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Application of In-Test Model Updating to Earthquake Structural Assessment

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Analytical methods are frequently utilized for structural assessment due to their simplicity and cost-effectiveness. However, modeling of material inelasticity and geometric nonlinearity under reversed inelastic deformations is still very challenging and its accuracy is difficult to quantify. On the other hand, realistic experimental assessment is costly, time-consuming, and impractical for large or spatially extended structures. Hybrid simulation has been developed as an approach that combines the realism of experimental techniques with the economy of analytical tools. In hybrid simulation, the structural is divided into several modules such that the critical components are tested in the laboratory, while the rest of the structure is simulated numerically. The equations of motion solved in the computer enable the integration of the analytical and experimental components at each time increment. The objective of this article is to apply a newly developed identification and model updating scheme to acquire the material constitutive relationship from the physically tested specimen during the analysis to two complex hybrid simulation case studies. The identification scheme is developed and verified in a companion article, while the two experiments presented in this article are selected such that they address different structural engineering applications. First, a beam-column steel connection with heat treated beam section is analyzed. Afterwards, the response of a multi-bay concrete bridge is investigated. The results of these two examples demonstrate the effectiveness of model updating to improve the numerical model response as compared to the conventional hybrid simulation approaches.

Keywords Model Updating; Pseudo-Dynamic Tests; Hybrid Simulations; Constitutive Relationships; Optimization Algorithms

1. Introduction

Pseudo-dynamic (hybrid simulation) experiments are assessment tools that combine the advantages of both experimental and numerical techniques [Hakuno *et al.*, 1969; Takanshi *et al.*, 1975]. Hence, this approach has been conventionally used to evaluate structures including few components that show intense nonlinear behavior [Hashemi *et al.*, 2014]. Hybrid simulation excel quasi-static experiments as it takes into consideration the inter-dependency between the experimental and numerical modules during the analysis [Mahin and Shing, 1985]. Additionally, it is suitable to assess the response of large-scale structures such as bridges and high-rise buildings that cannot be investigated using the traditional shaking table experiments. Therefore, hybrid simulations provide the realism of

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experimental techniques, while preserving the simplicity and cost efficiency of analytical methods.

Analytical methods frequently fail to represent the response of actual members that are subjected to intense plastic deformations. Therefore, in applications where the analytical components have a significant contribution to the structural response, the value of hybrid simulation diminishes [Elanwar and Elnahai, 2014]. There are several sources of uncertainties associated with the numerical modelling. In this article, the focus is directed toward the identification of the constitutive relationship behavior as a fundamental material property from the physically tested specimen. In literature, several reasons have been thoroughly discussed to demonstrate that the analytical constitutive relationships might not be adequate to represent the actual model response. For instance, the nonlinear behavior of the stress-strain model varies for different coupon tests, even if the tested specimens share the same material specification and geometry [Lowe, 1999]. In addition, the constitutive models show complex behavior in representing some features such as strain rate effect, thermal effect, isotropic strain hardening, reinforcement bars buckling, etc. [Lowe, 1999; Gomes and Appleton, 1996]. Moreover, the manufacturer errors might reach 10% for both concrete and steel materials [Elnashai and Chryssanthopoulos, 1991; ACI Committee, 2002]. These are some examples of the challenges that impact the constitutive relationship reliability.

In this article, a novel approach is proposed that aims to identify the constitutive model behavior from the tested specimen during hybrid simulation experiments. Several of the constitutive relationship uncertainties are specific to the experiment characteristics such as loading, geometric, and manufacturing conditions. Therefore, it is adequate to utilize the valuable information provided by the tested specimen and reflect them to the corresponding analytical modules. The proposed model updating approach enhances some of the hybrid simulation features such as: (1) it reduces the gap between the analytical idealizations and the actual structural response through updating the constitutive relationship behavior incrementally; (2) model updating can be applied to assess structures with multiple critical components such as multi-span bridges. Whereby, it is sufficient to test a representative sample of the critical components and use its identified characteristics to update the corresponding numerical parts; and (3) model updating does not entail further complications to the conventional hybrid simulation approach. Yet, it provides improvement to the numerical component behavior and hence, the overall structural response.

2. Model Updating Approach

Model updating requires several modifications to the conventional hybrid simulation procedure, which allows it to identify and modify the constitutive relationship properties during the test. This section discusses the main components of the model updating approach.

2.1. Model Updating Procedure

In this section, a brief description of the model updating components is presented. A more detailed discussion can be revisited in the companion article titled "A Framework for Online Model Updating in Hybrid Simulations." The simulation coordinator program UI-SIMCOR is adopted as a tool that can communicate between the numerical and experimental modules during hybrid simulation tests [Kwon *et al.*, 2007]. ZeusNL is utilized as a finite element software, which can handle large-scale problems subjected to dynamic loadings [Elnashai *et al.*, 2002]. Two of the constitutive relationships available in the ZeusNL library are considered in this article, which are the bilinear steel model and a modified Mander concrete model [Mander *et al.*, 1988; Martinez-Rueda and

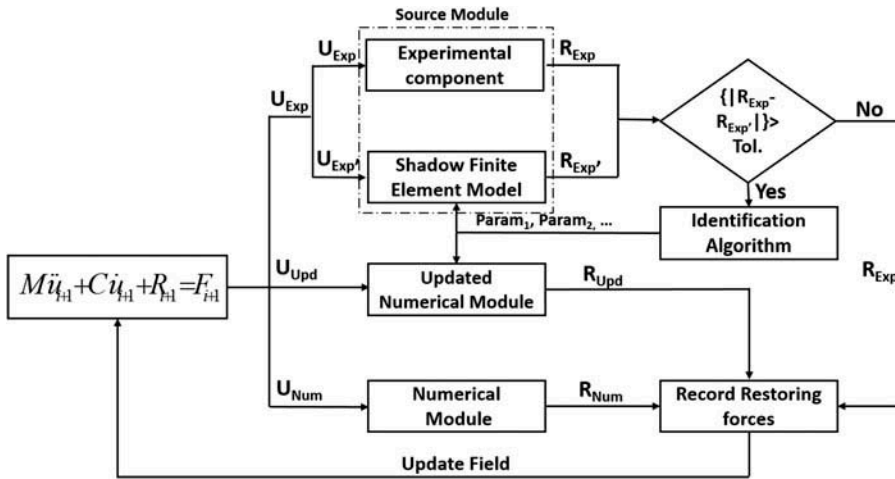


FIGURE 1 Schematic diagram for model updating procedure.

