Numerical Hybrid Simulation Modeling Verification for a Curved 3-Pier Bridge (Investigation of Combined Actions on Reinforced Concrete Bridge Piers (CABER) Project)

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ABSTRACT

Reinforced concrete bridge piers are subjected to complex loading conditions under earthquake ground motions. Bridge geometric irregularities and asymmetries result in combined actions imposed on the piers as a combination of displacements and rotations in all six degrees of freedom at the pier-deck juncture. Existing analytical tools have proven their inadequacy in representing the actual behavior of piers under these combined actions, particularly in their inelastic range. The objective of this investigation is to develop a fundamental understanding of the effects of these combined actions on the performance of RC piers and the resulting system response.

This paper describes a part of the CABER project that verifies the numerical hybrid simulation of the curved bridge. In this part two models were introduced, a whole model and a sub-structured hybrid model. The whole model was established using the Zeus-NL analysis platform, which is capable of performing inelastic nonlinear response history analysis of the whole curved bridge. The hybrid model was divided into three modules which comprised the deck, left and right piers, and the middle pier of the bridge. The three modules were modeled by Zeus-NL as a static analysis module interface. The simulation coordinator (SimCor) software was utilized to communicate between these modules using a Pseudo-Dynamic time integration scheme. Results obtained from both models were compared and conclusions were drawn.

Keywords: Numerical/Experimental Hybrid Simulation, RC Bridges, Combined Actions and Inelastic Dynamic Analysis.

1. INTRODUCTION

The numerical hybrid simulation analysis discussed in the paper was performed as a partial requirement for the completion of the numerical-experimental hybrid analysis of the CABER project. The CABER project involves modeling a curved bridge with three piers of varying heights in unique soil conditions and with unsymmetrical spans along the curve of the bridge deck (Figure 1). The three piers will be tested experimentally at the Multi-Axial Full-Scale Sub-Structures Testing and Simulation (MUST-SIM) facility at UIUC. Two piers comprising one module will be tested on the large strong wall at a scale of 1:3, while the third pier will be tested simultaneously at the small scale facility located at the same site. The deck, abutments, and soil will all be modeled computationally. However, in this paper, the three piers are modeled numerically along with the deck, abutments and soil. This is done in anticipation of encountering various phenomena to explore, as well as challenges in controlling the experimental specimens to overcome prior to conducting the complete hybrid experiment described above.

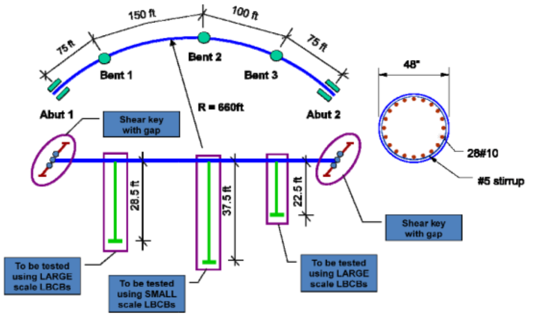

Figure 1: Conceptual drawing of complex curved bridge for CABER project hybrid analysis.

New and advanced considerations that must be addressed in this specific project involve:

- Functional constraints due to the skewed bridge deck and the torsional moments that will develop in the structure as a result
- Geometric constraints due to uneven spans and heights of the three piers
- Structural constraints due to the modeling of the joints and soil-foundation interaction
- Multi-directional motion of the applied earthquake record

Addressing these issues requires significant advances in the control software used to implement the prescribed displacements provided by the simulation coordinator software, SimCor. These actions are applied through the use of the Load and Boundary Condition Boxes (LBCBs) in all six degrees of freedom. In addition to considerations regarding controls, the UI-SimCor platform will require updating for use of the multidirectional event and the functional constraints introduced by the increasing complexity of the structure. The following section provides a brief overview of the concept of hybrid simulation, in order to give the reader insight into the facilities and software used.

2. OVERVIEW OF HYBRID SIMULATION

Hybrid Simulation is a platform for the analysis of structures using any combination of computational and experimental testing methods. Traditional experimental and computational approaches can be performed simultaneously through sub-structuring of the given system into separate modules of interest. Through the application of a simulation coordinator platform, communication is enabled between the experimental or computational modules of the structure being analyzed. This allows for increased flexibility in testing programs along with an improvement of the accuracy and efficiency previously available through traditional standalone experimental or computational testing programs (Watanabe et al. 1999, NSF 2000, Tsai et al. 2003, Kwon et al. 2005, Pan et al. 2005, and Takahashi et al. 2006).

