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SHAKING TABLE STUDY OF THE SEISMIC INTERACTION OF AN ISOLATED BRIDGE DECK WITH THE ABUTMENT UTILIZING SMALL-SCALE MODELS AND NUMERICAL SIMULATIONS

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Abstract. *It has been recognized that an isolated deck develops horizontal displacements of considerable amplitude during a strong earthquake. In this case the possibility of mobilizing the abutments in moderating such large amplitude horizontal response is beneficial for the safety of the structure. Thus, apart from lowering the seismic forces by the low-stiffness isolator units, the interaction between the deck and the abutments in the form of pounding for large horizontal deck response amplitudes aims at limiting through this mechanism excessive horizontal deck displacements. Such a problem was examined at the laboratory of Strength of Materials and Structures of Aristotle University using a small-scale physical representation that retains in a qualitative way the following important features: 1. A relatively stiff steel platform, representing the bridge deck, which is supported on a shaking table by two flexible supports, representing the isolator units; it is subjected to simulated horizontal earthquake motions developing large amplitude horizontal displacement response. 2. The possibility of bridge deck pounding on the abutment was introduced through a connector device that became active after the deck response exceeded a certain amplitude, introducing an initial gap within this connector. Despite the fact that these two basic response mechanisms, flexibility of isolator units and connector force-displacement characteristics, are crude small-scale representations of the actual mechanisms that are mobilized in a prototype bridge deck, the qualitative characteristics of this problems are retained. A number of simulated earthquake tests provided the necessary measured acceleration and displacement response of the model steel platform of the small-scale model and the force-displacement response of the connector and the flexible supports of the steel platform with the shaking table. This was next utilized to validate numerical simulations of this small-scale experimental representation of the bridge-deck pounding problem. By comparing the numerical predictions with the measured response of this small-scale experimental representation of the bridge-deck pounding problem it can be concluded that such numerical simulations can yield quite accurate predictions provided that the force-displacement characteristics of the isolator units as well as the force-displacement characteristics of the mechanism representing the bridge deck-abutment pounding are defined with reasonable accuracy for the prototype bridge.*

1 INTRODUCTION

The basic principle of conventional earthquake resistant design is to ensure an acceptable safety level, while avoiding collapse and loss of life. This approach can be considered adequate for most types of structures. However, for important structures, such as bridges, higher level of performance is required, as bridges should maintain emergency communications even after severe earthquakes. Over the last twenty years, a lot of research has been conducted in order to raise the safety level of bridges, while keeping construction costs reasonable. Seismic isolation has had numerous applications during recent decades [1] [2] [3], especially in important structures such as bridges, which should maintain the emergency communications, with appropriate reliability, after the design seismic event [4]. One of the goals of the seismic isolation is to shift the fundamental frequency of a structure away from the dominant frequencies of earthquake ground motion. The other purpose of an isolation system is to provide an additional means of energy dissipation, thereby reducing the transmitted acceleration of the deck, which represents the critical structural element of the bridges, [1].

However, large seismic displacements of flexible isolated bridge systems increase the requirement at expansion joints, which are expected to have large movement capacities. Hence, their cost is increased, while large deck displacements increase the likelihood of span unseating. To reduce these implications, supplementary damping with dampers is developed to reduce deck's movements. To minimize extra displacement-related costs at expansion joints, movement capacities are limited by sizing the gaps (clearances) with 80% of the seismic design action according to AASHTO's section 9 [5] and 40% according to Eurocode 8-2 [4]. No consideration for seismic displacements is given in expansion joints in international literature [6] under the concept that the backwall and the expansion joint are expendable non-structural elements that may be damaged and replaced after the main seismic shock thus accepting indirectly the impact between the deck and the abutments. Despite the vast of analytical [7][8]and experimental studies [9][10] involving or not SSI effects at bridge abutments [11], there are no experimental studies investigating the dynamic bridge-abutment interaction neither qualitatively nor quantitatively. However, this approach has the following implications. First, damage may result from pounding that will not be confined only to the parts of the bridge which were designed to accommodate it. Second, the dynamics of the pounding system may differ substantially from those that were taken into account in the design without considering the pounding. This change in the dynamic system introduced by the pounding was investigated without taking a-priori that it will always have beneficial consequences for the bridge deck response. Extended research has been carried out aiming to identify the fundamental characteristics of this deck-abutment interaction utilizing a series of numerical simulations.

