Experimental Modal Analysis of a Twin Composite Filler Beam Railway Bridge for High-Speed Trains with Continuous Ballast

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ABSTRACT: In the framework of the project DETAILS (Design for optimal life cycle costs of high-speed railway bridges by enhanced monitoring systems, contract-No.RFSR-CT-2006-00032), supported by the European Research Fund for Coal and Steel, dynamic tests are performed on a railway bridge between Aachen and Cologne in Germany. The monitored bridge consists of two parallel composite filler beam girders, each with one ballasted railway line. The bridge is used by normal- and high-speed passenger trains but also by freight trains. As a first step ambient vibration tests have been carried out to determine system properties in terms of system identification. The results of this campaign are presented within the paper. The next step will be the development and installation of a permanent monitoring system on the bridge, which will provide system information for a time period of two years. The aim of the dynamic tests is to get more information about the dynamic system behaviour so that a better prediction of the dynamic behaviour of filler beam bridges will be possible.

1 INTRODUCTION

1.1 The filler beam bridge „Erfttal Bridge“

The monitoring campaigns are performed on a composite filler beam bridge, which is called “Erfttal Bridge”.

Figure 1: View on the filler beam bridge “Erfttal Bridge” near Kerpen, Germany

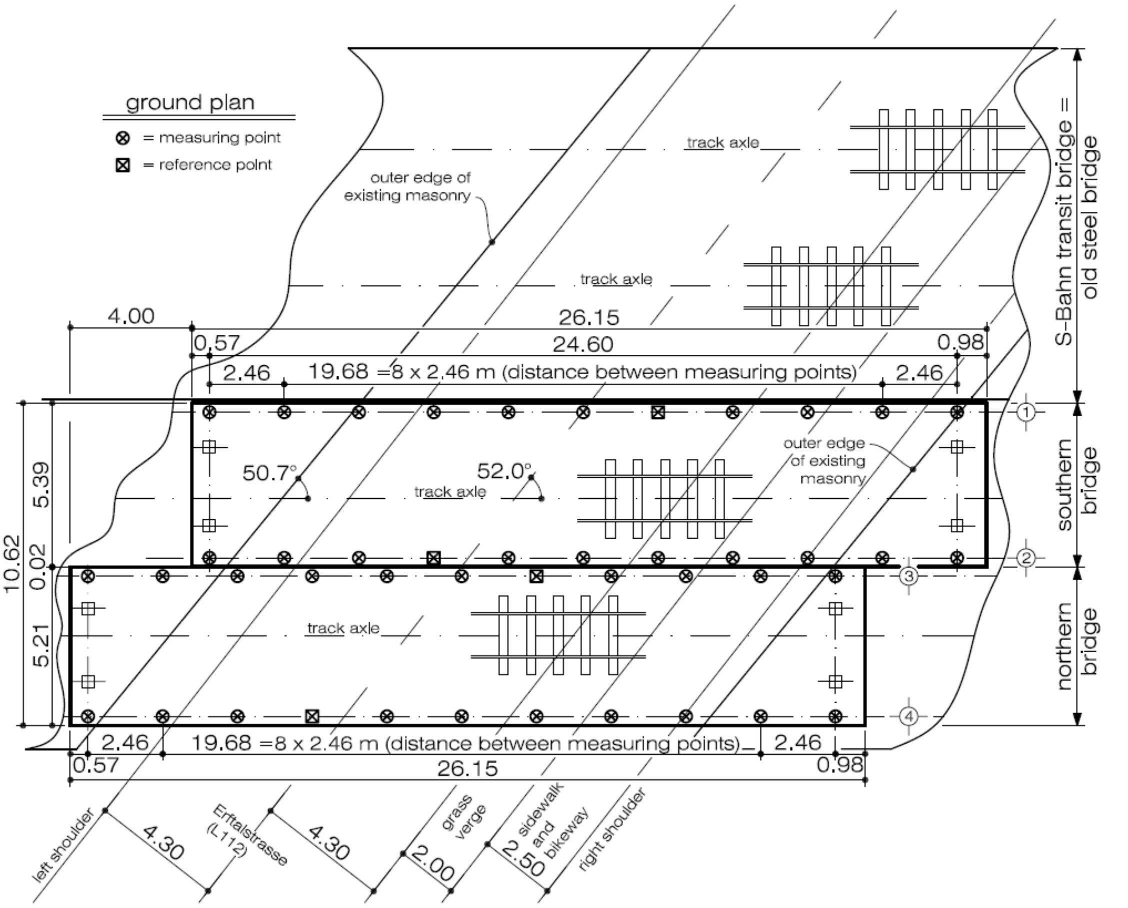


Figure 2: Erfttal Bridge (northern and southern bridge), plan view. Dimension in meters.

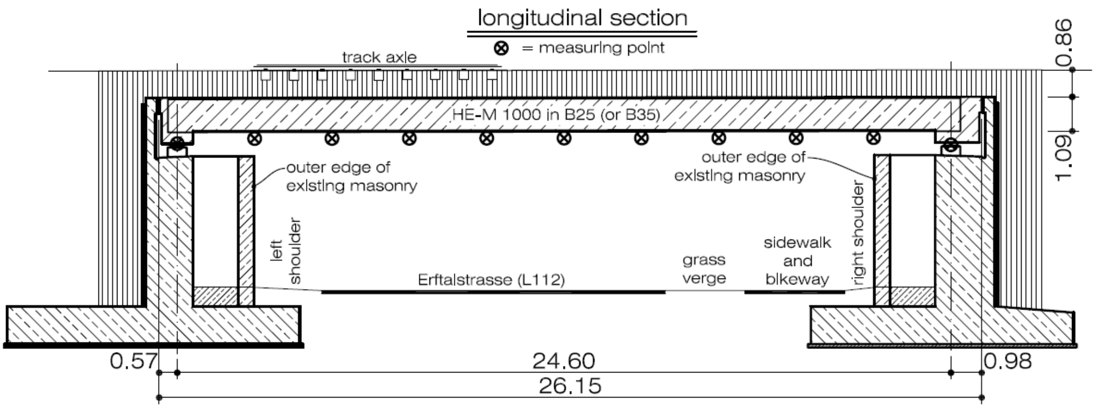


Figure 3: Erfttal Bridge, longitudinal section. Dimension in meters.

This railway bridge was built in the year 2000 next to an old steel bridge crossing the Erfttal-straße near Kerpen, Germany. It is part of the high-speed line between Cologne and Aachen where velocities up to 250 km/h are possible for ICE and the TGV trains. But not only passen-ger, also freight trains are using the bridge frequently.

The structure consists of two parallel sections divided by a 2.0 cm wide gap (Figure 4), whereas the ballast on the bridge is continuous. This construction type is often used by the

Deutsche Bahn Company. In this case interaction effects between the two substructures have to be expected. Each part of the Erfttal Bridge is a single span system with a span of 24.6 m and in both parts of the bridge eleven steel sections HEM 1000 are used. The depth of the cross section is about 1.10 m. Both substructures of the bridge are supported by four elastomer bearings, so that the substructures are not fixed in horizontal track direction.

