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Engineering model for the seismic analysis of complex existing viaduct

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SUMMARY

The paper deals with the engineering modelling of the existing Downtown viaduct in Las Vegas, which has a very complicated structural system and seismic response. The structure consists of sixteen segments, which are supported by more than a hundred columns. The segments of the viaduct are connected within intermediate hinges. The connections change due to the atmospheric conditions as well as the intensity of the seismic load. Consequently, the structural system changes during the response. This makes the seismic analysis quite challenging.

The paper presents a model of the viaduct intended for the non-linear dynamic analysis. The modelling of several elements, which are not usually included in the modelling of the viaducts is described. These elements are abutments, restrainers, shear keys, and different types of impacts. The influence of some important parameters on the response of the viaduct in Las Vegas is analysed. The properties of the abutments, properties of connection elements within the intermediate hinges and the size of the gaps of these elements have a crucial role in the viaduct response.

Key words: *seismic analysis, engineering model, viaduct, retrofitting, non-linear time-history analysis.*

1. INTRODUCTION

A structural system of the majority of the viaducts seems to be simple. However, if the structure is very long in some cases the structural system can be quite complex with many hinges which provide unconstrained thermal deformations. This makes the already complex seismic response of viaducts even more complicated.

An example of such a complex structure is the Downtown viaduct in Las Vegas. It was built in the late sixties of the previous century, when little attention was paid to seismic design of viaducts. At that time it was also believed the threat of a serious earthquake in the Las Vegas Valley was minimal. Therefore, the structural system and some details of the structural elements are quite inadequate for seismic areas.

However, over the years the assumptions about the seismicity of the Las Vegas Valley have changed significantly. Earthquakes up to a magnitude 7 are presently expected in this area. Since the viaduct is one of the busiest in the state of Nevada (ca 160000 vehicles a day use a bridge), in 2001 an extensive project was started in order to find an adequate system for the retrofitting of the viaduct.

The extensive analytical studies are also a part of the project. To perform these studies, an adequate model has been developed. This has been a quite challenging task, since both the structural system and the seismic behaviour are quite complex. The structural system consists of 16 separate segments (smaller structures), which are connected within intermediate hinges. The properties of the connections change due to the changes in atmospheric conditions and maintenance as well as under different seismic load intensity. Therefore, the structural system also constantly changes during the response. The variations of the structural system are numerous. The paper presents the modelling of this complex structure (Section 3) as well as the most important parameters, which influence the response (Section 4).

2. DESCRIPTION OF THE VIADUCT

The length of the Downtown viaduct in Las Vegas (see Figures 1 and 2) is *568 m*. It is curved with skewed supports. It is divided into two parts, west (W) and east (E). These two parts are connected within an intermediate hinge, along the whole length of the viaduct (see Figure 3). The superstructure is a reinforced concrete box girder, with a variable width. The viaduct is supported by 22 skewed piers which include more than 100 columns. Most of the piers are multi-column including 2 - 4 columns. Exceptions are single column piers at the right side (P17 - west part, P18, P20 and P21). There are two main types of columns supporting the superstructure:

a) So called “diamond” columns (see Figure 3), which are fixed into the superstructure and pinned at the connection with footings. They are situated in most of the piers.
b) Columns in single column piers, which are fixed into the superstructure, fixed into the footings in the stronger direction and pinned into the footings in the weaker direction.

Fig. 1 Downtown viaduct in Las Vegas

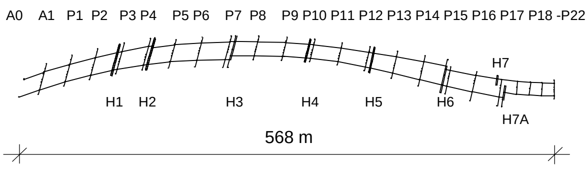


Fig. 2 Plan view of the superstructure of the Downtown viaduct in Las Vegas

Fig. 3 “Diamond” columns and the longitudinal hinge of the viaduct

The viaduct has seven transverse hinges, which divide both parts of the structure (east and west) into eight segments (totally 16 segments). Each hinge is denoted as H_i, where *H* means hinge and *i* is the consecutive number of the hinge (see Figure 2). In general there are two types of transverse hinges:

a) hinges where only two segments of the viaduct are connected - hinge type 1,
b) hinges where the viaduct is also connected with the offshore ramps - hinge type 2.

