Measurements of dynamic deformation behaviour of masonry arch bridges

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ABSTRACT: The deformation behaviour of masonry arch bridges due to train crossing was intended to be recognized by dynamic measurements. For this purpose a pilot field test was created. The gained experiences should help to demonstrate the technical and economical feasibility. The improved measuring system should lead to a standard test to get knowledge about change of condition and force flow and the influence of damage and fill material of masonry arches.

1 INTRODUCTION

Due to increasing traffic volume (number of trains, higher speed and axle loads) masonry arch bridges are exposed to dynamic loadings for what they are definitely not to be designed. Many of the existing damages can be derived from this in direct or vicarious ways.

Dynamic actions to the arch are effected from the existence of backing, material properties and degree of compression.

General permission for increased axle loads or speed on masonry arches can lead to irreversible deterioration which may occur in the medium term.

This pilot project measuring the deflection of arches should recognize deteriorations and their time-depending developing at an early stage and save life time of masonry arches.

Before allowance for increasing speed or axle loads should be given, the measuring of the dynamic behaviour due to train crossing should be carried out on arches with a fill depth up to 1.5 m above the crown.

A pilot project has been initiated to check the defined objectives. The measurements took place on 28th April 2006 on the railway line connecting the towns of Wiener Neustadt and Sopron at the Hungarian border. The chosen masonry arch bridge carrying out the measurements is situated in km 19.734 near the village of Rohrbach. This masonry arch bridge, consisting of 5 openings each 6 m span, was built in 1847 and is in original condition without any interferences and repairs. The arch thickness is about 0.62 m, representing two brick length dimensions. The untypical arch shape is three-centered. Most of ÖBB-arches have semi-circular shape.

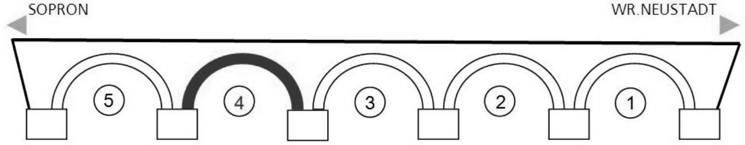

Figure 1 : Sketch of location of measuring activities

Important criterion for the pilot test was the easy accessibility to install and measure without deadline pressure or boundary conditions, see Fig. 1.

2 DEFINITION AND SPECIFICATION

2.1 Accuracy of sensor and precision of fastening

The resolution of the applied displacement transducers and the sampling rate were chosen to 0.01mm and 100Hz. Thus, the dynamic movement of the masonry arch bridge during train crossing will be recorded sufficiently. The chosen displacement transducers of series CDP-10 and CDP-25, respectively, are based on strain gauge principle and show a high output signal, an excellent long-term stability and a high precision, see Fig. 2. The applied transducers are best suited for dynamic measurements and show a high resistance in case of adverse environmental conditions. The maximum displacement of the transducer is limited by 10 and 25 mm, respectively.

In order to fix the transducers to the masonry arch a special rack made of aluminium was created. The rack serves the sub construction for the transducers, where a space of about 0.3 m between rack and surface of the masonry arch at the point of measurement should be provided. In order to avoid loss of contact of the transducers to the surface, which may lead to falsifications of the measured data, the top of the sensing device of the transducer was non-relocatable fixed on the surface of the masonry arch. Hence, the movements of the masonry arch are transmitted directly to the displacement transducers. Due to the very low mass of the sensing device of the transducer a negligible inertia force growths up during train crossing and resulting arch vibrations, respectively.

Figure 2 : Photograph of applied displacement transducer

2.2 Measuring system and analysis

The measuring system should perform the conditions of simplicity in view of assembly and disassembly, appropriate for outdoor measurements, consisting of only a few components, less space requirement, possibility to fasten a lot of transducers and the direct in situ release of the measuring data without special transformations.

