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NUMERICAL MODELLING OF A FOUR-SPAN BRIDGE, BI-AXIALLY TESTED ON THREE SHAKE TABLES

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Abstract. *Most of existing experimental investigations of bridges were under slow cyclic loading. Data about the dynamic response of bridge components are relatively rare. The experiments investigating the response of the whole bridge are only few. One of these very rare (dynamic) tests of the whole bridges was recently performed at the University of Nevada, Reno. Large scale model (scale 1:4) of an asymmetric, four-span, torsionally sensitive bridge was bi-axially tested on three shake tables. Additionally, the influence of the abutments to the seismic response of the whole bridge was also investigated, exciting the bridge in the longitudinal direction simultaneously with actuators attached to the abutment seats. The response of the bridge was very complex, exhibiting large in-plane deck (torsional) rotations.*

The results of this test were used to evaluate the existing numerical models of different bridge components, and their interaction. The 3D analytical study of the bridge was performed using the OpenSees programme platform. Beside the standard existing fibre models of columns, different models of less investigated bridge components were evaluated. The crucial elements, having the significant influence on the overall response were the abutments. Two types of elements (zeroLengthContact3D and zeroLengthImpact3D), which were capable of modelling the impact as well as the friction between the superstructure and the abutments, were tested. It was found that the impact between the abutments and the superstructure was one the most important parameters influencing the response. Although the bridge was straight, the centre of its rotations was significantly changing, due to the impact between the abutments and the superstructure, substantially amplifying its in-plane rotations.

1 INTRODUCTION

There are many different numerical models available, which are commonly used to model various structural components of reinforced concrete bridges. The evaluation of these models has been commonly performed using the experimental data, which were obtained within the test of individual structural components. In most of the cases these experiments were under slow cyclic loading. Data about the dynamic response of bridge components are relatively rare. The experiments investigating the response of the whole bridge are only few.

One of these very rare (dynamic) tests of the whole bridges was recently performed at the University of Nevada, Reno [1]. Large scale model (scale 1:4) of an asymmetric, four-span, torsionally sensitive bridge was bi-axially tested on three shake tables (see Figure 1). Additionally, the influence of the abutments to the seismic response of the whole bridge was also investigated, exciting the bridge in the longitudinal direction simultaneously with actuators attached to the abutment seats. The response of the bridge was very complex, exhibiting large in-plane deck (torsional) rotations, which were importantly influenced by the impact of the abutments and superstructure. The short overview of the experiment and the main findings are presented in Section 2.

Figure 1: The investigated bridge was bi-axially tested on three shake tables (courtesy of UNR)

The results of this test were used to evaluate the existing numerical models of different bridge components, and their interaction. The 3D analyses of the bridge were performed using the OpenSees [2] programme platform. The numerical model is briefly introduced in Section 3.

Beside the standard existing fibre models of columns, different models of less investigated bridge components were evaluated. The crucial elements, having the significant influence on the overall response were the abutments. Two types of elements (zeroLengthContact3D [2] and zeroLengthImpact3D [3]), which were capable of modelling the impact as well as the friction between the superstructure and the abutments, were tested. Only zeroLengthImpact3D element is briefly described in Section 3, since it was included into the final numerical model of the analysed bridge.

The analytical and experimental results are compared in section 4. The main findings of the analysis are summarized in Section 5.

2 BRIEF OVERVIEW OF THE EXPERIMENT

The bridge was tested in a large scale 1:4. The main dimensions of the specimen are presented in Figure 2a. It is a four span bridge, supported by three two-column bents. The length of the end and inner spans was 7.47 m and 8.84 m, respectively. The deck was prestressed. The bridge was supported by circular columns of diameter 30.5 cm. The length of the columns was 1.52 m, 2.44 m and 1.83 m in bents: B1, B2 and B3, respectively. The geometry of the typical bent is presented in Figure 2b. The columns were reinforced by 16 bars of diameter 9.5 mm. The transverse reinforcement consisted of spiral reinforcement, with a diameter 4.9 mm. The space between the transverse bars was 32 mm.