All segments of the viaduct are named *iW* or *iE*, where *i* is a consecutive number of the segment, starting from the left abutment, and *W* and *E* means west and east part of the viaduct, respectively.

3. DESCRIPTION OF THE MODEL

Since the structural system of the Downtown viaduct in Las Vegas is changing, its response is very complex, and since this is a very important structure, the only acceptable method of analysis is the non-linear time-history analysis. The program Drain 3DX [1] has been used to analyse the structure. A spine model (see Figure 2) of the viaduct has been used in the analysis because of the large size of the model and the limitations of the program Drain 3DX. Using the spine model the size of the model is substantially reduced as compared to some more complex models. However, the model is still quite complex. Beside the standard elements representing the superstructure and columns, which are usually used when modelling viaducts, a substantial number of other special elements is also included into the model. They represent abutments, shear keys, restrainers, impacts between the viaduct’s segments and the impact between the viaduct and offshore ramps. All types of elements included into the model are briefly described in the next subsections.

Superstructure

The superstructure is modelled with elastic beam elements (element No. 17 in Drain 3DX), which follow the centre of gravity of the cross section along the whole length of the east and west part of the viaduct. Since the width of the superstructure varies along the length of the bridge there are several types of elements representing the superstructure. A number of these types is reduced to a minimum. It is assumed the superstructure would crack under both vertical and horizontal loads. Therefore the moments of inertia of the cross-section are reduced for *50%*.

Columns

The columns are modelled with fibre beam elements (element No. 15 in Drain 3DX). This is a beam element, which is usually divided into smaller segments. Each segment can have elastic or inelastic behavior. The cross-section is constant over the whole length of the segment. Cross-sections are divided into certain number of fibers. Each fiber type is described with a related steel or concrete stress-strain diagram.

Two general models of the columns are included into the model of the viaduct. The "diamond" columns are modelled as it is shown in Figure 4. An element representing the column is divided into two segments (see Figure 4c). Since the maximum moments are expected at the top of the column, the top segment is modelled as a fibre segment and the rest of the column is modelled as an elastic segment. The length of the fibre segment is 12% of the column height. This is an approximate value of the length of the plastic hinge which was calculated based on the formula proposed in [2]. The cross-section of the fibre segment is divided into 16 concrete and 16 steel fibres (see Figure 4a and 4b). The properties of the concrete fibres are equal for all "diamond" columns. The properties of the steel fibres vary depending upon the type of reinforcement. The fibre mesh of the cross section is rough, especially for the concrete fibres. The number of segments along the column is also low. In spite of the low number of fibres and sections, the separate analysis of a single column of this type [3] proved that the model is sufficiently accurate.