The chosen measuring system consist of a special designed rack, the hereon fixed displacement transducers connected to StrainBUSters and a CAN bus cable to one convenient central place, e.g. laptop. The StrainBUSter perform A/D-converting, where each StrainBUSter has 2 separate input channels. For the communication between laptop and StrainBUSter, the CAN bus is used. The speed of the CAN bus is chosen according to the total cable length of 100 m to 500 kbit / s. In the chosen configuration of the measuring system the simultaneous use of a total number of 45 displacement transducers would be possible. The in situ analyses as well as post processing of the recorded arch displacements due to train crossing were performed by a standard measuring software providing data files in txt-format which can be easily handled by commercial software tools like excel, e.g..

Within the pilot project a total number of five displacement transducers have been fixed on the rack and the masonry arch, respectively. The measuring points were situated at the intrados of both abutments, at the crown and the both third points underneath the range of one rail, see Fig. 3.

Figure 3 : Photograph of position of measuring points and special designed rack

2.3 Mobile flexible light aluminium rack to fix the displacement transducers

The technical and economic requirements for the framework are flexibility, stability and simplicity. The assembly and disassembly of the framework should be made by only 2 persons and in short duration. Furthermore, the approximation of the shape of masonry arches with variable span should be possible.

In view of the posed technical and economic requirements a special rack consisting of aluminium ladder elements with variable inclination of the joints has been designed, see Fig. 3. Each ladder element has a length of 1 m and two transverse girders are mounted between in order to stiffen the element. The position of transverse girder is variable and serves additionally for the mounting of the displacement transducers. The approximation of the framework to the shape of the arch is performed by proper chose of the number of ladder elements. The variation of the number of ladder elements allows the application of the framework to arches up to 10 m span.

Figure 4 : Photograph of the developed mass-spring-system at the base of the framework

In order to keep the vibrations of the framework due to dynamic actions during train crossing as small as possible a mass-spring-system for the basement has been developed. The mass and spring of the system are given by the self weight of the framework and by conventional car tyres, see Fig. 4. In case of dynamic ground vibrations the mass-spring-system acts like a low-pass filter where a wide range of the excitation energy is significant reduced, see Kothmayer et al. (2006). The realized mass-spring-system decouples the dynamic ground movement and the vibrations of framework. In case of vibrations due to strong winds it is essential to seal the arch entrance off from the outside.

In Fig.4 it is shown that the tyres and the base plate are screwed together, where horizontal adjustments are achieved by thread rods with screw-nuts.

In order to prove the effectiveness of the mass-spring-system a field test has been performed. The obtained results show, that due to impacts close to the tyres no vibrations of the framework can be observed.

In addition at the measurement day the excitations of the framework due to wind gusts were found to be negligible. Nevertheless, for such reasons like winds or other unfavourable weather conditions, a canvas top is planned to be fixed and hung up at both sides of the spandrel walls to close the opening.

3 DYNAMIC MEASUREMENTS

3.1 Results

After the installation and check of the equipment, 14 trains had been measured and recorded by video. All vehicles and their axle loads and axle arrangements could be identified.

The type of traffic on this line is characterised by passenger trains, either locomotive hauled trains or motor coaches of series ÖBB 5047. As the line is not electrified, only one kind of series of diesel locomotives , the "Hercules" ÖBB 2016, are used for operation, see Fig. 5.

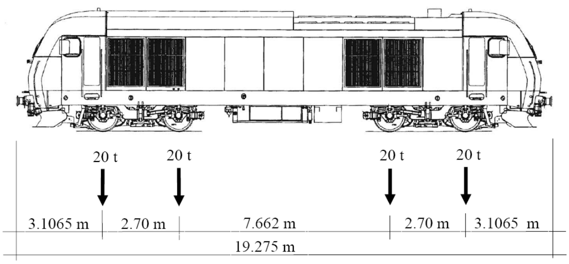

Figure 5 : Locomotive ÖBB 2016

The operating trains and their time of arrival were well known because the train time table had been studied in advance. The maximum axle loads of the vehicles are listed in Table 1.

Table 1 : Axle loads.

	Axle load (t)
Diesel locomotive 2016	20.0
Passenger coaches	8,0 and 10.5
Motor coach 5047	11.5

The sensors were located underneath of one rail profile and not in track axes. The measurements due to train crossings could be observed "online", so that the success of the recording data could be checked immediately on site.

The measured data files could easily be transformed to Excel-format for further editing and handling without the use of specific transformation tools or special software products.