a) Tested bridge b) Typical bent

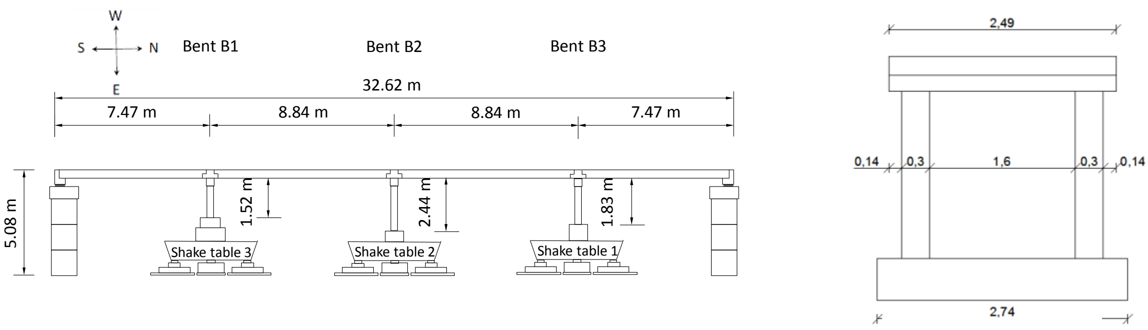

Figure 2: Scheme of the tested structure

At both ends of the bridge an additional mass of 40.8 t was applied (for more details see [1]). Consequently, in the analysis, an axial force of 183 kN and 175 kN was taken into account in columns of the side and central bent, respectively.

The bridge was tested bi-axially on three shake tables. It was subjected to different seismic intensity levels. The main investigation consisted of 7 high amplitude tests, denoted as tests T1D – T7 (see Table 1). All these tests were included in the analytical studies. In between the main tests, additional white-noise tests and test of the abutments were performed. They were not considered in the analytical investigation of the bridge.

Direction	Test T1D	Test T2	Test T3	Test T4D	Test T5	Test T6	Test T7
Transverse	0.075	0.15	0.25	0.50	0.75	1.00	1.00
Longitudinal	0.09	0.18	0.30	0.60	0.90	1.20	1.20

Table 1: Target maximum accelerations expressed as a percentage of the acceleration due to gravity

In the transverse direction of the bridge, the target intensity of the table accelerations was varied between 0,075 g (T1D) and 1.00 g (T7) (see Table 1). In the longitudinal direction the maximum target accelerations were between 0.09 g and 1.20 g. According to [1] most of the damage was observed in the columns of the side bents (B1 and B3). The damage of the columns of the central bents was significantly smaller. Even during the strongest tests T6 and T7 these columns were exposed to very limited yielding. Response of the side bents was essentially elastic during the initial three tests (T1D – T3). Their yielding was firstly observed during the tests T4D and T3 for bent B1 and B3, respectively. The significant damage of the side bents was observed during the test T5, when the significant permanent displacements in the transverse direction were noticed, on the east and west side of bent B1 and B3, respectively. Some of the longitudinal bars were ruptured and the majority of them buckled in the columns of the bent B1 during the test T7. Damage in bent B3 was similar, however smaller number of the longitudinal bars were buckled. Some damage of the superstructure and abutments was observed during the last three tests, particularly at the north abutment.

3 NUMERICAL MODEL OF THE BRIDGE AND THE INPUT MOTIONS

Numerical model of bents and their connections to the superstructure is presented in Figure 3. Columns were modelled using nonlinear "Beam with Hinges" force based fiber model [4]. The length of the plastic hinges was determined based on the standard formulas [5], which were proved to be accurate enough in the previous investigations of the similar bridge [6]. The cross section of the columns was divided to 16 radial segments. The cover concrete was defined with three segments, and the core of the cross section was divided onto 12 segments. For the cover concrete the properties of the unconfined concrete, reported in [1] were taken into account. The core concrete was modelled taking into account the confinement, using the standard Mander's model. In both cases the Concrete04 [2] was used.

Each longitudinal bar was represented with one corresponding fiber having the properties of the steel reported in the [1]. Steel02 model was used [2].

Superstructure and beams were modelled with elastic elements. Connection of the beams and the superstructure were pinned in the longitudinal direction of the bridge and fixed in the transverse direction.

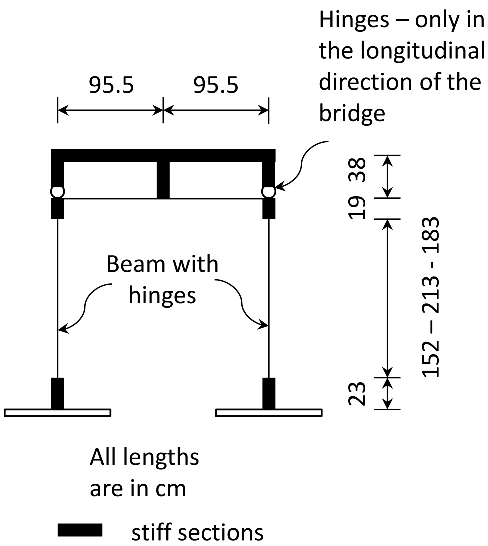

Figure 3: Numerical model of bents

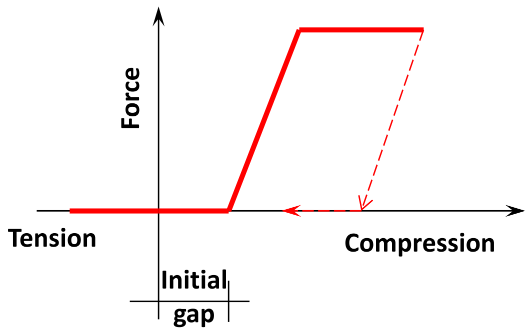

Figure 4: ZeroLengthImpact3D element: Force-displacement relationship in the direction of the element