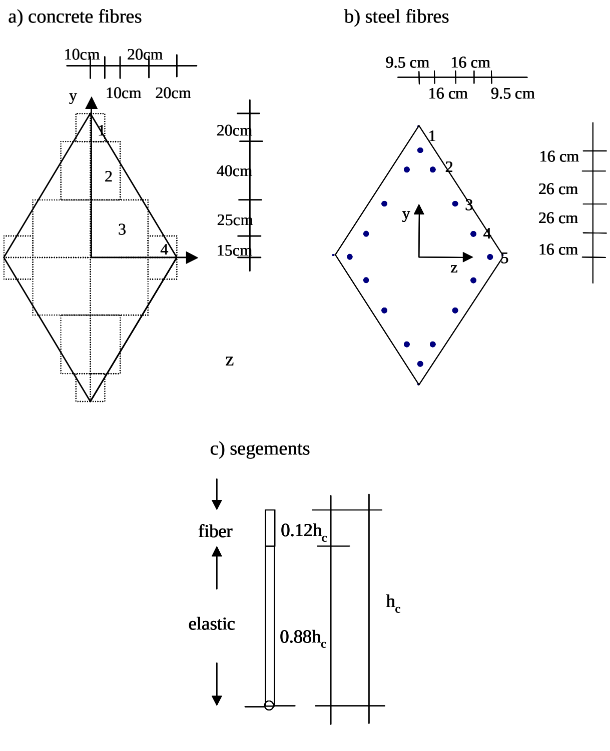


Fig. 4 Model of the "diamond" columns

The columns in single-column piers are also modelled with the fibre element. The element is divided into 9 segments (see Figure 5a). Since the columns are fixed into the superstructure large deformations are expected at the top of the column. Therefore the two top segments are modelled as fibre segments. The third segment from the top of the column is elastic. The rest of the segments are also fibre since these columns are fixed into the footings in the transverse direction of the viaduct. The fourth and fifth segments are of the same type as those at the top of the columns. The cross-section of the rest of fibre segments (sixth - ninth from the top of the column) is different from the previous sections, since they represent a column pedestal, which has larger dimensions than the column itself. These columns are fixed to the footings in the stronger direction and pinned in the weaker direction. Concrete fibres are the same for all columns (see Figure 5b). The properties of steel fibres depends on the reinforcement in the column.

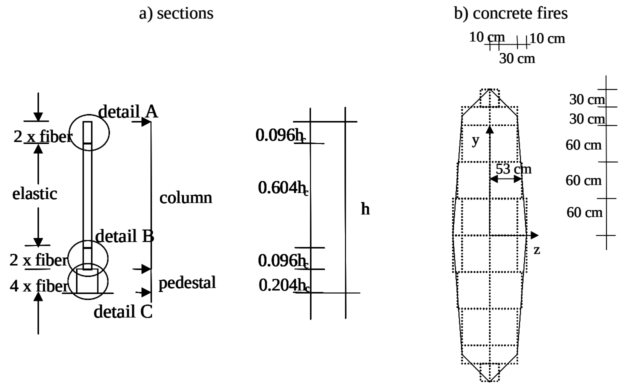


Fig. 5 Model of the columns in the single column piers

It is assumed that the connection between the top of the columns and the superstructure's neutral axis is infinitely rigid. To reduce the size of the model, this connection is modelled by slave nodes representing the top of the columns to the node representing the centre of gravity of the superstructure.

Model of hinges in the transverse direction of the viaduct

There are two types of transverse hinges in the viaduct: hinges where two adjacent segments of the viaducts are connected (Type 1) and hinges where the viaduct is also connected with the offshore ramps (Type 2). Each hinge of Type 1 consists of 6 nodes (see Figure 6). Nodes 1-3 represent the left segment and nodes 4-6 the right segment of the viaduct. The connections between all the nodes on the left are infinitely rigid. The same type of connection is used on the right side, too. Each pair of nodes 1 and 4, 2 and 5, 3 and 6 is connected with two elements. One element represents restrainers and the other is used to model the impact between adjacent sections of the viaduct. Elements representing restrainers are activated only in tension. Elements used to model the impact are activated in compression, only. Modelling of the restrainers is described in a special subsection (see subsection Restrainers).

The properties of compression elements are calculated according to the axial stiffness of the