2 DESCRIPTION OF THE BRIDGE MODEL-INSTRUMENTATION AND ANALYTICAL MODELING

Two elastomeric bearings with cross section 150x150mm and a height of 150mm (total thickness of the elastomer 120mm) were used to support on the shake table the steel platform which represented the bridge deck model, by fixing them with bolts both to the steel platform and the shaking table (see figure 1). Additional mass was rigidly attached on this steel platform so that the total model deck mass was equal to 0.988t. In this way, the fundamental frequency of the deck - elastomeric bearings model was within the 1Hz to 20Hz frequency range. In this frequency range the employed shaking table is capable of introducing horizontal motions of sufficient amplitude in terms of acceleration and displacement. The steel platform was provided with side rollers aimed to prohibit its motion at any other horizontal direction apart the longitudinal direction that coincided with the direction of the horizontal table motion.

The connector was fixed to either the shaking table or the steel platform with steel attachments of sufficient stiffness in a way that the load-displacement response of this link to be dictated by the properties of the copper connector itself and not by its attachments (see figure 1). The connector was made by a copper cylinder encased within a steel ring. A small gap between the copper cylinder and the steel ring was provided in order to simulate the gap between the bridge deck and the adjacent abutment. The amplitude of such a gap before the commencement of a strong earthquake motion cannot be exactly known as it depends on actual expansion and contraction movements of the deck prior to the seismic motion. The bridge model, with or without the copper connector in place, was subjected to a uni-direction simulated earthquake horizontal motion based on the horizontal components of the actual ground motion record of the Kern County, California 1957 earthquake. This simulated earthquake motion resulted from speeding up in the time domain the original recording in order to include sufficient energy in the above mentioned frequency range. Figure 2a depicts the frequency content of the simulated earthquake motion as it was found by the Fourier transformation of the shaking table acceleration recorded during the experimental sequence. Figure 2b depicts the fundamental frequency of the model deck - elastomeric bearings dynamic system as found from its acceleration response during one of the simulated earthquake experiments.

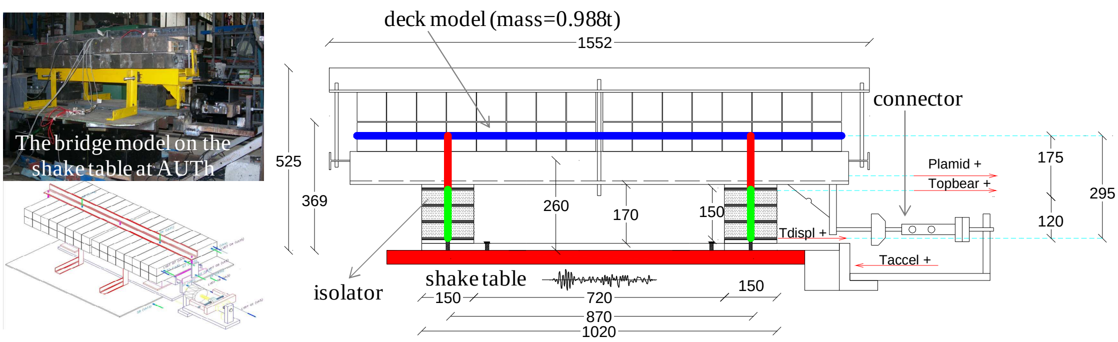
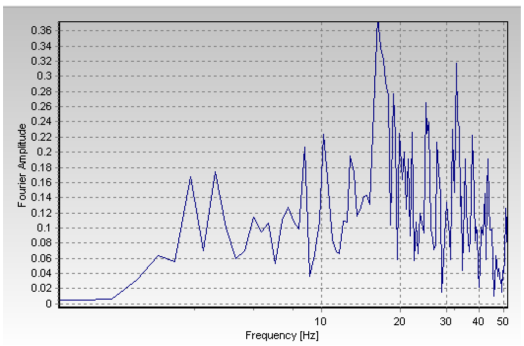
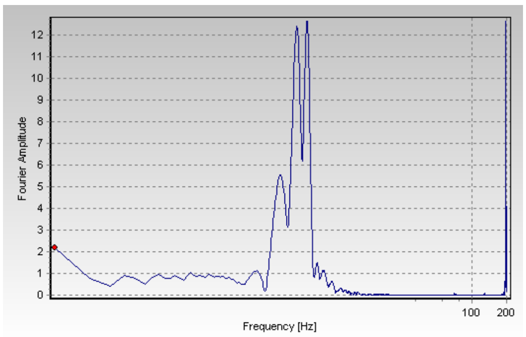


Figure 1: The geometry of the SDOF specimen as built on the shake table of the Laboratory of Strength of Materials and Structures @ AUTh and the model of the equivalent model bridge in commercial FEM code SAP 2000.