In the presented analysis the main point of interest was the influence of the impact between the superstructure and the abutments to the overall response of the bridge. Therefore a special attention was devoted to this problem. Several numerical models, available in OpenSees programme [2] were taken into consideration. The zeroLengthImpact3D element [3], which was recently included into the OpenSees programme, was included into the final model. This element was able to take into account the initial gap between the abutments and the superstructure as well as its changes. This is a quite new feature comparing to the other elements.

The envelope force-displacement relationship corresponding to the used element is presented in Figure 4. This relationship defines the response in the longitudinal direction of the bridge. When there is no contact between the superstructure and the abutment, there is no force in the longitudinal direction and the superstructure can move freely. When the gap (which is variable) is closed at the moment of the impact between the superstructure and the abutment, the superstructure is not subjected only to the force acting in the longitudinal direction of the bridge, but also in its transverse direction. The force in the transverse direction is a friction force between the superstructure and the abutment. It is limited by the product of the friction coefficient and the impact force in the longitudinal direction. Note that the friction reduces the displacements of the bridge in the transverse direction (particularly the residual displacements) and has no influence to the rotations of the bridge (similarly to other types of elements available in OpenSees that can be used to model the impact between superstructure and the abutments).

Due to the significant rotations of the superstructure and certain rotations of the abutments, the impact between the superstructure and the abutment occurred close to their corners, Therefore, two elements at each abutment were used to model the impact. Their position is presented in Figure 5.

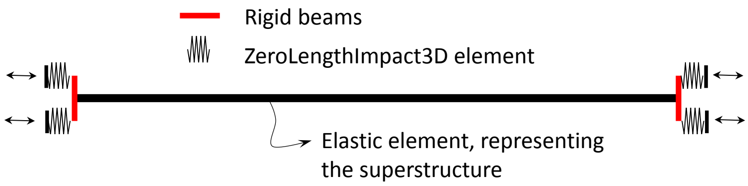

Figure 5: In-plane model of the superstructure

Note that the impact between the superstructure and the abutments did not occur exactly at the abutments’ and superstructure’s corners, however the position of the impact was not significantly distant from these points.

When the gap was closed, the stiffness of the springs was modelled to be large (10^6 kN/cm). The initial gaps were defined based on the measured relative displacements between the superstructure and the abutments: 2.0, 1.45, 1.90, 2.15 cm for the NE, NW, SE and SW abutments’ corners, respectively.

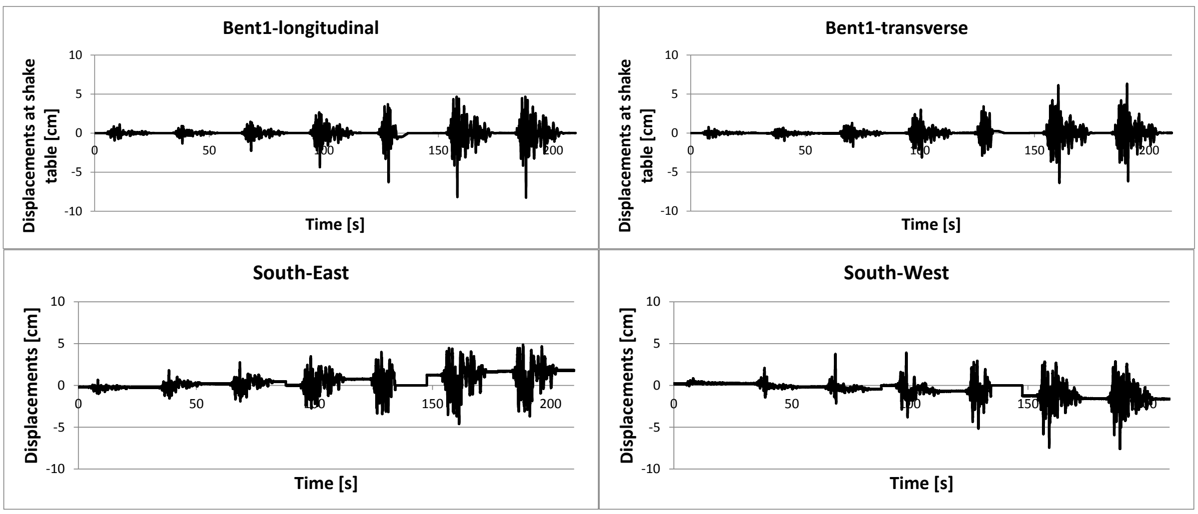

Figure 6: Input displacements at the shake table below bent B1 and longitudinal displacements at the corners of the south abutment (for all tests, that were considered in the analysis)

Since some friction between the abutments and the superstructure occurred at the moment of the impact, it was also taken into account. The best match with experimental data was obtained when the friction of 0.03 was considered and the stiffness of the abutments in the transverse direction of $5x10^3$ was taken into account.