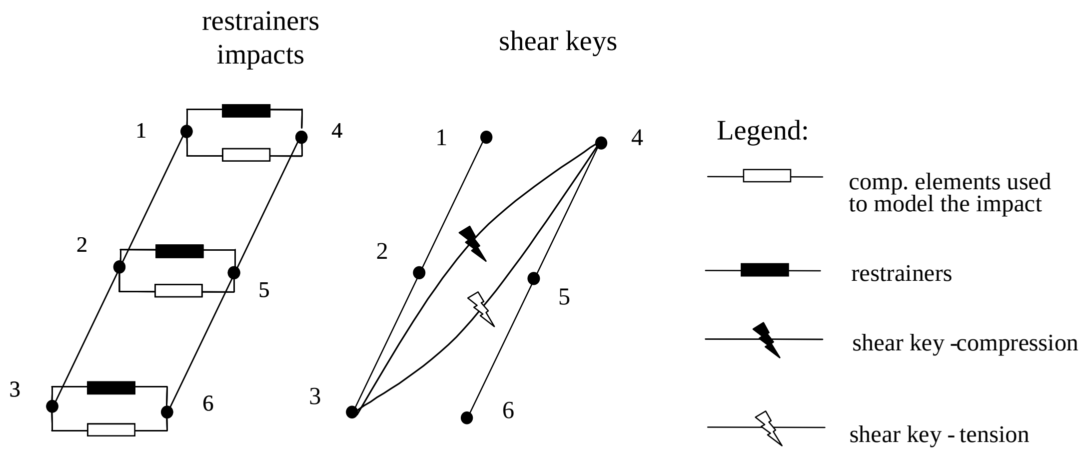


Fig. 6 Scheme of the transverse hinge - type 1

superstructure. The average value of the left and right segment of the viaduct is taken into account and then divided into three elements.

Each hinge includes a shear key, too. Shear keys are modelled with two elements. These elements are situated between nodes 3 and 4. Basic assumptions for modelling shear keys are described in the subsections Shear keys.

A hinge of Type 2 is similar to a hinge Type 1, but more complex. Beside the elements, which are the same as in the hinge Type 1, there are also additional elements representing the impact between the viaduct and offshore ramps. The properties of these elements are based on the properties of the offshore ramps (see the subsection Offshore ramps).

Model of a hinge in the longitudinal direction of the viaduct

Longitudinal hinge is a hinge between the west and east parts of the viaduct (see Figure 3). It is modelled with elements, which can carry a load just in compression, and are activated only when the impact between the west and east parts of the viaduct occurs. These elements are situated at each pier and each hinge. Their properties are based on the axial stiffness of the superstructure in the transverse direction of the viaduct. The initial gap of *3.8 cm* is taken into account when modelling a hinge.

Restrainers

The elements representing restrainers carry a load just in tension (see Figure 7). An initial gap of the restrainers is taken into account. Forces in these elements occur only when these gaps are closed.

The properties of elements representing restrainers are obtained by dividing the total stiffness of the restrainers by the number of elements representing restrainers. The stiffness of one restrainer is calculated based according to formula $k=AE/L$, where k is stiffness, A is the area of the restrainer, E modulus of elasticity, and L is the length of restrainer. The yielding force F_y is determined based on the formula $F_y=f_yA$, where A is the area of restrainer's cross-section and f_y is a yielding stress of the steel. The yielding displacement dy is then calculated as $d_y=F_y/k$.

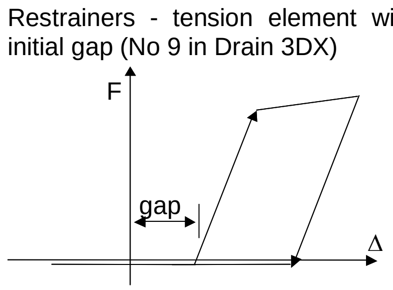


Fig. 7 Model of elements representing restrainers

Abutment

The impact between the abutment and the viaduct is modelled with the elements which can carry only compression load (see Figure 8).

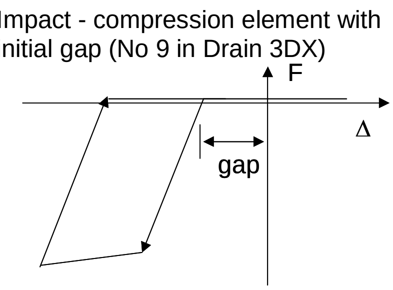


Fig. 8 Model of elements representing impacts

The properties of these elements are determined according to recommendations in Ref. [4]. First the stiffness of the abutment is calculated. A backfill soil of the abutment as well as all piles supporting the abutment are taken into account. The stiffness is determined using the formula $K=K_{soil}\cdot w+K_p\cdot n_p$, where K is the total stiffness, w is the width of the abutment, K_{soil} stiffness of the background soil, K_p stiffness of one pile and n_p number of piles. The yielding force of the element representing the abutment is calculated assuming the backwall breaks off, using formula $F_y=368\ kN/m^2 \cdot w \cdot h_b$, where w is the width of the abutment and h_b is the height of the backwall. An initial gap is also taken into account when modelling the abutment.

