges can be affected by impact forces. In this paper only piers and arches are considered.

3.2 Piers

Calculation examples show that due to the high stiffness of the piers of historical arch bridges only small amounts of the force migrate over the arch if the pier is hit directly. In the calculations carried out about 85 % percent of the impact forces were transferred directly from the pier to the foundation. 15 % were transferred over the arch, where a double arch was considered. Therefore only 7-8 % of the force was transferred over one single arch. On the left side of figure 8 the model including the location of the impact force is shown. Right above in figure 8 a cross section through the pier hit shows the principal stress inside the pier during a horizontal impact. In this example so called explosion chambers were found and had to be considered in the model

since they influence the migration of the force inside the pier. In general, the consideration of impacts on piers happens quite often for new build bridges.

3.3 Arch

During indirect loading, such as impact against the pier, the forces for the arch are rather low and the arch usually can take the load. Events considering a direct hit against the arch are in many cases not considered because the probability of such impacts happening is extremely low (less then 10^{-4} per year). Therefore not many investigations are carried out in that field and further research is required since the load bearing mechanism of the arch in such situations does not alone follow the traditional mechanisms: torsion has to be required as well. Preliminary calculations by the authors show that the consideration of the joint characteristics of the different elements of the superstructures (arch, backfill, sidewall, road or railway) is essential for modelling of such a force flow. Nevertheless the resistance capability is quite impressive (fig. 8 right bottom).



Figure 8: Finite Element Models of historical arch bridges considering impact (the left and the top right picture are considering horizontal impacts on piers, whereas the right bottom picture considers an impact against the arch)

4 CONCLUSION

Horizontal impact forces caused by accidental loads show a great diversity. They might be important for the existence of historical arch bridges, since under such conditions extreme stresses can occur. Since horizontal impacts are usually accidental loads with low probabilities, historical arch bridges with there extreme long life time and there ample horizontal face might be more exposed than other structures.

As demonstrated the resistance to such forces is quite impressive for both the pier and the arch itself. Nevertheless this type of load seems to be still underestimated. Only in the last few years the awareness of horizontal accidental loads has increased. The application of such experience together with the sophisticated modelling of historical arch bridges still requires further work.

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