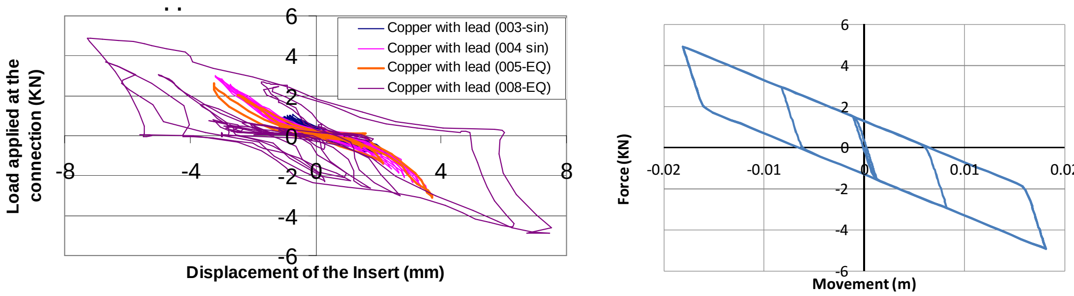
(a)



(b)

Figure 2: (a) Fourier transformation of the shaking table acceleration measured during the experiments utilizing simulated earthquake motions based on the Kern county 1957 prototype earthquake recordings, (b) Acceleration response of the model deck-elastomeric bearings system with peaks at 3.052Hz and 3.711Hz.

Instrumentation was provided in order to capture the acceleration and displacement response along the longitudinal axis of motion both of the shaking table level as well as of the



(a) (b)

Figure 3: (a) Measured cyclic load-displacement response of the copper connector and (b) numerical cyclic load-displacement response of the copper connector (no gap).

steel platform representing the model deck. For the model platform this was done both at the level corresponding to the center of mass as well as at the level just above the point of fixity of the elastomeric bearings with the steel platform (see Figure 1, Plamid, Topbear). Additional instrumentation was also provided to measure the vertical acceleration of the steel platform as well as the horizontal acceleration along the transverse horizontal direction. Finally, the actual load-displacement response of the copper connector itself was monitored independently by a load cell positioned in line with the connector as well as with a displacement transducer measuring the relative displacement of the two connector ends. At the beginning of the experimental sequence a gap of 1.5mm was introduced between the copper cylinder and the steel ring of the connector. This gap became larger during the experiments due to the plastification of the copper cylinder. The plastification of the cylinder is aimed at simulating the response of the soil surrounding the abutment during deck ponding. Figure 3a shows the cyclic load-displacement connector response as was measured during one particular experiment with a simulated earthquake motion whereas Figure 3b is the numerical simulation of the copper connector load displacement response that was used in the numerical investigation, which is presented next.

3 NUMERICAL SIMULATION

The deck - elastomeric bearings model response was numerically simulated employing a commercial software package (SAP 2000) and utilizing all the relevant information from the specific constituents of the elastomeric bearings, copper connector and steel platform in terms of mass and load-displacement characteristics. The load-displacement characteristics of the elastomeric bearings in horizontal shear, vertical axial force and bending moment as well as those of the copper connector were measured by specific experiments and as such were introduced to the numerical simulation through the options provided by the software. The actual geometry of the model deck-bearings-connector system was introduced in the numerical simulation through a 2-D representation. This is shown in Figure 1a (top right) as well as in Figure 4.

The steel platform representing the model deck is simulated by rigid frame elements that have very large stiffness and the total mass (red solid line, Figure 4). These rigid frame elements are located in the horizontal plane going through the center of mass of the steel platform (see Figure 1). The elastomeric bearings are simulated with link elements that are located vertically in a way coinciding with the central axis of the model elastomeric bearings (green solid line, figures 1 and 4). These link elements were given such non-linear properties as found from tests performed with the model elastomeric bearings, as shown in figure 5. Rigid elements with very large axial, shear and flexural stiffness values are used to connect these link elements representing the elastomeric bearings with the rigid frame elements representing the steel platform. Finally, a link element with non-linear axial load-displacement response properties coinciding with those of the copper connector (see figures 3a and 3b) is used to represent numerically the connection of the steel platform with the shaking table.