Elnashai, 1997]. It is worth mentioning that model updating requires modifications in the communication protocols between UI-SIMCOR and ZeusNL to be able to update the stress-strain information during the hybrid simulation analysis.

The flowchart shown in Fig. 1 illustrates the model updating procedure [Hashemi *et al.*, 2014; Elanwar and Elnashai, 2014]. In this procedure, the structure is divided into experimental, updated and numerical modules. The equation of motion integrates between the deformations applied (U) and the restoring forces (R) recorded from each module. During hybrid simulation tests, the experimental component provides a lot of information regarding the behavior of tested specimen. In order to utilize this information, a shadow finite element model is developed, which mimics the properties of the experimental component. Afterwards, identification algorithms such as optimization tools can be applied to determine the shadow finite element model parameters that minimize the difference in response with respect to the experimental component. These parameters are identified incrementally and they are used to update the corresponding numerical modules that are subjected to close geometric and loading conditions relative to the experimental one. Based on that description, the experimental component and the shadow finite element model can be called together the source module, while the corresponding numerical parts are called the updated modules. Identifying the physical specimen behavior during the test is a challenging task. Therefore, the procedure required to identify the model parameters from the source module will be discussed thoroughly in the “Methodology” section. Model updating procedure is intuitive and does not entail many complexities to the conventional hybrid simulation approach. Nevertheless, it provides valuable improvement to the numerical module response.

2.2. Literature Review

Recent efforts have been concerned with the application of online model updating in hybrid simulation tests [Yang *et al.*, 2012; Kwon and Kammula, 2013; Hashemi *et al.*, 2014; Elanwar and Elnashai, 2014]. Hybrid simulations provide some features that can be integrated with model updating components. First, the equation of motion determine the actions and deformations applied to each structural module in a stepwise manner [Kwon

et al., 2008]. This feature allows for updating the numerical model incrementally without interrupting the analysis procedure. Second, the experiment is conducted at slow rate, which provides the time required to identify the behavior of the tested specimen. Finally, the identified behavior is used to update the numerical model response, while the experiment is paused. It is important to mention that some studies address the application of this approach for real time hybrid simulations [Muller, 2014]. Most of the model updating studies focused on updating the model on a global level such as representing the structural member analytically using a rigid bar and connected to lumped springs at its nodes [Yang *et al.*, 2012], while in other cases the numerical substructure was updated based on the behavior of Bouc-Wen hysteretic model of the tested component [Hashemi *et al.*, 2013; Kwon and Kammula, 2013]. Analyzing the model on a global level provides simplicity to the updating procedure, where it relies on the deformation and restoring forces imposed by the actuator to evaluate the member characteristics. However, this approach cannot be used to assess the local behavior within the tested member. In addition, the tested component and the updated numerical module must satisfy stringent conditions with respect to the geometric and the boundary condition [Elanwar and Elnashai, 2014]. On the contrary, updating the model constitutive relationship addresses the uncertainties in the numerical model on a fundamental level, which allows flexibility in the analysis procedure. For example, the structural component can be discretized into several segments and each segment is updated according to the corresponding part in the actual model. In the verification example sections, two problems are investigated that update the numerical model based on the constitutive relationship response.

3. Methodology

Although updating the numerical model based on the constitutive relationship level provides many capabilities to the model updating approach, it is a challenging task to determine its characteristics from the source module during the test. This section describes the proposed identification procedure and the tools required for that purpose.

3.1. Constitutive Relationships

The constitutive relationship characterizes the relationship between the strain values and corresponding stresses. There are various instruments that can be used to measure the strains or the deformations from the tested component such as strain gauges, Krypton LED, linear variable transformers, etc. [Ayranci *et al.*, 2008]. However, there is no direct method to measure stresses from a certain fiber during the experiment. Therefore, the constitutive relationships are usually determined based on a simple experiment setup such as coupon tests or concrete cylinders, where the specimen is subjected to input load and by assuming linear distribution, the stresses can be evaluated [Nip *et al.*, 2010]. Nevertheless, the constitutive relationship shows a more complex behavior when the specimen is subjected to combined loading or intense plastic deformations. Consequently, analytical idealizations fail to represent the actual model response in a reliable manner. Inverse identification techniques can be utilized to determine the constitutive relationship behavior for models with complex geometric properties or subjected to combined loading [Endelt and Nielsen, 2005]. In these techniques, the solution algorithms aims to determine the constitutive relationship parameters such that the analytical solution approaches the actual model response [Cooreman *et al.*, 2008]. This approach allows for the determination of the stress-strain model characteristics indirectly, which can be applied to the physical specimen in the hybrid simulation experiments.

3.2. Identification Procedure

For model updating purposes, the inverse identification method is adopted with some modification in its procedure to be compatible with hybrid simulations applications. In this approach, the parameters that govern the constitutive relationship behavior are determined such that they minimize the difference between the responses of the analytical and the actual models. Tools such as optimization and neural networks can be utilized in the identification procedure as discussed in the companion paper. In this article, optimization tools are implemented to identify the required model parameters during the experiment. The restoring forces from both the numerical and experimental components will be utilized to evaluate the objective function. This approach is adopted due to the difficulty of measuring the stresses from the physically tested specimen. Interior-point method (IPM) is considered as a gradient based optimization technique, which requires the objective function to be continuous and differentiable. IPM consists of self-concordant barriers function, which is applied to convex problems [Nemirovski and Todd, 2008]. It is important to mention that the optimization toolbox available in MATLAB is used to run IPM algorithms. The general framework illustrated in Fig. 1 for model updating is implemented. However, Fig. 2 emphasizes on characteristics of the source module and the objective function evaluation criteria. The identification procedure can be described as follows.

- The source module represents the critical member, which is tested in the laboratory (i.e., experimental component). For this component, a shadow finite element model is developed representing the same geometric and loading characteristics. An analytical constitutive relationship is assigned to the finite element model and the parameters defining its behavior are initially assumed.
- A certain cross-section is selected by the user along the tested component according to the purpose and the configuration of the analyzed problem. The strain records are measured at the selected section using the attached instruments such as strain gauges, Krypton LEDs, etc.
- The strain records measured from the previous step are applied to the shadow finite element model. Afterwards, fiber analysis method is processed to determine the straining actions at the selected section.