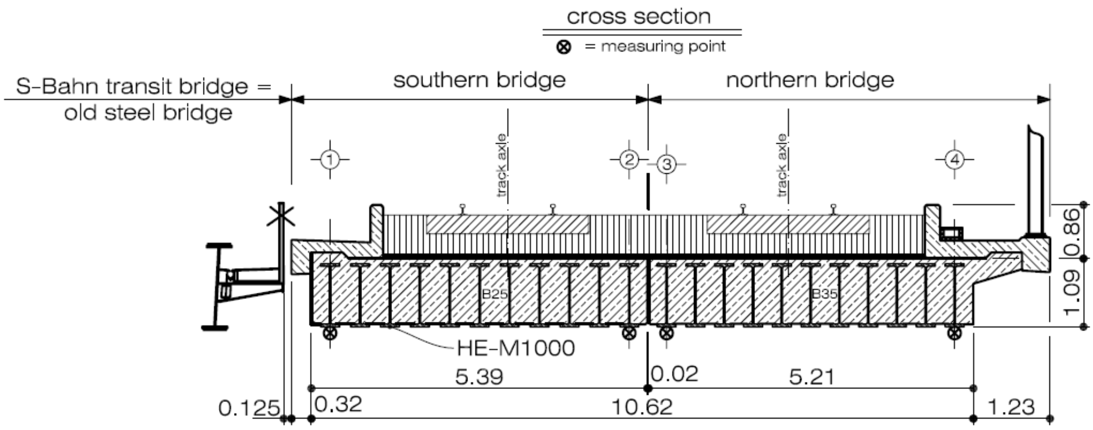


Figure 4: Erfttal Bridge, cross section. Dimension in meters. The measurement point lines 1 to 4 correspond to the ones given in Figure 2

1.2 Design of a composite filler beam bridge

For the design of composite filler beam railway bridges in Germany several codes, both European and national, have to be considered (CEN 2001; DIN 2003a, b; DB Netz AG 2003). Eurocode 1 (CEN 2001), which is implemented in DIN-Fachbericht 101 (DIN 2003a) defines the load models LM71 and SW/0 which are taken into account within the design process. Dynamic effects are considered by using a load factor Φ given also in Eurocode 1 to increase the static loads. However this approach is only allowed in case that resonance effects are not expected; if resonance effects might occur a dynamic analysis has to be carried out. Eurocode 1 provides a flow chart for determining whether a dynamic analysis is required. One of the main input values in this procedure is the first natural frequency.

Based on practical experience resonance effects are observed even though Eurocode indicates that there is no resonance to be expected; on the contrary bridges where resonance effects have been predicted show a favourable dynamic response. The reason for this incorrect prediction of the dynamic behaviour relates to the estimation of the first eigenfrequency and damping values, which differ from the real values. Also a more detailed dynamic analysis does not provide realistic results. The main challenge within the design procedure is the assessment of realistic system properties, so that the calculated dynamic reactions induced by train loads become reliable. In this regard e.g. the correct consideration of the ballast contribution is of great importance.

1.3 General aspects of the monitoring campaigns

The two monitoring campaigns of the Erfttal Bridge (ambient vibration tests and long term monitoring) are carried out in the framework of the European research project DETAILS. A main goal within this project is to gain knowledge about monitoring of bridge structures.

Bridge monitoring can be used effectively as an instrument to reduce maintenance costs and to optimize date and extent of repair work. Particularly the prevention of fatigue damage becomes an interesting application area of monitoring systems. But an important precondition for this application is the possibility of using the monitoring system for damage detection.

In this context one aspect of monitoring is of great importance: the proved coherence between the measured parameters and the linked process in the structure. That means that changes in the system behaviour, which have to be detected sufficiently by the monitoring system, can be related to a well-defined damage scenario without any doubt. If this coherence is not given or in question damage detection is not possible and the monitoring system does not provide the expected information. Therefore a systematic approach should be applied when planning, preparing and managing the monitoring system. Extensive knowledge of the structure is needed or must be achieved in the beginning of the monitoring campaign.

1.4 Aims of the monitoring campaigns

The ambient vibration tests, carried out in April 2007, have been performed to determine the system properties of the bridge in terms of system identification. The aim was to gain information about the structure for planning the long term campaign. Particularly the frequency ranges of the significant eigenfrequencies and maximum acceleration amplitudes during train passages are of interest for the long term sensor layout.

Furthermore the results of the experimental system identification were used for calibrating finite element models of the bridge using model updating techniques. This task is not discussed within this paper but is also an important part of the RFCS-project DETAILS. Also the measurement data of the long term campaign will provide extensive input for the model updating procedures.

By means of the monitoring campaigns the dynamic behaviour of the bridge and the changes in the dynamic behaviour due to long term effects are to be investigated. Aspects like concrete behaviour, slip between concrete and steel, contribution of tracks and ballast, bearing characteristics and climate influence are focused on.

The main goal of the monitoring project is to improve the current design concept, so that a better prediction of the dynamic behaviour of filler beam bridges is possible. Recommendations to estimate the first natural frequency more precisely would be a successful outcome in this context. The knowledge of the first eigenfrequency would allow a better adjustment of the design rules to the comfort criteria within the bridge design (cf. chapter 2.1).

