EVALUATION OF THE DYNAMIC RESPONSE OF A SOIL-STEEL COMPOSITE RAILWAY BRIDGE

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Abstract

The dynamic response of a long-span arch soil-steel composite railway bridge is studied. The bridge has a span of 11 m and a rise of 4.3 m. Strains, displacements and vertical ballast accelerations were measured during passages of a locomotive at different speeds. The results indicate that the speed of the locomotive has a large influence on the displacements, thrusts and moments. The structure was found to be safe when measured values of moments and thrusts were compared with the live load calculations according to design codes. However, dynamic amplification factors as high as 1.45 were obtained for the moments at the quarter point and this is found to be much greater than the values specified in bridge design codes. Despite this, due to the high damping involved, bridges of this kind are believed to be less sensitive to resonance problems from passing trains.

Key words: Soil-steel composite bridges; culverts, dynamic loads; field testing; monitoring; instrumentation; railway bridges

1. INTRODUCTION

Large span soil-steel composite bridges, also known as corrugated metal culverts, are composed of corrugated steel plates surrounded by compacted granular soil material. These types of composite structures are getting more popular in recent years because they are more economical and have shorter construction periods compared to traditional bridges.

The performance of soil-steel structures is governed by soil-structure interaction. The steel part of the structure has low flexural stiffness and is prone to deformations. The strength of the composite structure comes from the positive effect of the interaction between soil and metal components. The backfill soil produces earth pressure on the bearing structure and supports much of the load through confinement and resistance to deformation of the flexible metal walls at the same time.
Traffic induced vibrations can result in large dynamic displacements and stresses in this kind of structures. The amount of dynamic effects on a structure is usually quantified in design by so-called dynamic amplification factors (DAF). There are many parameters which can influence the amount of dynamic effects. Speed of the vehicle, the span and the mass of the bridge structure, surface roughness and vehicle-culvert frequency ratio are known to be important parameters that have large influence on the dynamic response. Number of axles and axle loads as well as the spacing of the axles can also have large influence on the dynamic response (e.g. resonance can arise due to passage of successive axles). In addition, very high DAF values can be obtained due to track irregularities and wheel defects (ERRI, 1999 and Karoumi, 1998).

There have been many efforts to establish an improved and more realistic understanding of the interaction and performance of soil-steel composite structures. For example, in Poland, dynamic load tests on a 6.3 m span box culvert road bridge were carried out (Manko & Beben, 2008). Dynamic coefficients as well as critical speeds and vibration velocities were obtained. The variation of the dynamic response, which was consistently higher than the static, was found to be depending on many different factors such as speed, load scheme, and the location of the point of measurement. Chen and Harik (2011) modeled the dynamic response of a culvert under road traffic and established a strong relationship between DAF and above mentioned factors.

![Figure 1. The construction stages of the culvert which was installed over the old masonry bridge over Skivarp creek. Top photo: placement of the culvert over the old bridge; bottom photo: ongoing backfilling process.](image)

In Sweden, an extensive static and dynamic field testing work was done on a corrugated steel arch soil-steel composite bridge with 11 m span (also referred to as culvert within this paper). The bridge is located on the railway line between Malmö and Ystad. This new bridge was placed on top of an existing masonry arch bridge (see Figure 1) with a gap in between, which leaves the old bridge structurally functionless. This paper focuses only on describing and presenting
the results of the dynamic testing on this bridge. For information on the other tests performed, see Bayoglu & Karoumi (2009a and 2009b), Bayoglu et al. (2005) and Bayoglu (2009).

2. DESCRIPTION OF THE BRIDGE AND THE DYNAMIC TEST

The culvert is a single radius arch with a radius of 5640 mm depicted in Figure 2. Maximum span is 10972 mm and the internal height from the footing level is 4332 mm. The steel plate is 7 mm thick. The backfill soil is gravel with 0-45 mm particle size and has a dry density of 2.1 g/cm$^3$. The degree of compaction (RP) of the soil is 93%. The section properties and more details about the structure can be found in (Bayoglu 2009).

Six strain gauges were glued on the steel culvert. All the strain gauges measured strains in the bridge's longitudinal direction. They were located at the top of the crown on the centreline (sensors 3 & 4), 762 mm eccentric from the centreline (sensors 5 & 6), and at the “quarter point” along the centreline of the bridge (sensors 1 & 2) (see Figure 3). The sensors were placed inside the culvert in couples of one at the bottom and the other one at the top of the corrugation. The vertical displacement of the crown was monitored (using the old masonry bridge as a base) by means of a variable differential transformer (LVDT). Vertical ballast accelerations were also recorded at two locations; one in between and one at the side of the rails close to the quarter point of the bridge. In order not to disturb the ballast the accelerometers were cautiously placed by removing a few ballast stones and replacing them with a bag containing the accelerometer surrounded by sand.

![Figure 2. Sectional dimensions of the culvert](image)

The tests were carried out using a Swedish RC4 locomotive engine that has four axles and has a total static service weight of 78 tons. Axle loads are taken as
equal and the axle spacing is indicated in Figure 2. In addition to the dynamic test presented in this paper, static tests with the RC4 locomotive positioned at different locations along the culvert, braking tests as well as measurements with random passing train traffic were made. For more information on these, see Bayoglu & Karoumi (2009a and 2009b) and Bayoglu (2009).