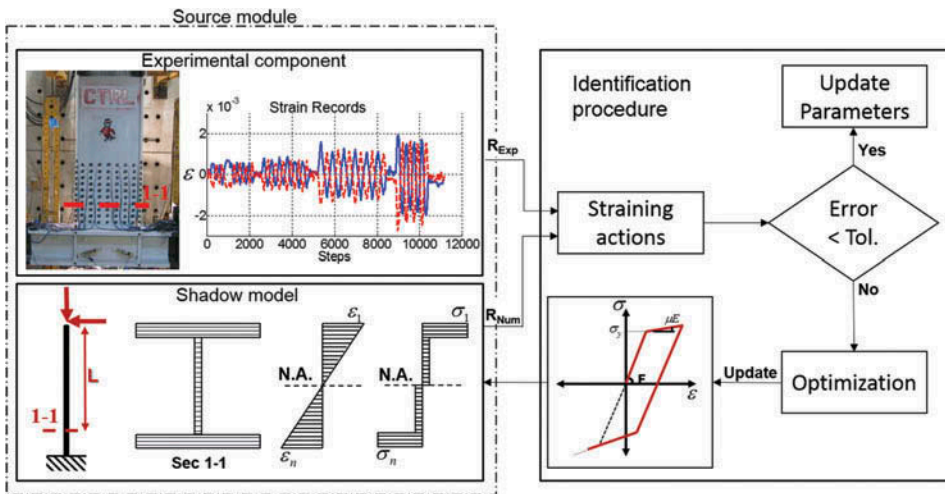


FIGURE 2 Identification procedure for the constitutive relationship parameters.

- The corresponding straining actions in the experimental component can be determined based on the equilibrium conditions according to the restoring forces applied by the actuators and the geometric configuration of the model.
- The difference between the analytically evaluated and the experimentally determined straining actions is calculated. If this difference exceeded a predefined tolerance, optimization tools will search for a new set of constitutive model parameters that minimize the difference in the straining actions value (objective function). The new parameters are then used to update the shadow model.
- The previous step keeps iterating until the minimum possible objective function is achieved or if the stopping criterion is satisfied.
- The identified parameters are recorded and then used to update the other numerical modules that share close characteristics to the tested one as discussed in the model updating framework.
- Finally, the same procedure is repeated at each loading increment.

In this approach, the inverse identification procedure was adopted as the stress values cannot be measured directly from the tested member. Therefore, it is convenient to consider a test configuration that allows applying the equilibrium conditions and performing fiber analysis method without entailing further complexities to the analysis procedure. This consideration is highlighted through the applications presented in the verification examples section.

3.3. Discussion

In the model updating framework, the numerical module behavior is modified to approach the response of the physically tested component. Nevertheless, there are several sources of uncertainties in the analytical idealization of the finite element method, especially in the modelling procedure [Cook *et al.*, 2001]. For instance, the modeling procedure requires defining the geometric configuration, material properties, loading/boundary conditions, and constitutive relationships of the analyzed material. Therefore, model updating relies on the response of the experimental component to account for various sources of uncertainties, not just those associated with the constitutive relationship. Even within the constitutive relationship behavior, uniaxial models might not be able to represent some material characteristics such as buckling of reinforcement bars or shear failures of the tested component. Hence, these characteristics are smeared within the identified model parameters. For future applications, it would be convenient to segregate the sources of the model uncertainties, and to update the analytical model by addressing each source explicitly. While considering these observations, the following section presents two verification examples that show the ability of model updating to improve the numerical module response in actual engineering problems.

4. Verification Examples

In order to assess the performance of model updating procedure, two of the previously conducted experiments are investigated. These experiments are selected such that they explore different fields of applications. The first experiment is a quasi-static beam-column steel connection with heat treated beam flanges. The second experiment is a hybrid simulation of multi-bay concrete bridge.

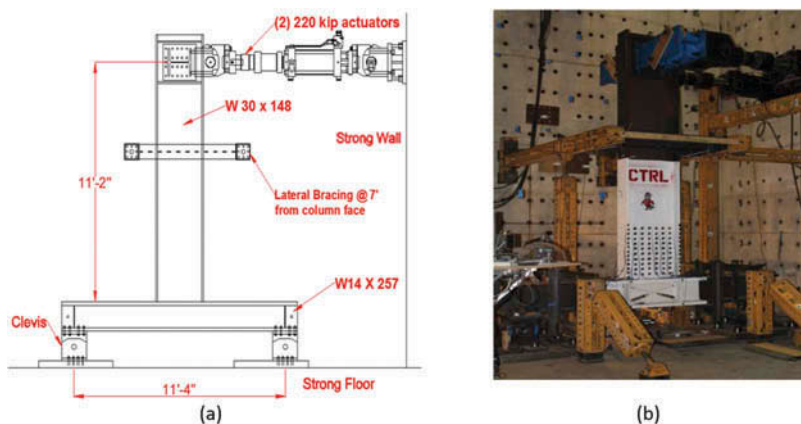


FIGURE 3 Test configuration for the beam-column steel connection: (a) schematic diagram, and (b) screen shot for the test [Schweizer, 2013].

4.1. Beam-Column Steel Connection

In 2012, a series of experiments were conducted to evaluate the seismic response of beam-column steel connections with heat-treated beam sections (HBS). The project was a part of the Network for Earthquake Engineering Simulation (NEES) program. The quasi-static tests were conducted at the Multi-Axial Subassemblage Testing (MAST) facility [Morrison *et al.*, 2012]. Figure 3a shows a schematic diagram describing the test setup, while Fig. 3b shows a screen shot for the tested connection. The dimensions of the column and beam cross-sections are $W14 \times 257$ and $W30 \times 148$, respectively. Two actuators applied lateral loads on the tip of the beam at a distance of 134 in from the column face. The beam was supported by a lateral bracing to avoid any out of plane deformations. The beam was subjected cyclic loading that follows the pattern suggested for seismic evaluation (SAC/BD-97/102), with lateral drift reaching 6% at the end of the test [Morrison *et al.*, 2012].

This test configuration represents some features that can be used to verify the proposed identification procedure. First, heat treatment for the beam flanges changes the behavior of the steel constitutive model, where it reduces the yield strength values significantly, while having a minor effect on Young's modulus. The purpose of the heat treatment process is to guarantee yielding in the beam rather than the column without losing much of the elastic stiffness. In addition, the test was heavily instrumented, which provides the records necessary for the model analysis. Moreover, the aspect ratio of the beam height to its depth implies that the beam is subjected to flexural actions, which simplifies the identification procedure. The test configuration does not impose many complexities to the analysis and, hence, most of the uncertainties can be related to the constitutive model behavior due to the heat treatment process. However, other sources of uncertainties can also have some effect on the model response such as loading combinations and manufacturer errors. The objective of this example is to identify the constitutive relationship parameters in a stepwise manner from a certain section of the beam. Then, to verify the adequacy of the identified parameters with respect to the response of the beam at a different section. The analysis procedure can be described as follows.