Shear keys

The shear keys are modelled with two elements. One element is activated in compression and the other is activated in tension. The resultant behaviour is presented in Figure 9. When modelling shear keys an initial gap is taken into account.

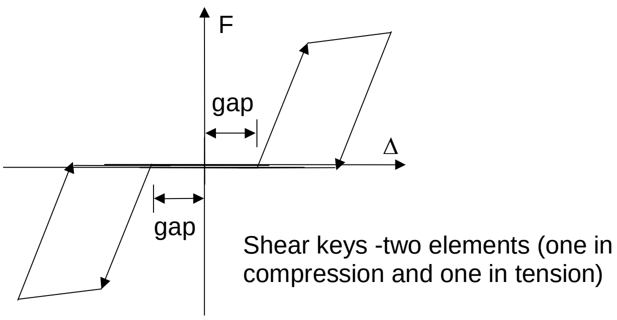


Fig. 9 Model of the shear keys

Offshore ramps

The impact between the viaduct and offshore ramps is also modelled with elements which are activated only in compression. Their properties are determined taking into account a flexural stiffness of the offshore ramps in the longitudinal direction of the ramp. This stiffness is based on the stiffness of their columns. The columns at the offshore ramps are pinned at the connections to the footings in the longitudinal direction of the bridge and fixed into the superstructure. Therefore, the stiffness of one column is calculated, using formula $k=3EI/h^3$, where k is the stiffness, E modulus of elasticity, I the moment of inertia of the column's cross-section and h the height of the column. The moment of inertia is calculated based on the cross-section of the first column. Then this value is reduced for *50%* because it is expected the columns would crack under the horizontal load. The total stiffness of the ramp is calculated as the sum of the stiffness of all columns.

Masses

Masses are lumped above all the columns and in all hinges' nodes at the level of the centre of gravity of the superstructure. They are calculated according to the tributary areas. One half of the column mass, the dead load of the viaduct (including the weights of the parapets) and *50%* of the live load defined by codes are also taken into account. The total mass of the viaduct is *24600 t*.

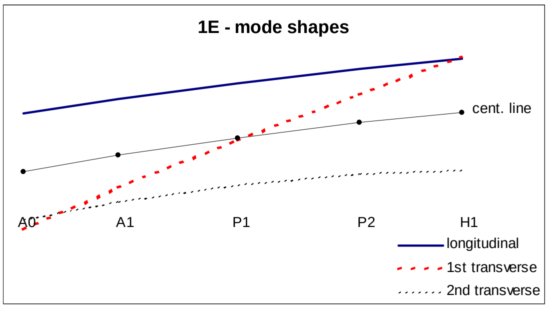
4. MOST IMPORTANT PARAMETERS WHICH INFLUENCE THE RESPONSE

Size of the initial gaps - variations of the structural system

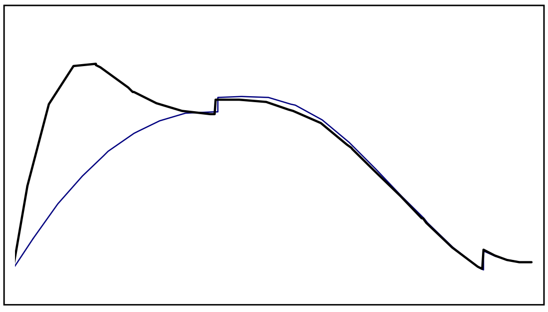
The structural system of the presented viaduct depends to a great extent on the size of the gaps in the intermediate hinges and connection elements. The size of the gaps depends on the atmosphere conditions (temperature, humidity, etc.) and the maintenance of the viaduct. They also depend on the intensity of the seismic load and therefore they vary during the response.

When the gaps are not closed, each segment of the viaduct behaves as a separate structure as long as displacements do not exceed the size of the gaps. In this case, three mode shapes, one in the longitudinal and two in the transverse direction (see Figure 10 a) are important for each separate segment of the viaduct. A totall of 61 mode shapes are important for the whole structure. The largest important period of the structure is $T_1=1.77$ s, while the shortest important period is only $T_{61}=0.12$ s. This indicates that the response is quite complex. Each segment of the viaduct is torsionally very sensitive since the first mode shapes in the transverse direction of the majority of segments are torsional (see Figure 10a).