The most distinctive feature of the MUST-SIM facility is the L-shaped post-tensioned concrete strong wall (Figure 2) and its three modular 6-DOF Load and Boundary Condition Boxes, LBCBs, shown in Figure 3. These boxes allow for precise application of complex load and boundary conditions.

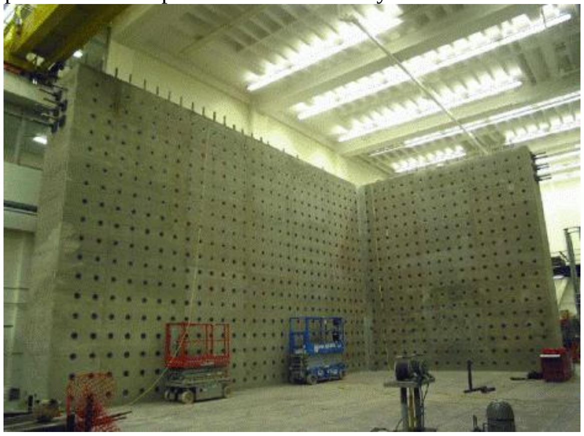

Figure 2: Strong wall at UIUC MUST-SIM facility.

The LBCBs can impose motions on structural specimens that are determined from the results of concurrently running numerical models of the test specimen and the surrounding structure-foundation-soil system through employing hybrid simulation.

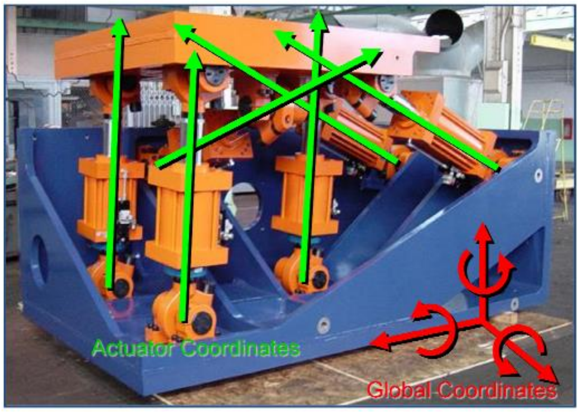

Figure 3: 6-DOF Load and Boundary Condition Box.

The computational tools of most interest in this investigation are the FEA programs compatible with SimCor, the simulation coordinator used at the MUST-SIM facility. The programs currently supported by the SimCor platform are Zeus-NL, OpenSees, FEDEASlab, ABAQUS, and Vector2.

The simulation coordinator (SimCor) provides the communication between modules necessary to perform hybrid analysis. This framework provided allows for the utilization of any combination of analytical platforms and experimental facilities to be integrated and simulate a larger, more complex system. SimCor utilizes pseudo-dynamic (PSD) simulation for distributed analysis and experimentation. This concept involves the substructuring of the complex/whole system into smaller modules that can be solved with individual computers connected through a variety of available communication protocols. The time integration scheme is performed in SimCor and modules perform static analysis based on the information received from SimCor. A more detailed explanation of this process is illustrated in the figure below.

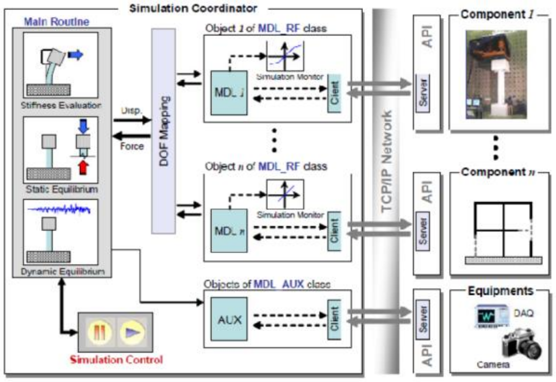

Figure 4: Hybrid simulation framework in SimCor.

3. NUMERICAL HYBRID MODEL

In this section, a whole Zeus-NL model of the curved bridge is introduced (Figure 5). The curved bridge system is also split up into three Zeus-NL modules as shown in Figure 6. The first module consists of the superstructure, and the second module is the inner pier representative of the small-scale experimental structure for the final experiment. Finally, the third module includes both of the outer piers, which represent the portions of the structure that will eventually be tested on the large strong wall.