3. Results

The tests results for only one of the travel directions will be presented in this paper. Data filtering was necessary to achieve values free from noise. The cut-off frequency for low-pass filtering the data was chosen as 30 Hz. Comparison made between results filtered at 30 Hz and 60 Hz cut-off frequency showed negligible differences.

Calculations were carried out according to a certain sign convention where; tension, tension at the bottom of the section, elongation and upwards displacements are positive. The strains measured at the top (\(\varepsilon_{\text{top}}\)) and the strains measured at the bottom (\(\varepsilon_{\text{bottom}}\)) are used to calculate stresses \(\sigma_{\text{top}}\) and \(\sigma_{\text{bottom}}\). Section normal forces \(N\) (also called thrusts) per unit width of the structure can then be calculated for every passage of the locomotive as given in Equation 1. Section moments \(M\) are calculated using Equation 2. Extrapolated values were used for the top strains.

\[
N = A \cdot \left(\sigma_{\text{top}} + \sigma_{\text{bottom}}\right)/2 \quad \text{(kN/m)}
\]
Evaluation of the dynamic response of a soil composite railway bridge

\[ M = W \cdot \left( \sigma_{\text{bottom}} - \sigma_{\text{top}} \right) / 2 \text{ (kNm/m)} \]  

Where \( A \) is the cross-sectional area per meter width (m\(^2\)/m) and \( W \) is the section modulus (m\(^3\)/m).

Dynamic amplification factors (DAF) were calculated for each run of the locomotive. The DAF on vertical displacement of the crown (\( \Phi_{\text{disp}} \)) are calculated according to Equation 3. DAF with respect to moments and thrusts (\( \Phi_{\text{moment}} \) and \( \Phi_{\text{thrust}} \)) are also calculated in the same manner.

\[ \Phi_{\text{disp}}(i) = \frac{\delta_{\text{dyn}}(i)}{\delta_{\text{sta}}} \]  

Where \( \Phi_{\text{disp}}(i) \) is the DAF for speed \( i \), while \( \delta_{\text{sta}} \) is the maximum static displacement, and \( \delta_{\text{dyn}}(i) \) is the maximum dynamic displacement for speed \( i \).

3.1. Displacements

Dynamic tests were conducted with the passage of a locomotive with speeds up to about 120 km/h. Figure 4 (top diagram) demonstrates the displacement measurements taken at different passages of the locomotive. The highest displacement measured is 0.86 mm for the highest measured speed of 119.5 km/h. The increase in dynamic excitations with increasing speeds can clearly be seen.

3.2. Normal forces and moments

Normal forces (thrusts) during the passage of the locomotive vary depending on the position of the locomotive on the bridge. Figure 4 (middle diagram) shows one demonstration of this at the crown centerline level, during passages of the locomotive with different speeds. Maximum thrusts at the crown are observed when the centre of the locomotive is on the crown centreline. The increase in the maximum thrusts with increasing speeds is quite pronounced. As shown, a steady and consistent increase from approximately –60 to –66 kN/m is obtained.

The moments at the crown centerline during the passage of the locomotive are shown for different speeds in Figure 4 (bottom diagram). According to the figure the moments change direction as the locomotive passes over the bridge. The range for moments at the crown is 1.73 to –1.80 kNm/m. Moments are mostly positive during the passage with peaks as the axles are on the crown centreline. Negative moments are observed as the middle of the locomotive is over the crown centreline and they tend to increase with increasing speeds. For speeds 90 km/h and up, the maximum negative moments are larger in absolute values than the positive moments.

In Figure 5, moments and thrusts at different locations on the culvert are compared for one selected passage of the locomotive. The moment values for the
crown centreline and crown eccentric are very close to each other with crown centerline being marginally larger. The moments at the quarter point are relatively much smaller. The most critical moments are at the crown. The asynchrony in curves between the crown and the quarter point is due to delay in the loading sequence between them. Quarter point thrusts, shown in Figure 5 (a), indicate however that the compression level due to train passage is more or less the same within the structure.

![Figure 4. Measured vertical displacement of the crown (top), thrusts at the crown centerline (middle), and moments at the crown centreline (bottom) for different locomotive speeds. Note that each figure is a collection of 5 individual passages into one plot.]

### 3.2 Dynamic amplification factors

The additional dynamic stresses and displacements in the structure are usually considered in the design by DAF. The method of evaluating the amount of dynamic effects from the field measurements is explained previously by Equation (3). There are various alternatives of determining the DAF. DAF can be
calculated e.g. considering the response for the entire train passage or for certain axles, boogies, or wagons of the train. It can be calculated considering the positive and the negative response separately or just by taking the maximum absolute response for the point under study.