When the initial gaps of the connection elements (restrainers, elements representing impacts, abutment, shear keys) are closed, the structural system of the



a) mode shapes of one segment



b) 1st mode shape in the model without gaps

Fig. 10 Some of the mode shapes for two different models of the viaduct bridge is drastically changed. The viaduct responds as one unit and the mode shapes are completely different than in the previous model (see Figure 10b). In this structure the number of important modes is reduced to 17. The longest period is $T_1=0.62\ s$ and the shortest important period is $T_{18}=0.14\ s$. In reality some connection elements will be activated and some not. The response will be something in between the response of the two structures, described above.

The non-linear time history analysis also proved that the size of the initial gaps is very important in this viaduct. If the structure with initial gaps (Model 1) is loaded in the longitudinal direction with the same seismic load as the structure where the gaps are neglected (Model 3), the envelopes of displacements of the superstructure are drastically different (see Figure 11). In the first case the largest value of displacement is ca *9 cm*, while in the second case displacements of only *0.8 cm* are obtained.

In the first case the structural system is changing during the response, due to the closing and opening of the gaps. In one moment the segments respond as separate units, later when the gaps are closed two or more segments behave as one unit. Since the properties of the segments are quite different and since they can move independently the maximum values of displacements vary along the viaduct.

In the second case, when the gaps are closed all the time, the structure behaves as one unit and the displacements are approximately the same along the whole viaduct. Small displacements are influenced by strong and very stiff abutments as well as the columns in the single-column piers (see explanation in the next subsection).

Properties of the abutment

The complex response of the Las Vegas viaduct does not depend only on closing and opening of the gaps between the viaduct segments. The abutment, the properties of the connection elements as well as the very stiff columns in the single column piers also have a significant influence on the response. In this subsection the influence of the abutment properties is illustrated and explained.

Each segment of the viaduct is the space frame, which is pinned into the footings (see a simplified example in Figure 12). It consists of at least two frames. Each of these two frames is unstable in the longitudinal direction of the viaduct, while it is not connected to another one by the superstructure.

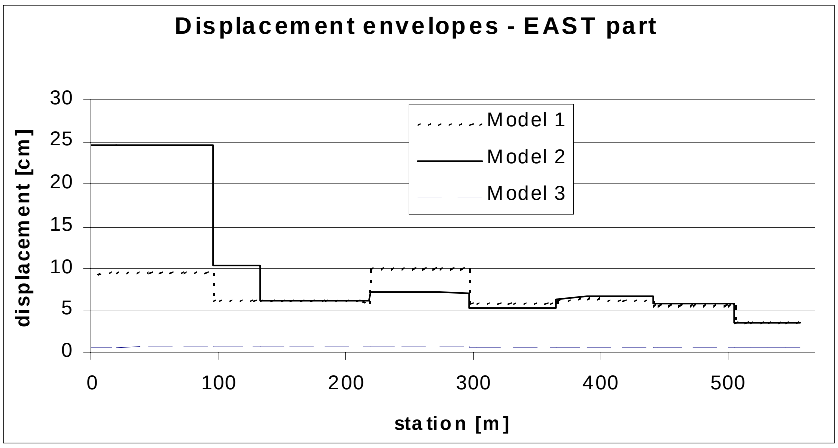


Fig. 11 Envelopes of the superstructure displacements obtained with three different models of the viaduct