But not only filler beam bridges, also other bridge types with similar properties are investigated in the framework of the monitoring project. Especially for bridges with fatigue relevant details the expected results are of high interest. It is intended to provide methods for damage detection (cf. chapter 1.3) and to improve design and calculation methods for the prevention of fatigue damages. These methods will be based on the knowledge of realistic loads and bridge response gained by the monitoring.

2 AMBIENT VIBRATION TESTS

2.1 Instrumentation

As mentioned above the ambient vibration tests were performed aiming at the verification and improvement of numerical models of the bridge. A prediction of the dynamic bridge properties by numerical methods only is very difficult, as there is a number of parameters which are not known sufficiently. The interaction between the two bridges caused by the common ballast, the contribution of the rails and the influence of the bearings can not be neglected and shall be determined by the measurements.

The girders had to be instrumented all along the gap and they had also to be instrumented close to the bearings. To be able to distinguish between bending and torsion, each girder was instrumented at the two outer steel beams (Figure 2 and Figure 4). This led to a rather dense grid of 44 measurement points. The number of references was chosen to 4. To cover the 40 remaining points in four setups, 10 moving sensors were necessary. The sensors measured the vertical acceleration. Two additional channels were used to check the behaviour of the bridge in the transverse and longitudinal directions.

The four setups had to be carried out in two days. As discussed later, the layout of the references' positions and the sequence of the measurement points to be covered by the four setups were heavily influenced by logistic boundary conditions. The first setups 1 and 2 were performed during day one, when the right part of the Erfttal road was closed (see top view on Figure 4). Setups 3 and 4 were performed during the second day, when the other part of the road was closed (see Figure 5). On both days the reference points in the middle of the bridge (Figure 2) had to be accessible.

Figure 5: View underneath the Erfttal Bridge on measurement day 2. Closed lane to the right, paved “green strip” and bicycle/pedestrian lane to the left

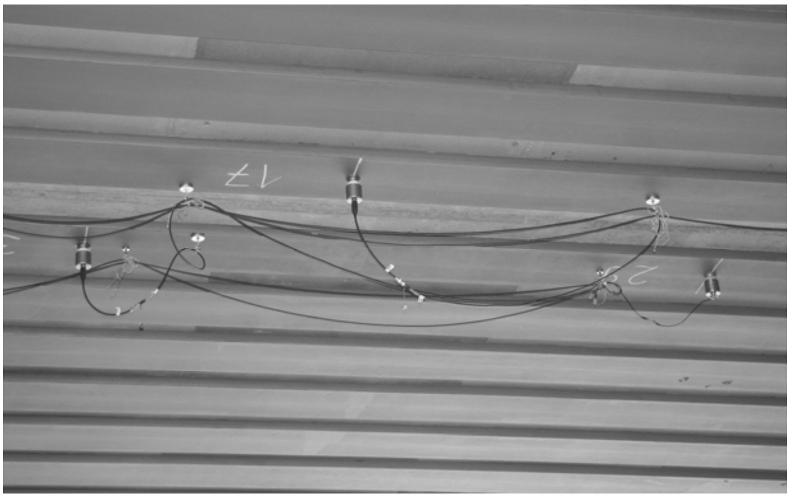


Figure 6: Attachment of PCB sensors and cable fixation by using magnets

The used sensor type was PCB 393B31 with a sensitivity of 10 V/g. The sensors were fixed to the steel beams by magnetic attachments (Figure 6). An intermediate plastic layer provided electric isolation of the sensors. Concerning measurements of bridges used by electrically driven trains, this is essential in order to minimize disturbances of the recorded signals.

The top of the bridge was not accessible so that the accelerometers could be attached only to the bottom part of the bridge. The Erftal road is frequently used by heavy traffic since it represents an important route to the German highway A4. Thus a complete closing of the road was impossible. It could only be reduced from two lanes to a single lane during time windows from 9 am to 3 pm on two days (period of 6 hours the day).In order to keep sufficient clearance required by the traffic the cables were fixed to the steel girders with small magnetic devices every two to three meters.