1. Two sections are selected along the beam height, which are located at distances of 1 and 3.5 in from the face of the column for the first and second sections, respectively. These sections are selected, where the strain gauge records are provided at these locations.

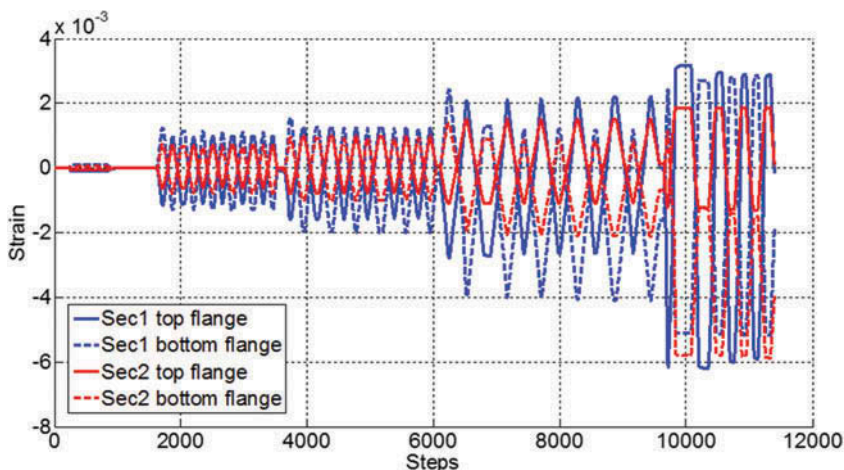


FIGURE 4 Strain gauge data for two beam sections.

2. The moment values at the two sections of interest are calculated using equilibrium conditions according to the loads applied by the actuators and the arm of the moment. It is important to mention that due to the test configuration, the beam section is only subjected to moments and shear forces, while the moment values dominate the behavior due to the beam dimensions.
3. The strain gauge data recorded at the top and bottom flanges for the two sections are shown in Fig. 4. The strain data pattern and values are consistent with the applied cyclic loading. In addition, the first section is subjected to higher moments and hence, the strains show higher values in most of the steps.
4. The strain distribution along the cross-section is assumed to follow a linear relationship, where in this example plane section is assumed to remain plane during the analysis. Afterwards, fiber analysis method is used to evaluate the analytical moments at the beam section.
5. For the fiber analysis method, the bilinear steel model is used to define the constitutive relationship behavior. Bilinear model is characterized by three parameters, which are Young's modulus, yield strength, and strain hardening factor. The initial guess of the three parameters is evaluated according to the coupon test results provided in the experiment report regarding the HBS material [Schweizer, 2013].
6. Through comparing the experimentally and the analytically evaluated moment values for the first section, IPM is processed as an optimization algorithm to incrementally determine the new bilinear model parameters.
7. In order to verify the proposed procedure, the identified model parameters are used to determine the analytical moment values at the second section. Afterwards, these moments are compared to the experimentally evaluated ones.

Figure 5 shows the moment values obtained at the second section in the beam for three different cases, which are: (1) the experimentally evaluated moments as a reference solution; (2) analytical solution, where the constitutive relationship parameters were define according to the coupon test results without applying optimization; and (3) model updating case, which is similar to the analytical solution but the bilinear model behavior was updated incrementally based on the parameters identified from the first section. From the

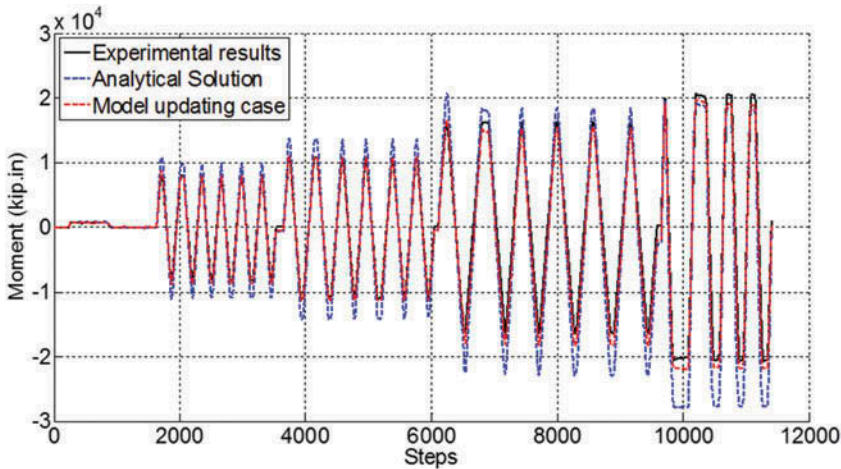


FIGURE 5 Moment results for the different analysis cases at the second section of the beam element.

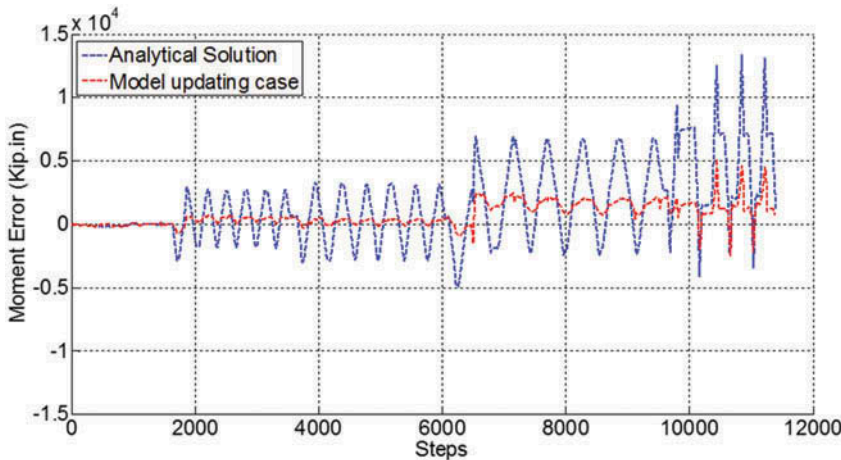


FIGURE 6 The error in the identified moment for the second section of the beam.

figure, it is obvious that there is inconsistency between the experimental and the pure analytical results. However, the analytical moment results improved significantly when model updating approach was applied.

Figure 6 shows the error in moment values for the analytical solution and the model updating case. The experimental moment values are used as a reference solution to evaluate the value of the error in both cases. The errors reduced considerably in the model updating case, especially in the elastic stage. During the nonlinear stage, the errors increased in both cases, but they were much significant in the pure analytical solution. Quantitatively, the average error values are 2412.1 kip.in and 858.7 kip.in for the analytical and model updating cases, respectively.