A compilation of the dynamic factors for all three measured responses of crown centreline are given in Figure 6. As seen, the increase with speed is very similar for the displacements and thrusts. The amplification factor for the crown displacement reaches 1.2 for the highest speed tested. Results show that the crown moments (the maximum absolute moment values) are not affected much by increase in speed. On the contrary, moment at the quarter point show very large increases with speed and the DAF reaches up to 1.45 for the highest speed. The highest DAF for the thrusts is about 1.25 observed at the crown eccentric point, see Bayoglu & Karoumi (2009a).

The resulting DAF are compared with the values obtained from Eurocode (2002) which suggests the usage of Equation (4) for the dynamic coefficient for the well maintained tracks.

\[
\Phi_{\text{Eurocode}} = \frac{1.44}{\sqrt{L_{\Phi} - 0.2}} + 0.82 \quad \text{with } 1.0 \leq \Phi \leq 1.67 \quad (4)
\]

\(L_{\Phi}\) is the determinant length in meters.

The Eurocode does not provide \(L_{\Phi}\) specific to steel culverts. In Sweden, however, it is suggested that the value of \(L_{\Phi}\) shall be twice the culvert span.

In case of arch bridges and concrete bridges of all types with a depth of cover (\(h_c\)) more than 1.0 m, DAF factors may be reduced by subtracting \((h_c - 1.0)/10\). Accordingly, a design DAF value of 1.14 (or 1.06 as reduced DAF) is obtained. These DAF values are much lower than those obtained from the dy-
3.3 Ballast accelerations

Large amplitude vibrations of railway bridges can cause damage, such as ballast instability leading to changes in the geometry of the track and in the worst case scenario, to train derailment. Thus it is interesting to measure ballast accelerations to check the bridge safety. To provide safety against ballast instability, the European bridge design code specifies a limit of $3.5 \text{ m/s}^2$ for the maximal vertical deck acceleration (Eurocode 2002).

Consequently, the vertical ballast acceleration was also monitored during the test at two points on the track, about 4 meters from the bridge crown point. Figure 7 shows the relation between the maximum vertical ballast acceleration measured in the ballast between two sleepers at the middle of the track versus the locomotive speed. The signals have been filtered at 30 Hz according to the requirement in the code. The results show very low acceleration levels, much lower than the code limit of $3.5 \text{ m/s}^2$. Thus, no ballast instability problems should be expected for this bridge, not even for higher train speeds than tested.

Damping ratios were also roughly evaluated from the spectrum of the signals and have shown to be very high and strongly amplitude dependent. Some estimates of measured bridge eigen-frequencies and damping ratios are presented in Bayoglu & Karoumi (2009a). However, these need to be verified by additional tests and theoretical analysis.
4. CONCLUSIONS

Soil-steel composite bridges have increased in popularity in recent years because they are more economical and have much shorter construction periods compared to traditional bridges. In this paper, the actual dynamic response of a long-span corrugated steel culvert railway bridge is studied. The performed full-scale dynamic testing brought out valuable information about the dynamic properties and performance of this not well investigated bridge type. The following conclusions can be made:

− The speed is found to have a great influence on the dynamic response.
− The moments measured at the quarter point are much smaller than those measured at the crown. However, much greater dynamic amplification factors (DAF) for moments are obtained for the quarter point than for the crown.
− When the DAF are calculated considering the maximum absolute moment values, it is found that the crown moment DAF values are not as much affected by the speed as the thrust and vertical displacement DAF values.
− DAF values as high as 1.45 were obtained for the moments at the quarter point. This is not as significant as the crown amplifications given the low moments values at the quarter point. The DAF for the crown displacement reaches 1.2 for the highest speed tested. These values are higher than the design DAF values obtained form the Eurocode, when $L_\phi$ is chosen to be twice the culvert span.
− Measured ballast accelerations are much lower than the specified code limit against ballast instability.
REFERENCES


Streszczenie

Zbadano dynamiczne reakcje kompozytowego stalowo-ziemnego mostu kolejowego o dużej rozpiętości. Most ma rozpiętość 11 m i wysokość 4,3 m. Dokonano pomiaru odkładania, przemieszczeń i pionowych przyspieszeń zasypki podczas przejazdów lokomotyw z różnymi prędkościami. Rezultaty wskazują, że prędkość lokomotyw ma znaczný wpływ na przemieszczenia, siły osiowe oraz momenty. Stwierdzono, iż konstrukcja jest bezpieczna po porównaniu zmierzonych wartości momentów i sił osiowych z obliczeniami obciążenia dynamicznego wynoszące nawet 1,45 dla momentów w punkcie ćwierććwątowym, co znacznie przekracza wartości podane w przepisach projektowych. Jednakże, uzyskano współczynniki wzmocnienia dynamicznego wynoszące nawet 1,45 dla momentów w punkcie ćwierććwątowym, co znacznie przekracza wartości podane w przepisach projektowych dotyczących mostów. Mimo tego, z uwagi na występowanie wysokiego poziomu tłumienia, mosty tego typu uznaje się za mniej wrażliwe na problemy powodowane rezonansem wywołanym przez przejeżdżające pociągi.

Słowa kluczowe: stalowo-ziemne mosty kompozytowe, przepusty, obciążenia dynamiczne; próby terenowe, monitoring, oprzyrządowanie, mosty kolejowe