Four different alternatives of the non-linear properties for the link elements representing the elastomeric bearings were examined (figure 5). These alternative non-linear properties were based on the target displacement, the damping areas and the stiffness of the loading and the unloading branch of the tested bearings. Modeling these non-linear model elastomeric bearing characteristics the option of Wen load-displacement constitutive law was adopted offered by the software. From these four alternative numerical simulations of the model elastomeric bearings cyclic response the second alternative was selected based on the comparison of the numerical predictions with the corresponding load-displacement hysteresis loops obtained during testing, as shown in Figure 4. This 2nd alternative was found to simulate in a satisfactory way the stiffness variation and the hysteretic damping of the bearing, the shear deformation at the bearing's yielding point and the effective stiffness of the bearing under the maximum target displacement measured during the experiments. It was also found to illustrate accurately the unloading branch of the hysteresis loops which was observed during testing.

The numerical response of the deck-elastomeric bearing model without the connector was validated by comparing it with the corresponding experimental measurements. Figure 6 depicts this comparison in terms of deck displacement of the center of mass. As can be seen from this figure reasonably good agreement was obtained between numerical and measured displacement response in the time domain. The maximum predicted model deck displacement agrees quite well with the measured value. Based on that, the numerical simulation was extended to the model with the connector in place.

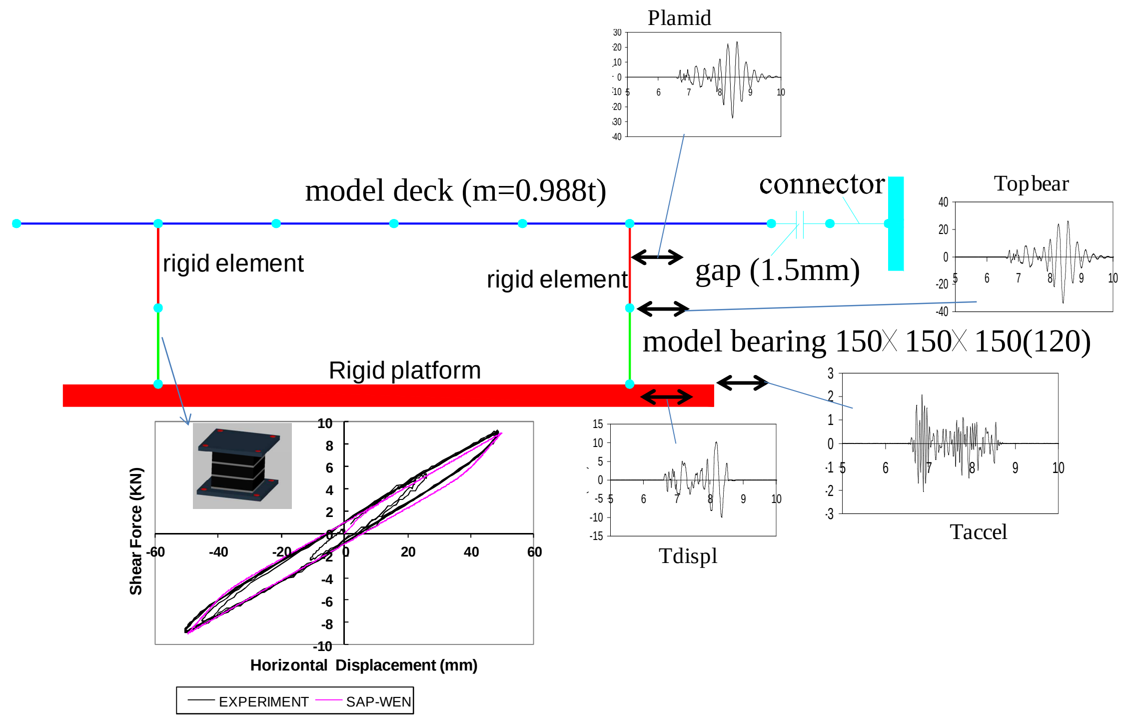


Figure 4: The idealized model deck with the bearings and the connector. The recorded time histories of the model and the hysteresis loops of the model bearing are shown.