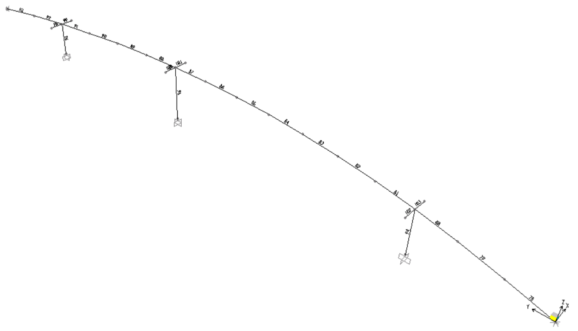

Figure 5: Whole Zeus-NL model.

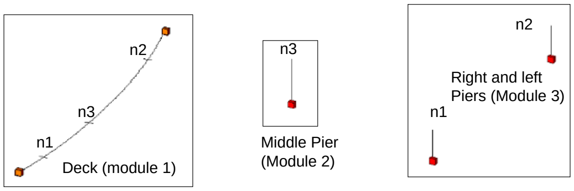

Figure 6: Three modules of the numerical hybrid model.

The bridge deck was divided into sixteen segments; each segment is 25 ft. long. The curvature of the bridge was taken as 1/ (650 ft.). The deck, piers, and transverse beams cross sectional dimensions are shown in Figure 7. In this analysis, the deck and transverse beams were assumed to remain in the elastic range during the analysis, which is usually the case for these types of bridges. Moreover, the strains at critical locations along the deck and transverse beams were monitored throughout the analysis and it was revealed that the strains have not exceeded the cracking strains of concrete. Hence, inelasticity and failure were only assumed at the piers which will be eventually modeled experimentally.

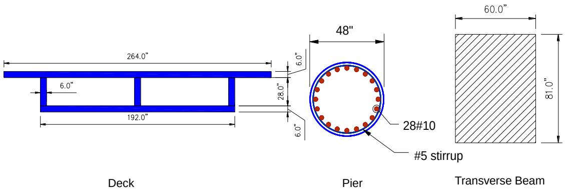

Figure 7: Deck, piers, and transverse beams cross sectional dimensions.

The loading of the bridge included bridge self-weight as well as the weight of pavement, utilities and finishing. Traffic load was also included as the assigned structure live loads. Seismic loads were applied as earthquake ground accelerations at the pier bases. The acceleration records were applied without scaling on the transverse direction of the bridge while at the transverse direction the same record accelerations were scaled by 0.25.

Four scalings of the same synthetic record were applied in series in this response history analysis. The scalings represent earthquake motions compatible with response spectra of MCE-Cracking, -Yielding, -Design Level, and -Failure subsequently as shown in Figure 8.

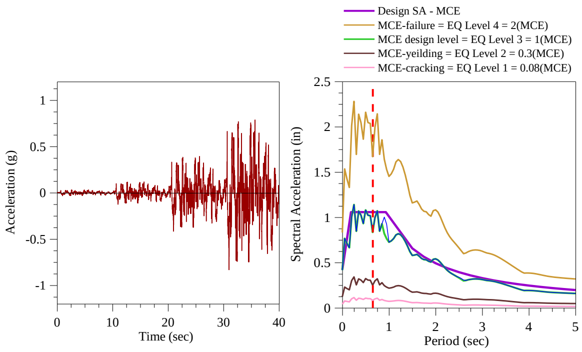

Figure 8: Earthquake record.

The boundary conditions of the bridge are assumed as follows:

1- The abutment-deck interface is simulated by two non-linear spring models as shown in Figure 9. The first spring model simulates the gap between the bridge deck and the abutment and can therefore account for pounding effects during earthquake shaking. The second spring model depicts the hysteretic response of the shear key element of the abutment as shown in the same figure. The two spring models are connected in series to yield an overall response shown in Figure 9.
2- Fixation is assumed at the base of each pier.

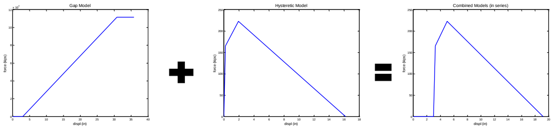

Figure 9: Two spring models in series and the overall spring model behavior.