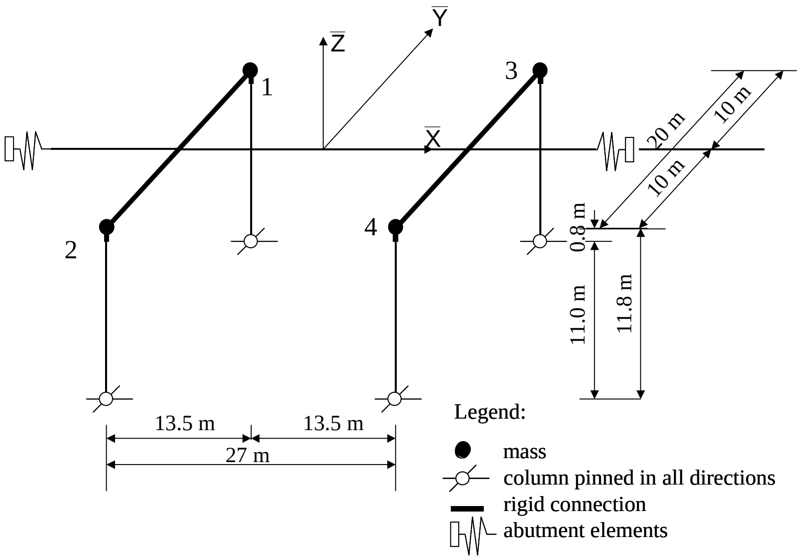


Fig. 12 An idealised structure, similar to the segments of the analysed viaduct

The stability of the space frame is ensured, while the connections between columns and superstructure are strong. When yielding of all columns occurs, the connections are weakened and the stability of the structure is very quickly jeopardized [3]. The displacements of the superstructure significantly increase after yielding of the columns is reached.

However, when the strong and stiff elements (e.g. abutments) are situated at both sides of such a space frame, these elements prevent large horizontal movements of the whole structure. Since the displacements are smaller, a stronger load is necessary to reach the yielding of the columns. The stronger and stiffer the additional elements are the greater is the stability of the structure. However, when yielding of additional elements occurs the stability of the structure can be lost quickly.

The influence of the abutment on the response of the Downtown viaduct in Las Vegas is evident from Figure 11. The envelopes of the superstructure displacements obtained by the model without abutments (Model 2) are compared with the displacements obtained with the model with abutments (Model 1). Large differences in the response are obtained in the segments close to the abutment. In segment 1E the displacements of *24.4 cm* were obtained when the abutment was excluded from the model. This means a drift in some columns is more than *2%*. However, when the abutment is included into the model, displacements in this section are reduced to *9 cm*. The influence of the abutment decreases as a distance of the segment from the abutment increases.

Torsional sensitivity of the structure

The parameters, which are described in the previous subsections, influence also the torsional sensitivity of the viaduct (a term torsional sensitivity denotes large rotations in the horizontal plane of the superstructure around the vertical axis of the viaduct). It is evident from Figure 10 that a separate segment of the viaduct is torsionally sensitive, since the first important mode in the transverse direction of the segment is torsional. This torsional sensitivity is in some segments caused by long end cantilevers (e.g. segments 1E and 1W) [6]. In some segments (e.g. 2E and 2W) large rotations are the consequence of large asymmetry (one end cantilever is long while the other is short). In some segments (e.g. 1W) the torsional sensitivity is increased due to the column reinforcement and the chosen model of columns. Due to the widening of the west part of the viaduct, some columns (which are more distant form the centre of the viaduct) have the same height but less reinforcement than other columns in the same pier. The smaller reinforcement of these columns causes additional torsion in such segments.

For example, let us consider again the structure presented in Figure 12 (without end cantilevers). It consists of two piers, which are supported by two columns each. Let us assume the structure is loaded with a static load in the longitudinal direction only. All columns of the structure have the same height, but columns 1 and 3 have less reinforcement than columns 2 and 4. Due to less reinforcement the stiffness of columns 1 and 3 is also smaller. Since the displacements of all columns in the longitudinal direction of the segment are the same, the shear forces in the columns with the smaller stiffness are smaller. The difference in the shear forces causes the moments around the vertical axis. To balance these moments, shear forces in the transverse direction occur. The forces in transverse direction of the structure also cause changes of the axial forces in columns.

Rotations around the vertical axis increased significantly, when the yielding of weaker columns started, since the difference in the stiffness of columns is additionally increased. Due to the torsion, the collapse of the structure is reached under a significantly smaller load than in the structure where all the columns have the same reinforcement. This is illustrated in Figure 13.