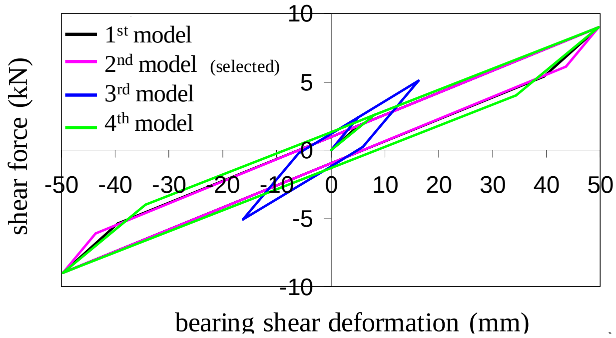


Figure 5: The alternative bearing models used in SAP 2000 for different target displacements, and unloading stiffnesses.

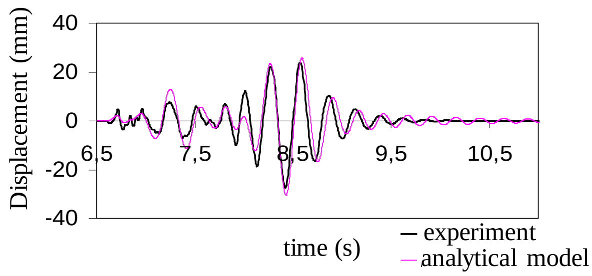


Figure 6: The time histories of the recoded response as the top of the bearing (Topbear).

4 NUMERICAL SIMULATION OF THE BRIDGE'S DECK-ABUTMNET POUNDING INTERACTION

In this part of the numerical study the bridge's deck-abutment pounding interaction will be examined by introducing in the numerical model the numerical simulation of the copper connector, which was used during the experimental sequence to physically simulated in small-scale this interaction. This has been already explained and presented in figures 3a and 3b. As can be seen, the employed copper connector possesses a non-linear force-displacement capability that is symmetric and represents in this way pounding of the deck in the two opposite abutments of the bridge. Modeling of pounding effects has been studied extensively during the last years[12] [13] [14] [15] [16]. In terms of amplitude, the maximum pounding force in a prototype bridge with total deck length equal to 100m is expected to be of the order of 12000kN [7]. The total weight was estimated approximately equal to 24800kN [17]. Thus, the maximum pounding force represents approximately 50% of the weight of the deck. Similarly, the model deck weights approximately 9.89kN and together with the maximum measured copper connector force (of the order of 5kN) form a similar ratio of maximum pounding force over deck weight as the previously mentioned prototype bridge deck. It is debatable, whether the force-displacement response that will develop between the abutment and the bridge deck during pounding will bear any similarity to the cyclic response of the copper connector depicted in figure 3a. Such a prototype deck-abutment force displacement relationship can only be defined from direct in-situ measurements and is beyond the present study. Thus, the current numerical examination is limited to demonstrate the effect of this interaction by assuming that the measured copper connector load-displacement cyclic response bears some resemblance with the deck - twin abutment pounding interaction of a prototype bridge. Moreover, when such a prototype force-displacement response becomes available from in-situ measurements it can be included into a numerical simulation in a way similar to the one that is followed here.

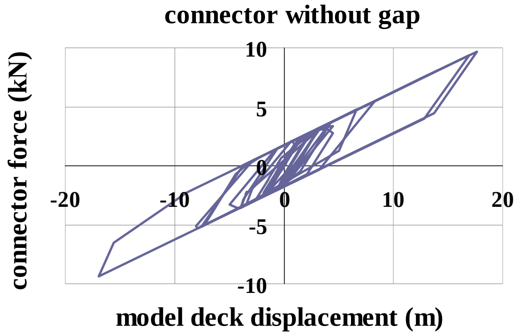


Figure 7: Connector force vs relative deck-connector displacement (no gaps)