The structure was subjected simultaneously in the longitudinal and transverse direction at the positions corresponding to the shake tables. The input displacements, which were registered during the experiment, were taken into account. At the abutments, displacements, which were measured at their corners, were applied simultaneously with the excitations of the shake tables. The input motions at the shake table below Bent 1 and at the corners of the south abutment are presented in Figure 6 as an example.

4 COMPARISON OF THE EXPERIMENT AND THE ANALYSIS

During the experiment absolute transverse displacements of the east edge of the superstructure were measured at stations, presented in Figure 7. Absolute longitudinal displacements were measured at the centre of the deck and corners of the abutments (DS1 – DS4). The relative displacements of the abutments and the superstructure were measured at the corners of the abutments (DS5 – DS8, presented in Figure 7).

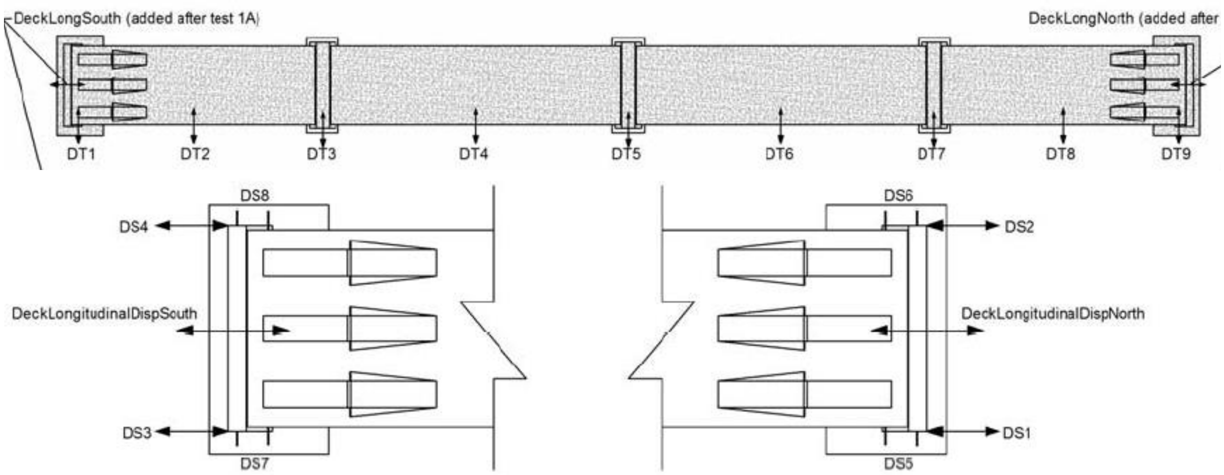

Figure 7: Scheme of the measured displacements (courtesy of UNR [1])

Measured and calculated displacements are compared in Figures 8 – 10. Displacements, which were observed during the tests T1D (essentially elastic response of bents), T4D (yielding of the side bents) and T6 (significant damage of the side bents) are presented. Since the longitudinal displacements of the centre of the deck at the south and north abutment are almost the same, only the displacements at the south abutment are presented in Figure 8. Transverse displacements of the deck above bents B1 and B3 are presented in Figures 9 - 10.

Quite a good agreement of the deck longitudinal displacements was obtained for tests T1D and Test T4D. At test T6 certain noise can be observed in some time intervals. This noise occurred for two reasons: a) all the moments of the impact were not perfectly captured in the analytical model; b) there is a certain noise in the input data. In the analytical model the impact between the superstructure and the abutments depends on several parameters such as: model of the columns, models of beams and superstructure, model of connection between beams and superstructure, model of the impact and input data.

Based on the discrepancy between the analysis and experiment in certain intervals of the test T6, considering the transverse displacements, presented in Figures 9 and 10, it can be concluded, that the model of the columns and the model of the superstructure need to be somewhat revised, particularly at the north side of the bridge.

Comparing Figures 9 and 10, it can be observed that the match between experiment and analysis is quite good above bent B1 (including test T6). Discrepancy between the analysis and experiment is somewhat larger above the bent B3, where the maximum displacements were different. This is an indication that the numerical model needs certain changes.

After the analysis of the measurements reported in [1] it was concluded that both, model of the bent B3 as well as model of the superstructure should be revised, since certain notable damage of the superstructure was observed near the north abutment. This will be done in further studies of the bridge.