4. RESULTS AND OBSERVATIONS

The results obtained from the whole model as well as the results of the hybrid analysis are provided in this section to demonstrate the success in running the hybrid simulation using SimCor to communicate between three modules that are representative of an ultimately more complex combined experimental/analytical hybrid test. The results are very satisfactory in the sense that the displacements and rotations obtained from the whole model matched very well with the hybrid analysis results. The deformations at the top of the inner pier obtained from the whole and hybrid models are plotted on top of each other and provided in Figure 10.

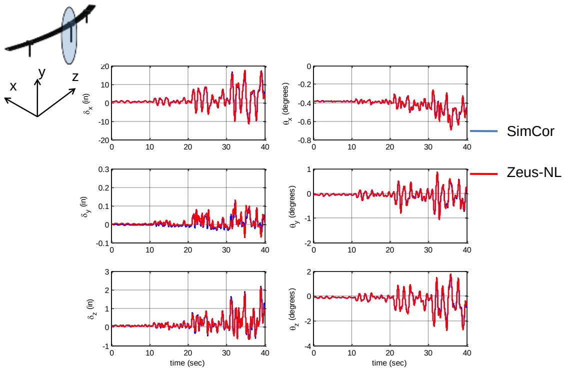

Figure 10: Deformations at the inner pier.

The stroke and force limits of the LBCBs are also checked in this study using the results obtained from the numerical models. The actuators of the large scale LBCBs to be used for the outer piers have stroke capacities of +/- 10 inches in the X-direction and +/- 5 inches in the Y- and Z-directions. The force capacity is -200/+300 for all actuators of the large scale LBCBs. The actuator forces and strokes were calculated using Matlab code developed for the MUST-SIM facility by SunJig Kim. This code is capable of calculating the actuator forces and strokes given the displacements and rotations imposed on the boxes in the 6-DOFs. Figure 11 and Figure 12 show the measured strokes and forces respectively for one of the outer piers that will be tested using the large scale LBCB. The anticipated displacements and forces do not exceed the capacities of the loading boxes. Similar checks were performed for both the other outer pier as well as the inner pier that will be tested using the small scale box.

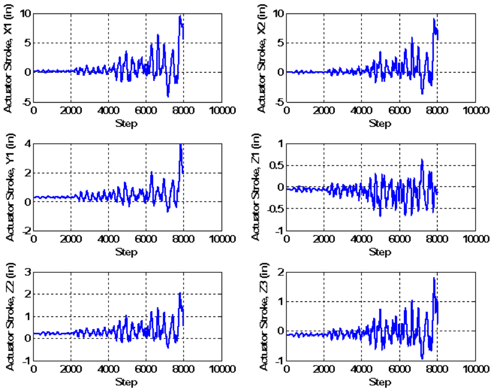

Figure 11: Strokes of LBCB actuators at one of the outer piers.

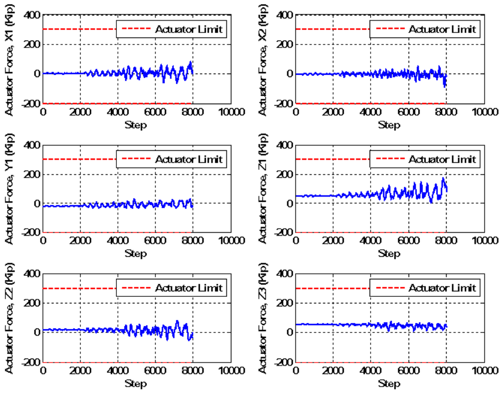

Figure 12: Forces imposed by the LBCB actuator on one of the outer piers.

5. SUMMARY AND CONCLUSIONS

In summary, hybrid simulation has been shown to be capable of providing an accurate and efficient analysis of complex structures not previously attainable through traditional methods. An overview of the methodology of hybrid simulation and the underlying motivation was provided. The experimental, analytical, and simulation coordinator components of the platform specific to the NEES MUST-SIM facility were provided, in addition to the variety of hybrid methods available through the use of these components. These distinct forms of hybrid analysis include mixed experimental and analytical tests, multi-resolution computational analysis, and multi-site geographically distributed experimental testing programs. An example from the literature was provided to study the aspects of each of these methods, and current shortcomings were addressed within the context of future work for a more complex hybrid analysis which the author will be involved in as a part of the ongoing CABER project. Finally, a hybrid analysis of a simple four-span bridge was performed in a test case designed to provide early exposure and orientation to the hybrid analysis capabilities of SimCor.

6. ACKNOWLEDGEMENTS:

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