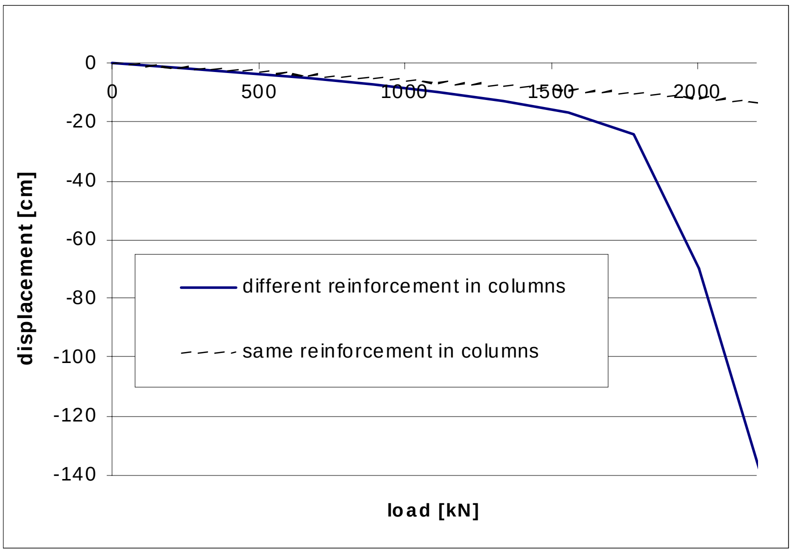


Fig. 13 Displacements of structures with different column reinforcement

Displacements of structure, where the columns have different reinforcement become significantly larger than in the structure with equal reinforcement in all columns. The differences become significant when the yielding in columns with less reinforcement occurs (at a load of *1000 kN*).

The torsion of the segments in the real viaduct depends on the size of the initial gaps and properties of the connection elements. If the gaps are larger and the connections between the segments weaker, the segments can move independently and the torsion is larger.

5. CONCLUSION

The seismic response of the Downtown viaduct in the Las Vegas is very complex due to its complex structural system. A model for the non-linear dynamic analysis is described in the paper. Although relatively simple elements (beam elements) are included in the presented model it is quite complex and difficult to control. The analysis of the viaduct is quite challenging, since the structural system changes during the response. It was found out that the most important parameters which influence the response are the size of the gaps in the intermediate hinges as well as the properties of the abutments and connection elements in the intermediate hinges. Since the properties of these elements change over the time and due to the changes of atmospheric conditions, it is necessary to vary their properties in order to estimate the response of the viaduct under different conditions.

6. ACKNOWLEDGEMENTS

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INŽENJERSKI MODEL ZA POTRESNU ANALIZU SLOŽENOG POSTOJEĆEG VIJADUKTA

SAŽETAK

U članku je prikazan inženjerski model, namijenjen potresnoj analizi vijadukta u centru Las Vegasa. Konstrukcijski sistem vijadukta je iznimno kompliciran. Vijadukt se sastoji od šesnaest segmenata (manjih konstrukcija), koje podupire više od stotinu stupova. Pojedinačni segmenti konstrukcije su međusobno povezani na mjestima unutarnjih zglobova. Veze među segmentima se mijenjaju u odnosu na atmosferske uvjete i intenzitet potresnog opterećenja. Posljedično se tijekom potresnog odziva mijenja i konstrukcijski sustav vijadukta. Zato je potresna analiza ovog vijadukta prilično zahtjevna.

Opisan je model vijadukta, koji je namijenjen nelinearnoj dinamičkoj analizi vijadukta. Prikazano je modeliranje nekoliko nestandardnih nosivih elemenata kao što su upornjaci, pridrživači, elementi koji onemogućavaju posmik vijadukta u poprečnom smjeru, različiti tipovi međusobnih udaraca nosivih elemenata. Analiziran je utjecaj najvažnijih parametara na odziv vijadukta. Karakteristike upornjaka, kontaktnih elemenata u unutarnjim zglobovima i dilatacije tih elemenata imaju naročito veliki utjecaj na potresni odziv vijadukta u Las Vegasu.

***Ključne riječi**: potresna analiza, inženjerski model, vijadukt, ojačavanje, nelinearna vremenska analiza.*