The speed level of the trains was in the range of 50 km/h to 90 km/h. Although the axle loads and speed level had been low, typical expected deformation arch behaviour could be indicated.

3.2 Analysis

Although the values of the measured deflections are located at a range of tenth of millimetres, the influences of the bogies of the locomotive of 20 t axle load, but even of the passenger coaches and motor coach 5047 could be identified. The maximum measured deflection was three tenth of millimetres.

Fig. 6 documents the chronological deflection behaviour of the arch during a locomotive hauled train is passing from the left to the right sides of the arch barrel.

Looking at the time period from 0.0 to 0.5 seconds of Fig. 6, still before the locomotive bogie is on the arch, a lifting of the crown and the adjacent point on the right side opposite of the train approach could be observed. At the same time the abutment on the left is moving inside the opening with the maximum of one tenth of millimetre. This first period of half a second, where no axle or bogie is situated on the arch, could be influenced by the earth pressure caused by train approach.

Within the next period of less than half a second, the crown section is loaded and reloaded by the locomotive bogie, whereas both abutments move outwards toward the embankment. This recorded train crossing, shown in Fig. 6, took place with a speed of about 60 km/h. There is only a small identification of the single bogie axle.

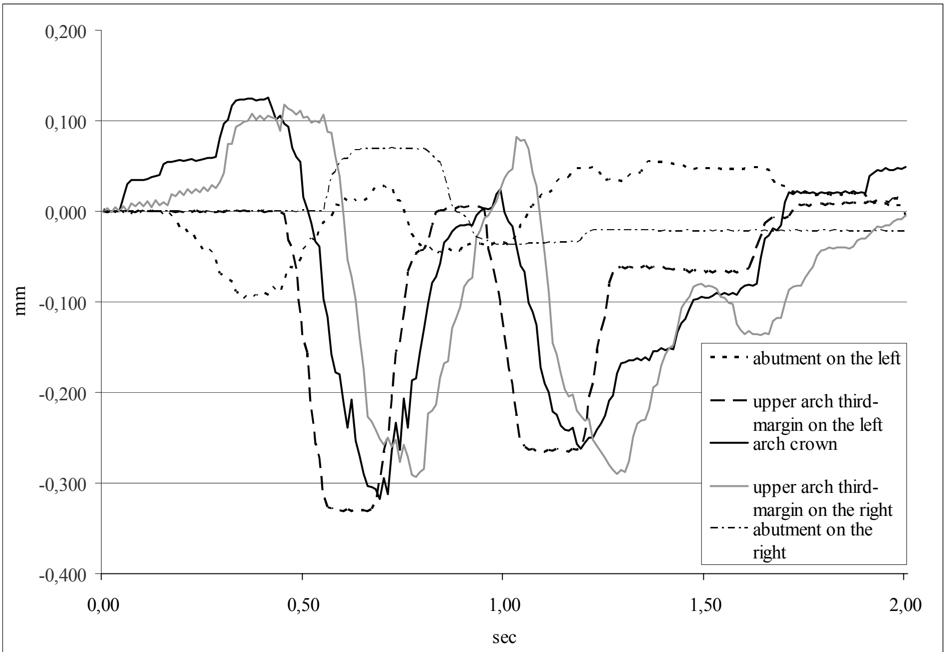

Figure 6 : Arch deflection due to 20 t axle locomotive at 60 km/h

Another result measured with a speed of 90 km/h shows that the sequence of loading is shorter and the shape of deflection gets a peak. At a speed of 90 km/h the deflection of the arch crown is explicit greater than the adjacent points.

Even according to the crossing of the light-weight motor coach 5047 with axle loads of 11.5 t the deformation behaviour and the influence of the bogie could be registered. In this case the maximum deflection of the crown was two tenth of millimetres. One of these registered motor coaches 5047 seemed to have bad running conditions. The impact and knocking on the track could be acoustically noticed. In this case the measured deflections had been duplicated.

Another phenomenon was the influence of the direction of traffic. In cases where the train operates from Sopron to Wiener Neustadt, from the left to the right, the arriving first bogie of the locomotive causes the maximum deflections. In the other way round, from the right to the left, the departing second bogie was relevant.