The measured signals were conditioned with an LMS Pimento 16-channel front-end. The sampling rate was chosen to 500 Hz, digitization was performed with a 24 bit resolution. These values were chosen with regard to the acquisition of signals measured during train passages. The traffic had also an influence on the measurement values.

The adjustment of the measurement sensitivity and the acquisition of adequate time windows for the later system identification algorithms had to be adapted to the different conditions with and without train passages. For the ambient vibrations a high sensitivity and sufficient time windows without train passages were needed. Since the train schedule on the Erfttal Bridge is very dense and irregularities in schedule often take place, only one or two time windows with ambient conditions could be identified during each measurement period. For the measurements during train passages, which also should have been acquired, the sensitivity had to be reduced in order to avoid overloads while converting the data from analogue to digital.

2.2 Signal processing and test results

During the two days of measurement 23 datasets were acquired. Since the time schedule of the trains was not reliable, all files with ambient conditions (cf. chapter 2.1) had to be truncated because of unexpected train traffic, mainly at the end of the measured time window. Finally, the dynamic characteristics of the bridge could be derived from ambient time windows, each with a time length of 410 seconds.

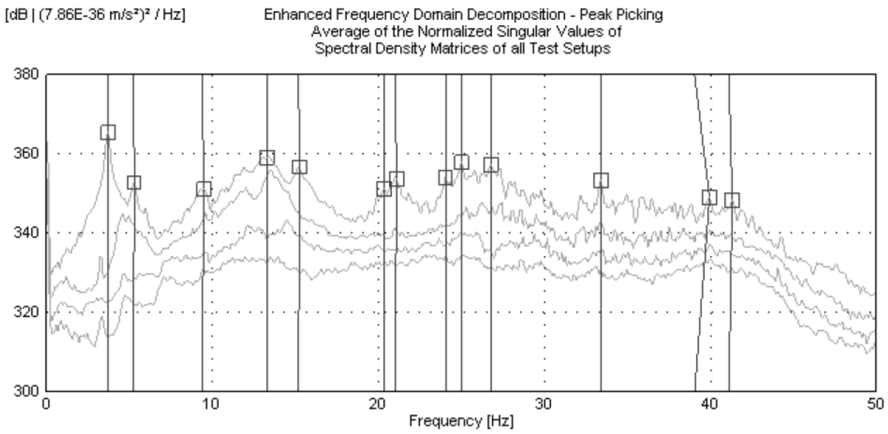


Figure 7: EFDD SVD diagram determined by application of Artemis Extractor routines

Application of the Artemis Software Suite and usage of the EFFD routines (Enhanced Frequency Domain Decomposition) allowed the identification of 13 bridge modes with a frequency range f = 3.68 ... 41.1 Hz. By decimating the data with factor 5, the Nyquist frequency was reduced to f = 50 Hz. The SVD diagram presented in figure 7 shows that the number of projection channels was chosen to 4. The number of frequency lines for f = 0 ... 50 Hz was chosen to 512. Mode No. 5 could not be identified by using the EFFD technique. This mode with a frequency of 13.71 Hz was found by application of the Artemis SSI routines. Whereas mode 4 at f = 13.24 Hz is the second bending mode with two girders being in phase, mode 5 turns out as the second bending mode with the girders being out of phase (cf. Figure 8).

The damping properties of the bridge could be derived from decay curves belonging to the acceleration data of passing trains. For the first eigenfrequency, which is mainly excited by trains, the critical damping ratio ranges between 2.5 and 3.0 %.