Figures 5 and 6 show that model updating approach can significantly improve the response of the numerical model response. In this example, the constitutive relationship parameters were determined from one section of the analyzed beam. Afterwards, these

parameters were applied to a different section to assess their effect on the numerical module. The bilinear steel model was utilized to represent the beam material. This model is characterized by three parameter, which are Young's modulus, yield strength, and strain hardening factor. Optimization algorithms were applied to update the values of these parameters incrementally. It was observed that the identified Young's modulus was slightly softer than the coupon test results. The yield strength was also smaller than the initially assumed value. The modifications in the two parameters were within 10% of the initial guess. On the other hand, the strain hardening factor was much steeper than the coupon test values. These results show the pattern of the identified constitutive relationship and the modification that took place due to the heat treatment process of the beam flanges. Optimization tools required about 5 min to determine the model parameters for the analysis procedure, which is a convenient time for quasi-static or slow-rate hybrid simulation problems. This example explored one of the possible applications of model updating approach. Whereby, it could be sufficient to test a representative segment of the analyzed component and update the constitutive relationship of the numerical module that share close characteristics accordingly.

4.2. Multi-Bay Concrete Bridge

In this example, a hybrid simulation experiment for a multi-bay concrete bridge is investigated. The Combined Actions on Bridges Earthquake Research project (CABER project) was conducted in the Multi-axial Full-Scale Sub-Structures Testing and Simulation (MUST-SIM) facility at the University of Illinois, Urbana-Champaign [Frankie, 2013; Abdelnaby *et al.*, 2014]. The objective of this project was to evaluate the seismic behavior of a curved concrete bridge subjected to combined actions. The experiment and the geometric configuration of the tested bridge are demonstrated in Fig. 7. The structure is a four-bay curved bridge supported on three piers. The piers were subjected to multi-directional earthquake records and due to the bridge configuration, six degrees of freedom actions were developed at each of the three piers [Abdelnaby *et al.*, 2014]. To ensure reliable structural representation, all the three piers were tested at the MUST-SIM facility, where the two



FIGURE 7 The experiment configuration for the CABER project [Frankie, 2013].

outer piers were scaled by a factor of 1:3, while the inner pier was scaled to 1:20 of the original dimensions to match the specifications of the utilized actuators. On the other hand, the superstructure was designed to behave in the elastic range, which was simulated numerically using ZeusNL [Frankie, 2013]. UI-SIMCOR was adopted to coordinate between the experimental and the numerical modules.

The bridge was subjected to two horizontal components of an earthquake records. In the transversal direction, the full-scale record was applied and one-fourth of that value was assigned in the longitudinal direction. The earthquake records represents an artificially generated ground record that follows the response spectrum in Seattle, Washington region. As shown in Fig. 7, the earthquake record was repeated four successive times, each of the records was scaled to a different magnitude [Frankie, 2013]. It is obvious that the test configuration of the CABER project is more complicated than the previous steel connections example. Therefore, it is expected that the analysis procedure will be more complicated, yet it allows to explore more features regarding the proposed model updating approach.

In this example, the constitutive relationship parameters will be identified from one of the physically tested piers to update the response of the analytical piers simulated in ZeusNL. Afterwards, the analytical solution resulting from ZeusNL before and after applying model updating will be compared to the experimentally evaluated responses. The outer left pier is selected to be the source module to identify the model parameters since it is subjected to the largest deformations relative to the other piers. In addition, the pier dimensions are suitable to assume flexural beam theory behavior. Another objective of this example is to show that updating the constitutive relationships is suitable for models with slightly different geometric properties, where the source and modified piers do not share the same length and cross-sectional dimensions. The procedure adopted to analyze this example can be summarized as follows.

1. The concrete pier is defined using three analytical constitutive relationships such that the modified Mander model is used to represent the concrete core and cover, while the bilinear steel model defines the reinforcement bars behavior.
2. A section is selected at a distance of 93 in from the pier cap. At this section, four strain gauges were attached during the experiment in two perpendicular directions. Figure 8 shows the strain records and a schematic diagram for the pier cross-section. It is important to mention that most of the strain gauges records at the different sections along the pier height were not available, whereby only the data were provided at the three sections closest to the pier support.

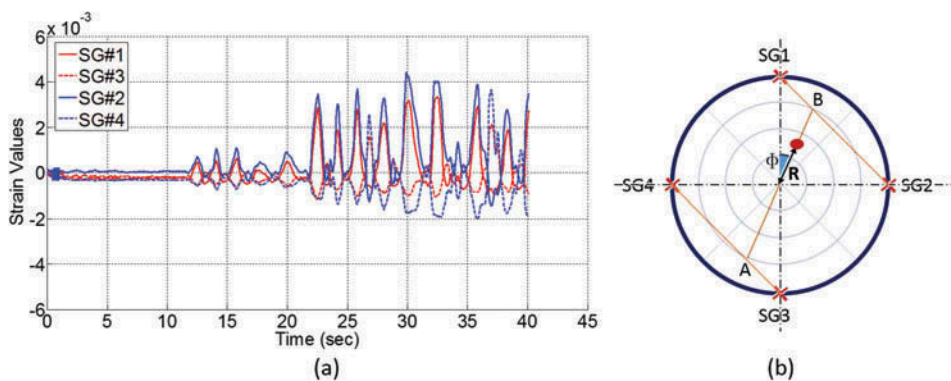


FIGURE 8 The analyzed section of the outer left pier: (a) strain records and (b) fiber analysis procedure.

3. The external straining actions applied at the selected section can be determined using the recorded restoring forces. The moment values can be determined based on the load applied by the actuators and the arm of the moment.
4. The section is divided into fibers and, for simplicity, plane section is assumed to remain plane throughout the analysis. Therefore, a linear relationship can be assumed for the strain distribution along the section. Hence, the strain values can be evaluated at any fiber based on its radial coordinates (R, Φ), as shown in Fig. 8b.
5. Fiber analysis method is used to determine the straining actions for the selected section using the defined constitutive model and the evaluated strain values. The initial parameters of the constitutive model are assumed according to the coupon test results provided in the CABER project test data for the concrete and steel materials [Frankie, 2013]. The bridge response of the pure analytical case is recorded to be compared with the reference experimental results.
6. The pure analytical case is considered once more but after applying the model updating, whereby the stress-strain model parameters in ZeusNL are updated incrementally according to the response of the outer left pier.