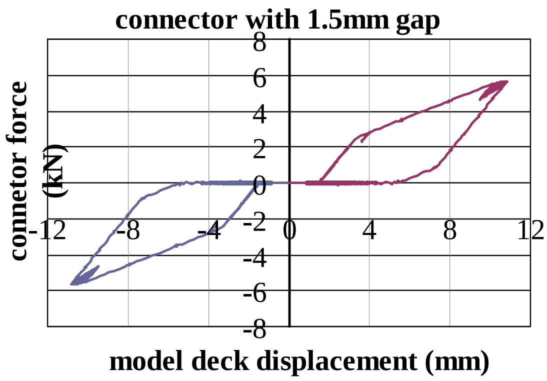


Figure 8: Connector force vs relative deck-connector displacement with 1.5mm gap

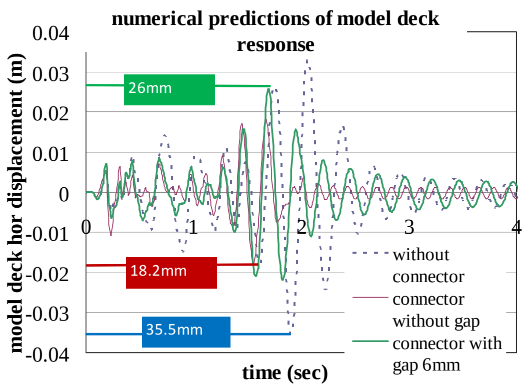


Figure 9: Comparison of the model deck displacement response without the connector or with connector in-place (with or without a gap)

Two different numerical models were utilized to simulate numerically the scale-model behavior when the copper connector was in place. The first model is a non-linear link element with an initial stiffness equal to 1500kN/m, a yielding force equal to 2.5kN and a post-yield stiffness equal to 30% of the initial stiffness (Figure 7). However, in this way it is assumed that the deck-abutment interaction starts as soon as the deck displaces horizontal. As this assumption is not realistic, a second numerical model was utilized in order to simulate the condition that a physical gap exists between the deck and the abutment. Thus, in order for the pounding interaction to commence the horizontal deck displacement should be of such an amplitude that exceeds this gap. The second model simulates the existence of a ±1.5mm gap between the deck model and the copper connector. This is done by connecting in line the previously described non-linear link element with a gap element having as an initial gap value equal to 1.5mm (see figure 8).

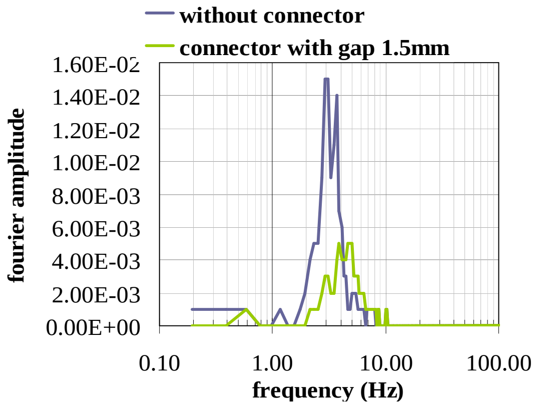


Figure 10: Comparison of the model deck displacement response without the connector or with connector in-place (with or without a gap) in terms of FFT plots

5 CONCLUSIONS

- It has been established in the past that the decks of isolated bridges interact with the abutments during strong earthquakes. This deck-abutment interaction has been evaluated in past experimental studies in scaled abutment models including their backfills.
- The influence of isolated bridge deck - abutment interaction from pounding was investigated in this paper by simple numerical tools that take into account the dynamic and non-linear nature of this interaction. The non-linearity springs from the isolator bearings themselves, but mostly from the deck to abutment interaction. This was introduced to the numerical simulation by a combination of non-linear link and gap elements
- An experimental study was also carried out utilizing a small-scale model to represent the isolated bridge deck and a copper connector to approximate qualitatively this deck-abutment interaction. A number of shaking table tests was performed without and with this connector in place. The numerical predictions of the maximum model deck displacement response are in reasonable good agreement with the measured values, when the gap element is employed.
- The presence of the connector results in a stiffer dynamic system that has a higher dominant frequency. Similarly, a prototype bridge is expected to become stiffer when the deck is pounding on the abutment and the backfill soil than in the case where a sufficient gap is provided to prohibit such an interaction.
- The force-displacement response that will develop between the abutment and the prototype bridge deck during pounding will be similar in a qualitative way to the force-displacement cyclic copper connector response utilized in this study. This can only be defined from direct in-situ measurements and is beyond the present study.
- The current numerical examination, which includes non-linear mechanisms arising from the gap between the abutment and the deck as well as from the deck-abutment interaction during pounding, is limited to demonstrate the effect of such an interaction. Despite the

inherent quantitative inaccuracies included in this study, it is believed that the most significant response mechanisms were included. Consequently, the employed numerical simulation is expected to yield reasonably accurate predictions for prototype isolated bridge decks interacting with their abutments during strong earthquakes provided that realistic estimates of prototype deck-abutment force-displacement response becomes available from in-situ measurements.

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