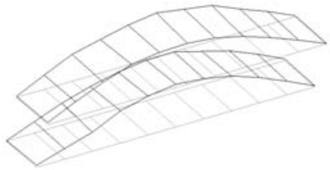
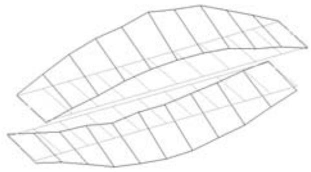
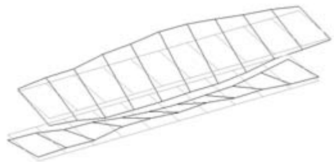
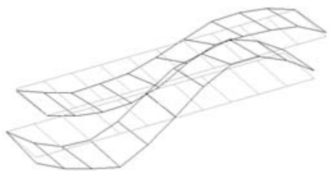
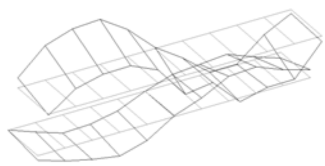
Mode No.	Frequency	Standard deviation	Mode shape
1	3.68	0.01	
2	5.24	0.03	
3	9.36	0.13	
4	13.24	0.13	
5	13.71	0.17	

Figure 8: Eigenfrequencies with standard deviation for the first five modes (Artemis analysis)

3 LONG TERM MONITORING CAMPAIGN

3.1 Long term effects and other phenomena

In regard to long term effects fatigue damage is a critical matter concerning steel or composite railway bridges. According to the experiences filler beam bridges are not susceptible to fatigue, since there are no welded components at all or other critical details. The composite action between steel profiles and concrete is enhanced by transverse reinforcement, which is threaded through holes in the webs.

Climate conditions (wind, temperature, sunshine) have an influence on the dynamic bridge response (Zabel et al. 2007) which will be observed and evaluated from the long term measurement data. In particular the ballast behaves differently at temperatures below 0°C due to frozen moisture cementing the aggregates of ballast and increasing its stiffness.

Furthermore the ballast changes its density and the track set over time due to the permanent impacts caused by train passages. When a tamping machine crosses the bridge, which is performed in regular periods, the density becomes higher again.

Another phenomenon concerning the ballast behaviour is the occurrence of non-linear effects, which are expected to be identified by the monitoring. It is supposed that the contribution of ballast to damping and stiffness depends on the vertical loads and vibration amplitudes.

Also the behaviour of the bearings may change over the time having an influence on the dynamic properties. However it is not expected to measure changes in the foreseen monitoring period.

3.2 Instrumentation

Regarding the circumstances of the project the design of the long term monitoring system is a very complex task. There are a lot of parameters that may have influence on the dynamic properties of the bridge and the importance of each parameter is not yet known. Particularly the question if the coherence between a measured parameter and a process in the structure can be identified is difficult to predict (cf. chapter 1.3). For example if higher strains in the steel girders due to long-term effects are measured, it is difficult to estimate if it results from a settlement, from climate influence, from shrink or creep effects, from changed composite behaviour or from changed ballast behaviour. The main question is: How many and what kind of monitoring devices have to be installed to gain sufficient information about the bridge behaviour and about the reasons for this behaviour.

The first option is to apply a limited number of sensors at significant positions. In this case the measured values at these positions must represent the significant characteristics of the dynamic behaviour (e.g. modal shapes) to achieve a sufficient monitoring system.

Another option is to use a high number (e.g. the same number as used for the ambient vibration tests) of sensors (accelerations and strains) covering almost all expected dynamic characteristics. Then the interpretation of the measured results shall be easier. A Disadvantage is the very high amount of data to be evaluated and handled. The signal processing program must be capable of processing the data.

4 CONCLUSIONS

To investigate the dynamic behaviour of filler beam bridges monitoring campaigns take place on the Erfttal Bridge in the framework of the European Research project DETAILS.

For system identification ambient vibration tests have been carried out in April 2007. In a set of four configurations accelerations at 44 points at the bottom of the bridge have been measured due to ambient loads but also due to train passages. By using output only methods (EFDD- and SSI-algorithms) 13 mode shapes in the frequency range f = 3.68 ... 41.1 Hz have been identified. The critical damping ratio for the first eigenfrequency ranges between 2.5 and 3.0 %. The identified mode shapes have been used successfully to calibrate a FEM-model of the bridge.

In regard to the upcoming long-term campaign the question has to be clarified, how many and what kind of monitoring devices have to be installed to gain sufficient information about the dynamic bridge behaviour.

ACKNOWLEDGEMENT

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