After analyzing the recoded data, the results of the axial forces and the moments at the selected section are shown in Fig. 9. The figure compares the experimentally evaluated values against the results of the pure analytical and the model updating results. In this figure, optimization algorithms were applied after processing the first input segment (i.e., first 10 s), because the recorded data was not reliable at the initial stage. This issue occurred due to the small amplitude of the input excitation, where the actuators could not develop the applied commands accurately and many correction steps were required. Therefore, based on the suggestion of the CABER project team leader, the identification procedure

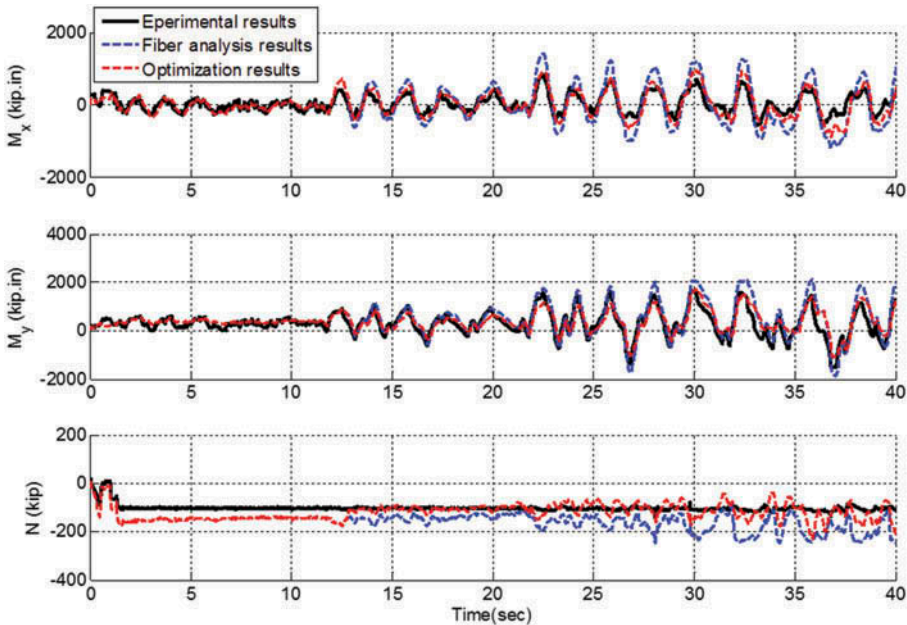


FIGURE 9 Moment values and axial loads applied at the pier section for the different analysis cases.

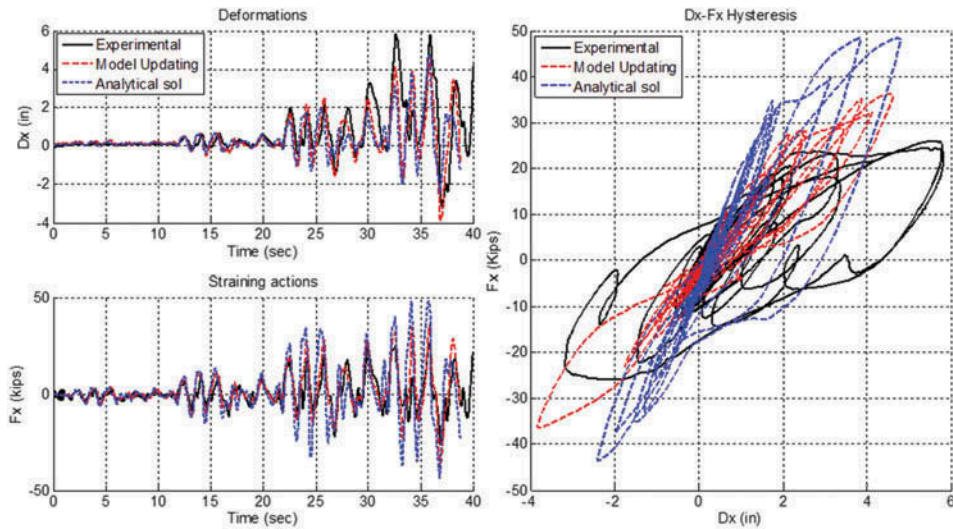


FIGURE 10 The left pier transversal deformations and forces for the different analysis cases.

was initialized after executing the first 10 s of the loading history [Frankie and Elanwar, 2014].

Figure 9 shows that there is a considerable improvement in the analytical results when model updating was applied. It can also be observed that the pure analytical case the results were in general stiffer than the experimental records. Therefore, optimization tools tended to assign softer constitutive parameters for both steel and concrete materials throughout the analysis. Although these results show the ability of model updating to improve the straining actions results on the section level, yet it is important to evaluate the global bridge response through updating the pier behavior in ZeusNL. Figure 10 shows the global response of the outer left pier for the three analysis cases. It includes the lateral deformation, forces, and hysteretic behavior of the pier in the transversal direction. The results show relative improvement in the model updating case compared to the pure analytical case. Several sources of uncertainties were induced while analyzing the pier response on the global level. For instance, the pier segments were not subjected to the same level of loading and, hence, their constitutive behavior might vary according to their location in the pier. In addition, the boundary conditions influence the level of deformations and loading in the pier. Therefore, model updating approach provided more significant improvement for the pier results on the section level compared to the global pier response. Figure 10 results also confirms one of the previous findings that the experimental behavior is softer than the analytical results. It is worth mentioning that in the original CABER project study, the same conclusion was also observed. Whereby, the softening issue was justified as complete fixation was not developed at the pier boundaries during the test. Hence, adding springs in ZeusNL model at the pier boundaries was suggested by the research team to overcome this issue [Abdelnaby *et al.*, 2014].

Instead of presenting the error plots for the twelve actions and deformations for the left pier, Fig. 11 summarizes the results collectively. The figure shows the average absolute errors for each degree of freedom. However, this error is normalized with respect to the peak response to emphasize the errors that occur at high response magnitudes, and reduce the contribution of the smaller ones. It can be noticed that for all the actions and the

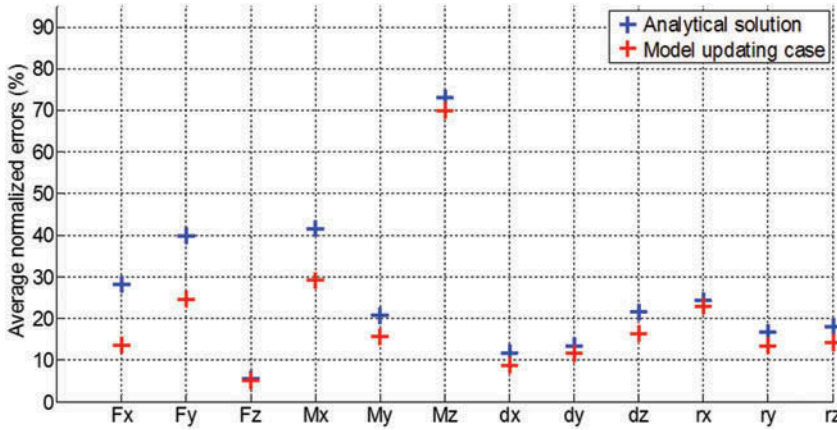


FIGURE 11 Left pier action-deformation errors for the analytical and model updating cases.