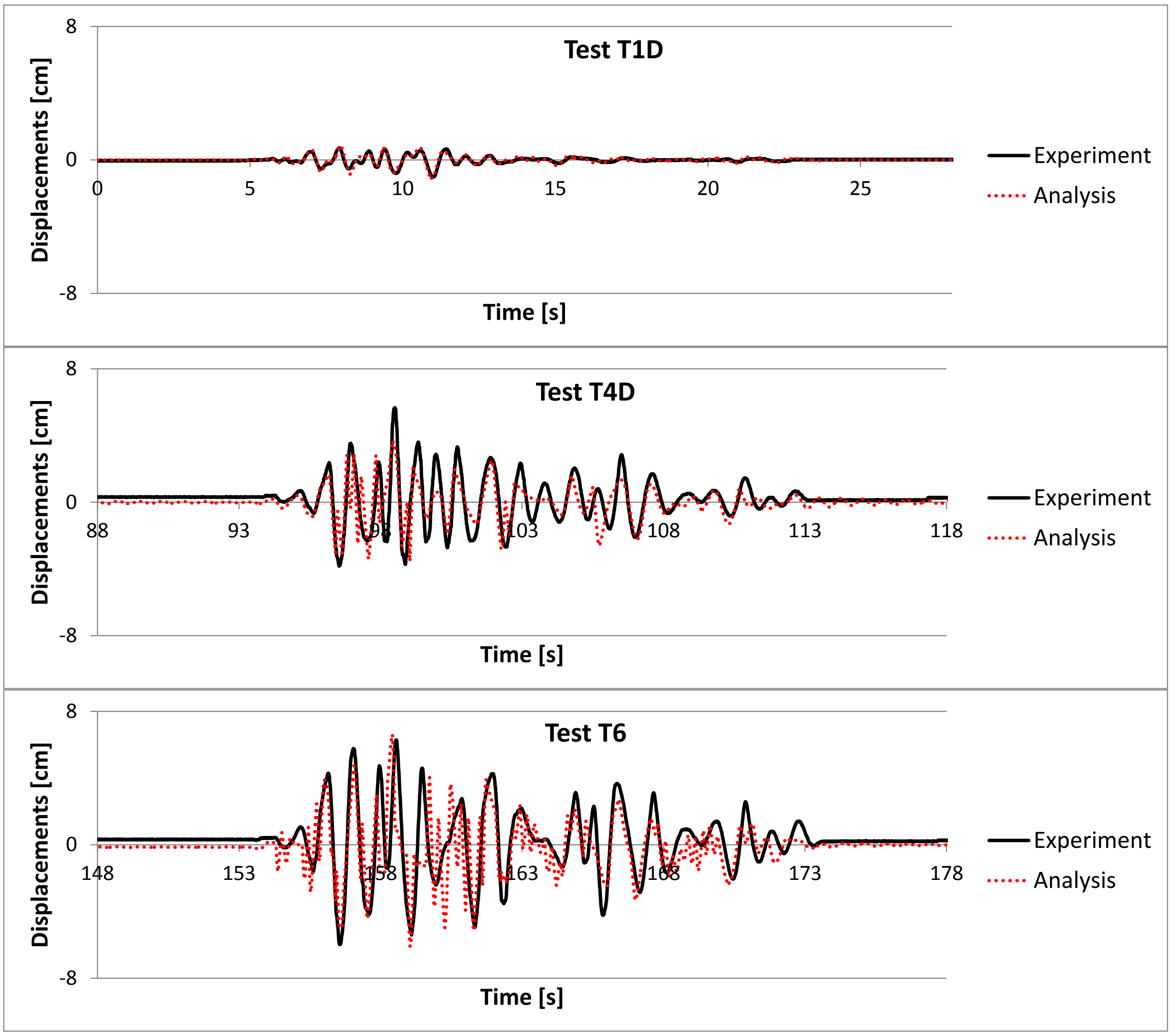

Figure 8: Longitudinal displacements of the centre of the deck

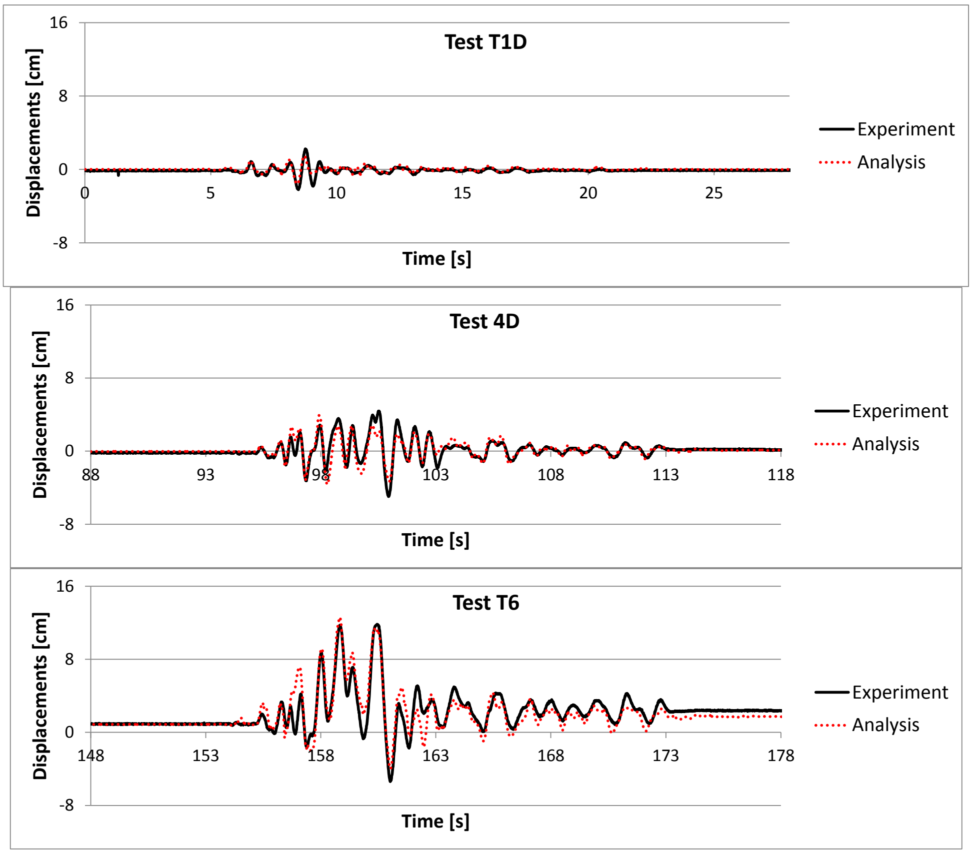

Figure 9: Transverse displacements of the deck above bent B1

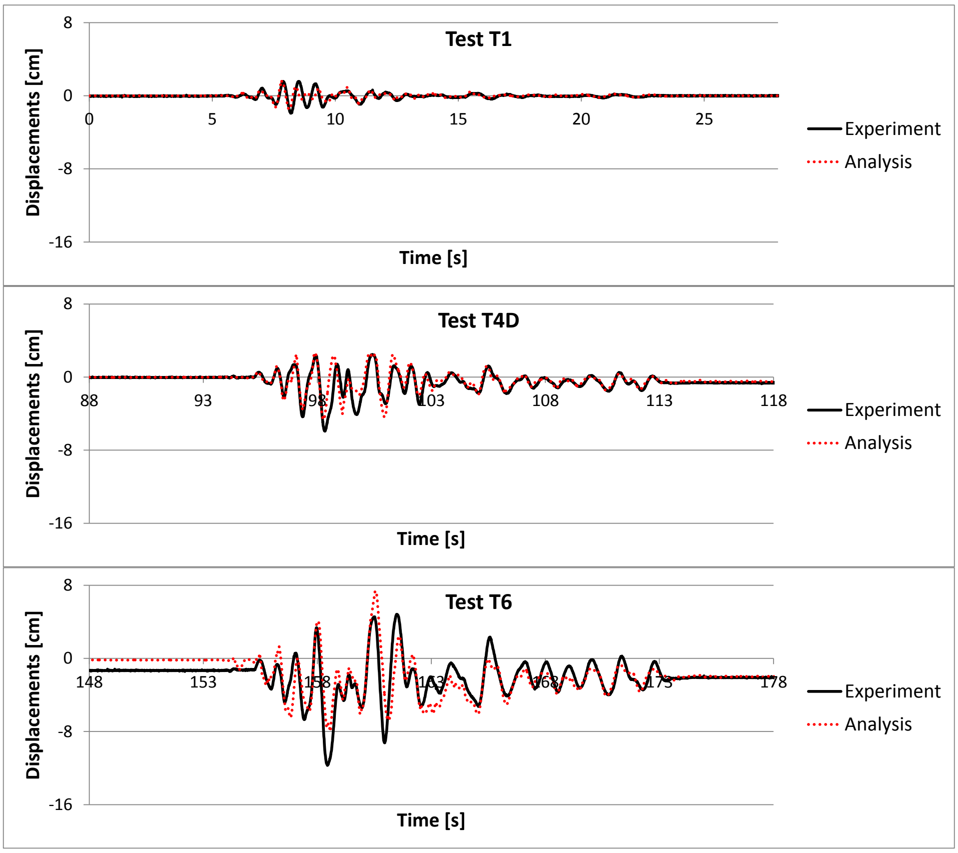

Figure 10: Transverse displacements of the deck above bent B3

5 MAIN FINDINGS OF THE ANALYSIS

The most important parameters that predominantly influenced the response of the analysed bridge are:

1) The impact between the superstructure and the abutments occurred close to the abutments' corners. This considerably changed the centre of the in-plane rotations of the bridge. The impact occurred due to different rotations of the superstructure and the abutments.
2) The initial gap size, which was not the same at all abutments' corners,
3) The excitations of the abutments,
4) The damage of bents.

