Numerical Response Estimations of a Frame-Spine-FLC System Prior to Experimental Dynamic Testing

Bryam Astudillo[1(✉)], David Rivera[1], Barbara Simpson[1], Larry Fahnestock[2], Richard Sause[3], James Ricles[3], Masahiro Kurata[4], Taichiro Okazaki[5], Yohsuke Kawamata[6], Zhuoqi Tao[2], Jessica Duke[3], and Yi Qie[5]

[1] School of Civil and Construction Engineering, Oregon State University, Corvallis, USA
{astudilb, riveratd, barbara.simpson}@oregonstate.edu

[2] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, USA
{fhnstck, zhuoqit2}@illinois.edu

[3] Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, USA
{rs0c, jmr5, jad418}@lehigh.edu

[4] Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
kurata.masahiro.5c@kyoto-u.ac.jp

[5] Division of Architectural and Structural Design, Hokkaido University, Sapporo, Japan
tokazaki@eng.hokudai.ac.jp, qieyi1990@eis.hokudai.ac.jp

[6] Hyogo Earthquake Engineering Research Center, National Research Institute for Earth Science and Disaster Resilience, Hyogo, Japan
kawamata@bosai.go.jp

Abstract. Numerical modeling is widely used in structural engineering to represent buildings response under seismic loading conditions. However, even though numerical modeling is a common tool to characterize the behavior of structures, modeling uncertainties can lead to a broad range of expected response, particularly when representing the behavior of novel systems or components. Addressing different modeling choices can provide more informed insights into the response of structures, especially prior to conducting experimental tests or participating in blind prediction contests. Herein, blind response prediction of a novel steel system was conducted before testing at the E-Defense facility in Japan. The full-scale specimen consisted of a weak Moment-Resisting Frame (MRF) retrofitted with steel spines and force-limiting connections (FLC). The set of pre-test predictions involved addressing of different modeling choices to overcome the many sources of epistemic uncertainties and to provide greater confidence in the design and experimental testing program. Several models were subjected to the records specific to the testing program (Northridge Sepulveda and JMA Kobe) to estimate drift and acceleration responses. Numerical results were compared to the experimental data from the shake-table tests. Although all

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the models were able to represent general trends in drifts and accelerations and enabled proper development of the testing plan, peak response varied significantly depending on the modeling choices, especially those altering the system's natural periods or those leading to different yielding patterns.

Keywords: Frame-Spine-FLC system · Strongback system · Higher-mode demands · Model uncertainty

1 Introduction

Numerical modeling is widely used in structural engineering to represent buildings response under seismic loading conditions. Nonlinear models can be used to predict demands due to ground shaking and inform the design of the building's structural and nonstructural components. However, even though numerical modeling is a common tool to characterize the behavior of structures, modeling uncertainties can lead to a broad range of expected response, particularly when representing the behavior of novel systems or components. Addressing different modeling choices can provide more informed insights into the response of structures, especially prior to conducting experimental tests, by enabling decision-makers to consider a set of possible responses to support the planning and supervision of the experiment.

The importance of characterizing modeling uncertainties and evaluating modeling techniques forms the basis of many blind prediction contests, where modeling inputs are gathered to facilitate the comparison and relative applicability of different modeling approaches. Herein, blind response prediction of a novel steel system was conducted prior to testing at the E-Defense facility in Japan. The full-scale specimen consisted of a weak Moment-Resisting Frame (MRF) retrofitted with steel spines and force-limiting connections (FLC) [1]. Although numerical models can be easily calibrated to fit experimental results, blind prediction of dynamic response, especially for new systems like the combined Frame-Spine-FLC system, are subject to modeling uncertainties [2, 3]. In particular, since the spine is designed to remain elastic in every mode, higher-mode accelerations were expected to depend significantly on the ground motion characteristics, with predicted peak demands that varied depending on modeling choices.

Prior to the shake-table testing, numerical models were developed to support the design of the specimens and the planning of the testing program. The set of pre-test predictions involved addressing of different modeling choices to overcome the many sources of epistemic uncertainties and to provide greater confidence in the design and experimental testing program. First, simplified models were analyzed under 80 + ground motions to characterize variations in expected dynamic behavior and record-to-record uncertainty. Then, several models were subjected to the records specific to the testing program (herein, Northridge Sepulveda and JMA Kobe) for more detailed estimates of drift and acceleration response.

In particular, uncertainty in the beam composite action, panel zone strength, and spine connection to the MRF was studied in detail to predict the range of expected nonlinear dynamic response, particularly in terms of story drifts and floor accelerations. Differences in nonlinear dynamic response were examined due to modeling choices and assumptions. Numerical results were compared to the experimental data from the shake-table testing program using an initial rapid-processing of the sensors. Although all the models were able to represent general trends in drifts and accelerations and enabled proper development of the testing plan, peak response varied significantly depending on the modeling choices, especially those altering the system's natural periods or those leading to different yielding patterns.

2 Shake-Table Testing

A collaborative team of U.S. and Japanese institutions was established to study a combined MRF, spine, and FLC system. The inclusion of a vertical, essentially elastic spine was leveraged to mitigate story mechanisms by imposing a more uniform drift distribution. Yielding in Force-Limiting Connections (FLCs) between the spine and MRF were then leveraged to control the magnitude of the forces transferred between the spine and base MRF, thereby limiting higher-mode acceleration and force demands that can develop due to the presence of the spine [6, 7].

The full-scale specimen consisted of a four-story steel building, representative of a hospital facility, and contained acceleration-sensitive medical equipment; see Fig. 1(a). Originally, the first three stories of the MRF were part of an existing Japanese project with Japanese beam, column, and panel zone details. The existing MRF was then retrofitted with spines and FLCs to test the new hybrid MRF-spine-FLC system. Testing included two specimens: [i] the MRF attached to the spines (i.e., no FLC action), termed the *Frame-Spine* model, and [ii] the MRF attached to the spines using the FLCs, termed the *Frame-Spine-FLC* model. The base MRF without the spines or FLCs, termed the *Frame* model, was studied numerically but not experimentally.