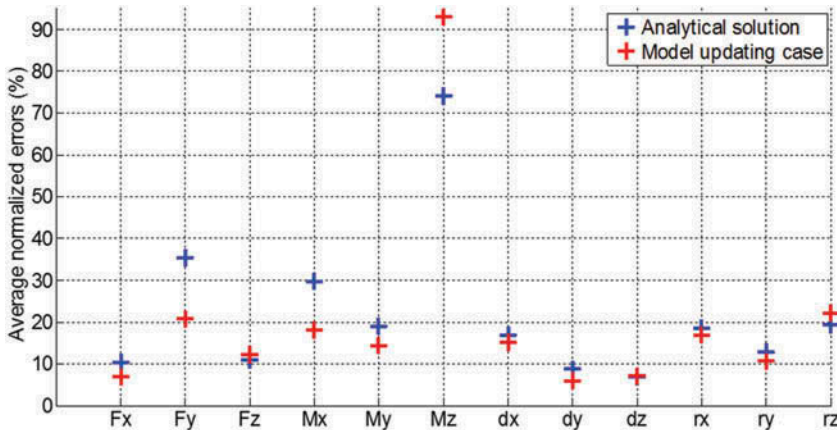


FIGURE 12 Right pier action-deformation errors for the analytical and model updating cases.

deformations, the results of the model updating case has relatively smaller errors compared to the analytical case. Meanwhile, the actions provided more considerable improvements compared to the deformations, which can be contributed to the inadequate analytical boundary conditions as discussed earlier. It can also be observed that the torsional moments in both cases produced exceptionally high error values. This observation was expected because the torque-twist model utilized in ZeusNL follows a linear relationship, which is independent of the constitutive relationship parameters [Abdelnaby *et al.*, 2014]. Therefore, ZeusNL could not represent the non-linear torque-twist behavior developed in the actual model. In order to evaluate the global bridge response, Fig. 12 shows the average absolute errors for the outer right pier for all the actions and deformations. Similar to the left pier results, model updating cases yield more convenient response for most characteristics, except for the torsional moment and the twist results. In conclusion, Figs. 11 and 12 show that updating the constitutive relationship parameters at a certain section had a positive impact on the global bridge response. However, due to the complexity of the test configuration and the corresponding source of uncertainties induced in the model, the

improvement in the CABER project response was not as obvious as the ones presented in the beam-column connection experiment.

In this example, it was shown that there is always a gap between the analytical representation and the actual structural response. Model updating can be used to reduce this gap through updating the analytical model parameters. However, there is still a potential to improve the numerical module response due to the presence of several challenges encountered during the CABER project analysis. For example, several source of uncertainties were present in the model behavior such as the effect of combined loading, the interaction between concrete and the steel reinforcement, and the adequacy of the simulated boundary conditions. These uncertainties, among others, were smeared in the identified constitutive relationship parameters and hence, impacted the efficiency of the model updating procedure. Another challenge encountered during the analysis is the distortions that occurred in the first 10 s of the recorded data. This issue occurred because the input magnitude at the first stage was relatively small compared to the actuators tolerance, which required several correction steps during the experiment. Consequently, the updating procedure was initialized after executing the static loads and the first 10 s in the input records. At this stage, permanent deformations were already induced in the model, especially due to the large initial static loads. These permanent deformations could not be recovered at later stages when model updating was applied. Finally, there were four strain gauges attached at the pier sections. Therefore, several assumptions were required in the fiber analysis method to determine the strain distribution at the section of interest. It is worth mentioning that the restoring forces and strain gauge data were determined based on behavior of the full-scale hybrid simulation experiment. For future model updating applications, the impact of the numerical model on the experimental component response need to be considered.

The identification procedure adopted in this example required long computational time compared to the beam-column connection example, whereby optimization was applied to three different material models concurrently, which are the concrete core, concrete cover, and the steel reinforcement bars. In addition, the relationships governing Mander model are much complicated relative to the bilinear steel model. In order to reduce the computational time, the number of loading steps were resampled to achieve smaller number of calculations. Moreover, the objective function was evaluated based on the response of the latest two loading cycles only. After utilizing these two approaches, the identification procedure required less than 2 h, which is reasonable with respect to slow-rate hybrid simulation applications. In future applications and with the availability of more strain gauge records at different sections, the analytical pier can be discretized into several segments and each segment is updated based on the response of the corresponding physical component. Moreover, nonlinear springs can be added at the pier boundaries and both the springs and the constitutive model parameters can be updated during the analysis based on the recorded data.

In conclusion, model updating can improve the numerical module response without entailing additional cost to the experiment setup. Therefore, it can be used for applications such as multi-span bridges, where a representative sample of the critical components can be physically tested. Afterward, the numerical counterparts that share close characteristics can be updated incrementally during the analysis. This approach saves a lot of cost and effort. Additionally, testing fewer modules simplifies the experimental procedure in terms of facility requirements and convergence issues. There is always a compromise between the accuracy of the model response and the complexity of the analyzed model. Model updating aims to benefit from the information available from the tested component to enhance the behavior of the numerical modules.

5. Conclusions

The reliability of the analytical models, especially the constitutive relationships, in hybrid simulations was discussed in this article. An approach based on optimization tools was introduced to identify the constitutive model parameters from the physically tested specimen during the experiment. The identified parameters are then used to modify the behavior of the analytical model. In order to verify the model updating identification procedure, two of the previously conducted experiments were investigated. The experiments were selected to address different applications; the first one was a beam-column steel connection, while the second experiment was a multi-span concrete bridge subjected to combined loading. Several observations were noted from the results of the two experiments, which can be summarized as follows.

- For both examples, the results of the model updating case were more consistent with the experimental records, when compared to the conventional analytical solutions.
- Several sources of uncertainties were represented in the model such as the effect of heat treatment and combined loading. However, the identification procedure was able to determine the constitutive relationship parameters, which improved the response of the numerical module significantly.
- Model updating has the ability to reduce the gap between the conventional analytical models and the actual experimental response. Therefore, the more accurate initial representation for the analytical model, the more reliable model updating results.
- The proposed identification and updating approach can be used for several applications. For instance, instead of testing the full size structural member, it could be sufficient to test a small segment in the laboratory, and then use its identified characteristics to represent the rest of the member numerically. Similarly, for multi-critical component structures, a representative sample of these components can be physically tested and the response of the corresponding numerical parts can be updated accordingly.