1) The initial eccentricity or the centre of the stiffness (rotations) was defined by different stiffness of the side bents. If the bents were uncracked and supposing that they were 100% fixed at the bottom and at the top in the transverse direction of the bridge, the initial eccentricity was 1.95 m in the longitudinal direction of the bridge and 0 m in the transverse direction (due to the symmetry of bents in the transverse direction) .

When the impact between the superstructure and the abutment occurred, the centre of rotation was shifted. Since both, the superstructure and the abutment were rotated, and these rotations were different, the impact of the superstructure and the abutments occurred close to the abutment's corner. The centre of the rotation was, therefore, shifted almost for the half of the abutment width, because the stiffness of the abutment was considerably larger than the stiffness of the bents. Since the width of the abutment was about 2.4 m, the shift of the centre of the rotation was considerable. The shift in the transverse direction was about 1.2m, which was comparable with the initial eccentricity in the longitudinal direction. Due to the shift of the centre of the rotation, the bridge rotated around the corner of the abutment as long as the impact between the superstructure and the abutment was provided (see Figure 11).

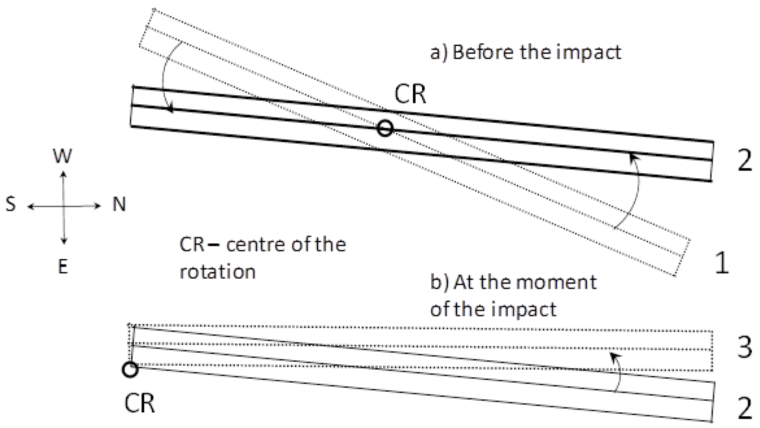

Figure 11: In-plane rotations of the superstructure: a) when there is no impact (at the moment before the impact); b) during the impact

For an illustration, an instance of the in-plane rotations of the superstructure, defined based on its measured displacements (during the experiment) in the transverse direction, is presented in Figure 12. The rotations before the impact (Figure 12a) and during the impact (Figure 12b) are illustrated. Note that rotations of the east edge of the superstructure (for which the experimental data are available) are presented (not the central line of the superstructure).

It can be observed from Figure 12 that the situation was even more complex than that presented in Figure 11. The superstructure was not infinitely rigid (it did not rotate as the perfectly rigid beam) and the centre of the rotation at the moment of the impact was slightly changing in the transverse direction of the bridge, due to the transverse displacements of the superstructure (for about 0.5 cm). However, the general trend was the same as that presented in Figure 11.

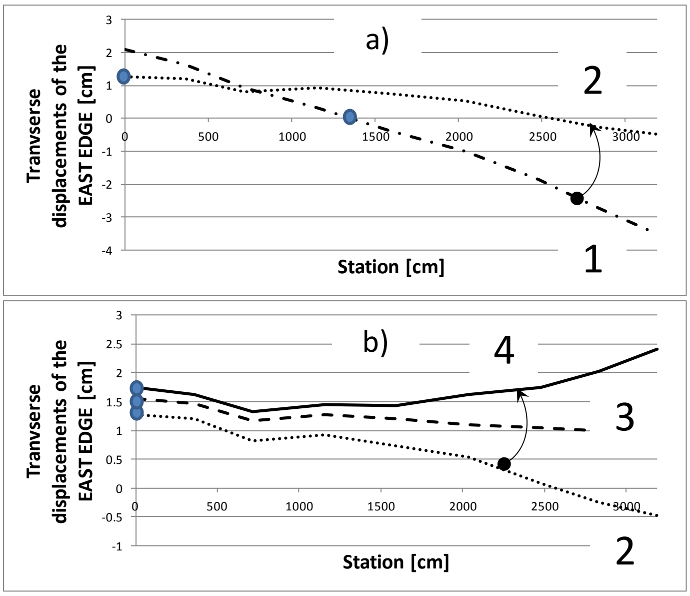

Figure 12: In-plane rotations of the superstructure before and at the moment of the impact, observed during the experiment