Due to the lack of data volume, these first results of the pilot project cannot be generalised. However, the received measurement data are worth to be interpreted at least.

4 IMPROVEMENTS AND FURTHER DEVELOPMENT

4.1 Choice of sensor type and fixing

The fastening of the top of the sensing device of the transducer to the masonry arch has exposed to be partly insufficient. After train crossing the screw anchors were checked and thereby some screws have found to become unfasten. The observed signal offset after train crossing is partly predicated on this fact. It is suggested to use special glue for fastening of the sensing device of transducers to the masonry arch or to use resin anchored bolts and screws. In view of following measurements a hinged connection via magnet is also suggested. Hence, canting of the sensing device will be disabled and an addition screw connection can be cancelled.

In alternative to the discussed mechanical displacement transducer it is suggested to use optical laser transducers, which are based on the principle of triangulation. The advantage of these sensors is the contact less fastening to the masonry arch, i.e. the optical sensor is only fixed on the framework. Hence, transfer of excitation energy during train crossing from the arch to the framework is impossible. After mounting the laser transducer to the framework a reflector on the arch surface is necessary. The accuracy in view of resolution and sampling rate of the optical sensors is equivalent to those of mechanical displacement transducers. One disadvantage of laser transducers are the prime costs, decreased in view of less installation and inspection costs.

4.2 Optimisation and extension of measuring devices

In addition to the measured dynamic deformations of the arch the corresponding time histories of train crossing and the actual train speed are relevant for data analysing. The quality and the conclusions of the dynamic analyses can be increased by comparing the actual deformation state of the arch with the actual position of the train bogie.

Within the following measurements it is suggested to install two light barriers in a defined distance laterally of the rail before and after the arch abutments. When the arriving train and the wheel set of the first bogie, respectively, passes the light barrier before the arch, the measuring system starts to record by sending a current pulse (automatic trigger). After crossing the arch and passing the second light barrier after the arch a second current pulse will be send to the measuring system. Hence, between the time differences of both recorded pulses the corresponding train speed can be evaluated.

Furthermore, the fastening of an increasing number of measuring points up to 14 (2 x 7) underneath the range of both rails are suggested. In addition the application of at least 2 accelerometers to the surface of the arch is suggested in order to study the dynamic excitations and vibration response during train crossing.

4.3 New Conception of rack design

Principally the practical suitability of the designed framework has been confirmed. However, due to the self weight of the ladder elements more than two persons were needed to built up the framework and some support elements had been arranged.

In view of following measurements the tested framework will be new constructed by considering the stability and stiffness problems. The new type of rack will have less self weight, two types of ladder elements with length of 0.5 and 1.0 m, the distance of both frames is about 1.4 m which performs higher stiffness and allows fixing sensors for measuring underneath both rails. If necessary some parts can be prefabricated and stiffening elements like towing ropes or tie-backs can be mounted.

5 CONCLUSIONS

Especially for masonry arches with small spans < 10 m and height of fill < 1 m the influence due to speed and axle load may cause dynamic impact. This leads to irreparable damages in a short time. The influence due to flat wheels increases this effect enormously.

Methods of repair have to be adopted due to the increasing dynamic influences. Mass-spring systems are able to protect the arch from dynamic impact.

Measuring dynamic arch deflection and other monitoring systems as well as non destructive material tests could help to understand the actual condition of the arch. Before allowing increased speeds or heavier axle loads detailed investigations should be done.

The results manifest the fact, that arches are loaded and reloaded due to one bogie. Train crossing induces many load cycles and dynamic effects to arches. Investigation in this field should be intensified to prevent arches to be overloaded due to increasing axle loads or speed taking dynamic cycling loading into account, see Melbourne et al. (2004).

The experiences gained from this pilot project are useful and encourage continuing this kind of test for masonry arch bridges.

The feasibility and effectiveness of this pilot project measuring the dynamic deformation behaviour of masonry arch bridges during train crossing have been demonstrated.

The recommended improvements resulting from the analysis of this pilot project will be adopted. A test series will be carried on to improve the modified equipment and to collect more data.

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