This research study showed that model updating is an efficient tool that can be used identify the constitutive relationship parameters based on the tested component response. The value of model updating becomes substantial for structures that include several critical components. Hence, this approach is expected to widen the conventional hybrid simulation applications.

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References

- Abdelnaby, A., Frankie, T. M., Elnashai, A. S., Spencer, B. F., Kuchma, D. A., Sivla, P., and Chang, C. [2014] "Numerical and hybrid analysis of a curved bridge and methods of numerical model calibration," *Engineering Structures* **70**, 234–245.

- ACI Committee 214 [2002] "Evaluation of strength test results of concrete," *ACI 325R-02*, American Institute, Farmington Hills, Michigan.
- Ayranci, C., Fahim, A., and Munro, M. [2008] "A novel strain sensor for reinforced concrete structures," *Strain* **44**, 191–200.
- Cook, R. D., Malkus, D. S., Plesha, M. E., and Witt, R. J. [2001] *Concept and Applications of Finite Element Analysis*, 4th ed., Wiley, New York, New York.
- Cooreman, S., Lecompte, D., Sol, H., Vantomme, J., and Debruyne, D. [2008] "Identification of mechanical material behavior through inverse modeling and DIC," *Experimental Mechanics* **48**, 421–433.
- Elanwar, H. H. and Elnashai, A. S. [2014] "On-line model updating in hybrid simulation tests," *Journal of Earthquake Engineering* **18**(3), 350–363.
- Elnashai, A. S. and Chryssanthopoulos, M. [1991] "Effects of random material variability on seismic design parameters of steel frames," *Earthquake Engineering & Structural Dynamics* **20**, 101–114.
- Elnashai, A. S., El-Ghazouli, A. Y., and Dowling, P. J. [1990] "Verification of pseudo-dynamic testing of steel members," *Journal of Constructional Steel Research*, **16**, 153–161.
- Elnashai, A. S., Papanikolaou, V., and Lee, D. [2002] "Zeus NL – A system for inelastic analysis of structures," Mid-America Earthquake Center, University of Illinois at Urbana-Champaign, Program Release Sept.
- Endelt, B. and Nielsen, K. B. [2005] "General framework for analytic sensitivity analysis for inverse identification of constitutive parameters," *Proc. of COMPLAS, 8th International Conference on Computational Plasticity*, Barcelona, Spain, September 5–7.
- Frankie, T. M. [2013] "Impact of complex system behavior on seismic assessment of rc bridges," Ph.D. dissertation, University of Illinois Urbana-Champaign.
- Frankie, T. and Elanwar, H. [2014] Personal Communication.
- Gomes, A. and Appleton, J. [1996] "Nonlinear cyclic stress-strain relationship of reinforcing bars including buckling," *Journal of Engineering Structures* **19**(10), 822–826.
- Hakuno, M., Shidawara, M., and Hara, T. [1969] "Dynamic destructive test of a cantilever beam, controlled by an analog-computer," *Transactions of the Japan Society of Civil Engineering* **170**, 1–9.
- Hashemi, M. J., Masroor, A., and Mosqueda, G. [2013] "Hybrid simulation with on-line updating of numerical model based on measured experimental behavior," Quake Summit 2012, NEES, July 9–12.
- Hashemi, M. J., Masroor, A., and Mosqueda, G. [2014] "Implementation of online model updating in hybrid simulation," *Earthquake Engineering & Structural Dynamics* **43**(3), 395–412.
- Kwon, O., Elnashai, A. S., and Spencer, B. F., Jr. [2008] "A framework for distributed analytical and hybrid simulations," *Structural Engineering and Mechanics* **30**(3), 331–350.
- Kwon, O. S. and Kammula, V. [2013] "Model updating method for substructure pseudo-dynamic hybrid simulation," *Earthquake Engineering & Structural Dynamics* **42**, 1971–1984.
- Kwon, O. S., Nakata, N., Park, K. S., Elnashai, A., and Spencer, B. [2007] "UI-SIMCOR user manual and examples," UI-SIMCOR v2.6 and NEES-SAM v2.0, University of Illinois at Urbana-Champaign.
- Lowes, L. N. [1999] "Finite element modeling of reinforced concrete beam-column bridge connection," Ph.D. dissertation, University of California, Berkeley.
- Mahin, S. A. and Shing, P. B. [1985] "Pseudodynamic method for seismic testing," *Journal of Structural Engineering* **111**(7), 1482–1503.
- Mander, J. B., Priestly, J. N., and Park, R. [1988] "Theoretical stress-strain model for confined concrete," *Journal of structural Engineering, ASCE* **114**(8), 1804–1825.
- Martinez-Rueda, J. E. and Elnashai, A. S. [1997] "Confined concrete model under cyclic load," *Materials and Structures* **30**(197), 139–147.
- Morrison, M., Schweizer, D., and Hassan, T. [2012] "Cyclic testing of WUF-W (control specimen)," *Network for Earthquake Engineering Simulation (distributor)*, Dataset, DOI:10.4231/D3TB0XV0D.
- Muller, A. [2014] "Real-time hybrid simulation with online model updating," MS thesis, Western Michigan University, Kalamazoo, Michigan.

- Nemirovski, A. S. and Todd, M. J. [2008] “Interior-point methods for optimization,” *Acta Numerica* 191–234.
- Nip, K. H., Gardner, L., Davies, C. M., and Elghazouli, A. Y. [2010] “Extremely low cycle fatigue test on structural carbon steel and stainless steel,” *Journal of Constructional Steel Research* **66**, 96–110.
- Schweizer, D. Q. [2013] “Experimental investigation of innovative seismic performance enhancement techniques for steel building beam to column moment connections,” MS thesis, Dept. of Civil and Environmental Engineering, North Carolina State University, Raleigh, North Carolina.
- Takanashi, K., Udagawa, K., Seki, M., Okada T., and Tanaka, H. [1975] “Non-linear earthquake response analysis of structures by a computer-actuator on-line system,” *Bulletin of Earthquake Resistant Structure Research Center*, Tokyo, p. 8.
- Yang, Y. S., Tsai, K. C., Elnashai, A. S., and Hsieh, T. J. [2012] “An online optimization method for bridge dynamic hybrid simulations,” *Simulation Modelling Practice and Theory* **28**, 42–54.