The main conclusion that can be obtained from the previously described response of the bridge is that the centre of the rotation will be shifted in all cases where the rotations of the superstructure and/or the abutments occurred during the impact and these rotations are different. The observed response can be expected also in straight bridges which are supported asymmetrically by columns of different heights, and where the considerable in-plane rotations of the superstructure can be expected – torsionally sensitive structures; in other words in structures, where the torsional stiffness is less than its translational stiffness, as it is the case in the investigated bridge. Note that the torsional sensitivity of the bridge is caused by relatively long side spans, which were not supported in the transverse direction. If the bridge were supported by strong shear keys, the response would be considerably different.

Based on the results of the experiment, and previous analytical observations, it can be concluded that in all cases, where considerable rotations of the superstructure and/or abutments are expected, their impact should be modelled by more than one element (as it was common in the past practice). The elements, which are used to model the impact, should be provided at the corners of the superstructure/abutments. This is particularly important in short bridges, which are supported by few bents. In longer structures the impact between the superstructure and the abutments would be important only locally.

2) If the gap between the superstructure and the abutment is large enough to accommodate relative rotations between the superstructure and the abutment, the contact between the superstructure and the abutment will not occur. That is why the size of the gap importantly influences the response. In the investigated case the gap size was not the same at both ends (abutments) of the bridge. Moreover the gaps at the corners of one abutment were also different, due to the different rotations of the abutments and the deck. That is why the rotations of

the abutments were important in the investigated case, since they influence the size of the gap and consequently the moment of the impact.

The gap size was important, since it defined the moment (time) of the impact and considerable changes of the dynamic properties of the bridge at the moment of impact. Small changes of the gap had considerable influence to the response, since the stiffness of the abutments was large and the gap size was small. Therefore the problem was poorly constrained and very challenging for numerical modelling.

3) To obtain the impact at the abutment's corner, the relative rotations between the superstructure and abutments are needed. The rotations of the abutments occurred due to the different motions of the abutments' corners. These rotations, combined with the relatively small size of the gaps, had considerable influence to the position as well as the moment (the time) of the impact between the superstructure and the abutment. The size of the gap and the rotations of the abutments had considerable influence to the residual transverse displacements observed during the tests T5 – T7 (see Figures 9 and 10).

4) The damage of the bents had a considerable influence to the torsional and the translational stiffness of the bridge, and consequently also to the eccentricity (centre of the rotations) and the rotations of the bridge in-between the impacts of the superstructure and the abutments.

6 CONCLUSIONS

The numerical analysis of the bridge which was bi-axially tested on the three shake table has been performed. This was a great opportunity to test some common numerical models of RC columns and new zeroLengthImpact3D model, which was used to take into account the impact between the abutments and the superstructure. It has been found that the accuracy of these models was quite good.

Since the tested bridge was torsionally flexible structure, substantial in-plane (torsional) rotations were observed. These rotations were significantly amplified at the moment of the impact between superstructure and the abutments, because the centre of the stiffness (rotation) of the bridge was shifted close to the abutments' corners. Based on this observation, it can be concluded that in all cases, where considerable relative rotations of the superstructure and/or abutments are expected, their impact should be modelled by more than one element (as it was common in the past practice).

Elements, which are used to model the impact, should be provided at the corners of the superstructure/abutments. This model should be used in all torsionally sensitive structures, even if they are straight. This is particularly important in short bridges, which are supported by few bents. In longer structures the impact between the superstructure and the abutments would be important only locally.

Certain friction was observed between the abutments and superstructure at the moment of the impact. It reduced the displacements in the transverse direction of the bridge (particularly the residual displacements). The new zeroLengthImpact3D element was able to model the friction in an appropriate manner. However, like the other similar elements, it did not increase the rotations of the superstructure when the friction occurred. This did not have significant influence to the analysis and the results.

The response of the bridge was significantly influenced by the size of the gap between the superstructure and abutments. When it is large enough to accommodate relative rotations between the superstructure and the abutment, there will be no impact and the amplifications of the superstructure in-plane rotations.

In the investigated bridge, small changes of the gap size had considerable influence to the response, since the stiffness of the abutments was large and the gap size was relatively small.

Therefore the problem was quite challenging from the numerical point of view, since it was poorly constrained.

The damage of the bents had a considerable influence to the torsional and the translational stiffness of the bridge, and consequently also to the eccentricity (centre of the rotations) and the rotations of the bridge in-between the impacts of the superstructure and the abutments.

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