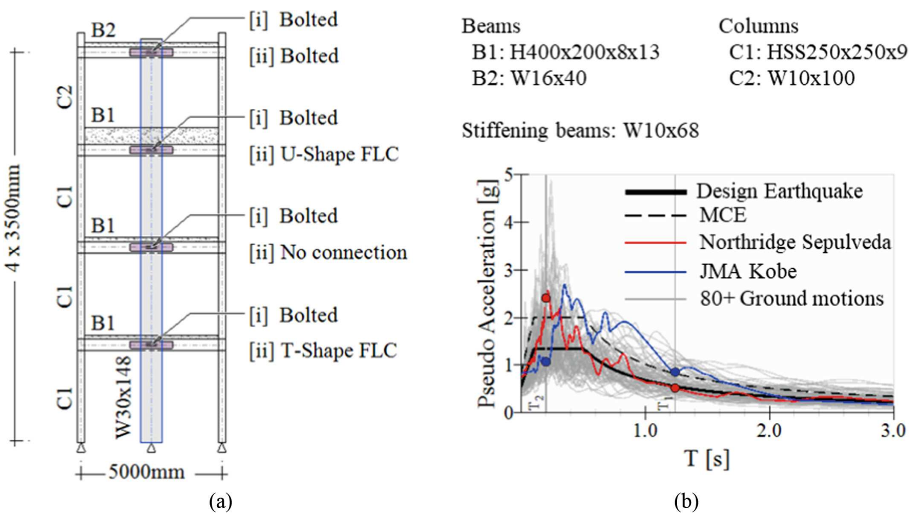

Fig. 1. a) Testing specimen and b) Spectral pseudo-acceleration response spectrum (S_{DS} = 1.33 and S_{D1} = 0.64).

2.1 Moment Resisting Frame

The testing specimen used to study the strongback spine and FLC concept consisted of a modified 4-story MRF. The original three-story MRF was base-isolated and was expected to suffer limited damage. To highlight the benefits of employing a strongback spine, the existing MRF was modified with pinned column bases to induce a severe tendency to form a first story mechanism in the base MRF [4]. Additionally, a fourth story, with considerable mass and wide-flange sections, was added to achieve elongated periods to better investigate higher-mode effects induced by the spines.

2.2 Spine and FLC Additions

The spines and FLCs were attached to the exterior of the modified MRF specimen. Two scenarios were tested in the full-scale experiment by changing the connection between the spines and base MRF between tests, resulting in the two testing cases shown in Fig. 1(a): [i] spine attached to the MRF (i.e., no FLC action in the *Frame-Spine* model) through slip-critical bolted connections and [ii] spine attached to the MRF through the FLCs (i.e., T-shape or U-shape yielding elements in the *Frame-Spine-FLC* model). Stiffening beams were attached to the MRF girders to re-distribute demands along the MRF beam.

3 Modeling Uncertainty

To support the planning and design of the experiments, two-dimensional numerical models of the south frame of the test specimen were developed using the OpenSees finite-element framework. To inform predictions of the shake-table testing, different models, from simple to refined, were developed to capture the range of expected response from the shake-table testing program. Modeling choices were intentionally varied to produce possible deviations in the simulated responses (e.g., yielding pattern, peak story drift ratio, peak floor acceleration, peak forces, etc.). Table 1 shows a summary of the principal epistemic uncertainties and approaches considered herein.

3.1 Simple Baseline Models

Relatively simple models were used to estimate periods and to characterize general behavior. These baseline models neglected the potential for composite action, panel zone yielding, and influence of the stiffening beams. The beams and columns were modeled using force-based beam-column elements with five integration points, Gauss-Lobatto integration, and ten fibers across the section. An elastic beam-column element was used to represent the spine. Connections between the spine and MRF were idealized with constraints to rotate freely at all floors (i.e., constrained in the translational degrees-of-freedom). The T-shape and U-shape yielding elements of the FLCs were modeled with perfectly plastic springs in the translational x-direction; note, FLCs were located at the first and third floors only and no connection existed in the FLC design at the second-floor level; see Fig. 1(a). Prior to building the specimen, weights were estimated as 331, 229, 510 and 510 kN from first floor to the roof level.

3.2 Refined Models

To develop more detailed predictions of shake-table response, more refined models of the base frame were developed to consider beam composite action, shear capacity of the panel zones, and contributions from the stiffening beams. The bolted connections between the frame and spine were modeled with several iterations, including: [i] constraints in the translational directions (same as the baseline), [ii] constraints in the translational directions with a constraint in rotation at the first-floor level, and [iii] springs with moment-rotation relations to represent the strength of the bolt pattern and estimated slip. The force-deformation relation of the yielding elements in the FLCs used calibrated force-deformation relations based on experimental component tests.

Table 1. Modeling uncertainties for pre-test response prediction.

Specimen	Component	Source of uncertainty	Modeling assumptions
Frame	Beam	Beam composite-action	▪ Non-composite beam fiber section ▪ Beam fiber section with slab fiber section and shear studs
	Panel zone	Joint model approach	▪ Elastic panel zone with offsets ▪ Parallelogram panel zones
Frame-Spine	Frame-Spine bolted connection[a]	Moment-rotation behavior	▪ Constraints in translation ▪ Constraints in translation and constraint in rotation (first-floor only) ▪ Moment-rotation relation
Frame-Spine-FLC	Force-limiting connection[b]	Force-displacement behavior	▪ Perfectly plastic force-deformation behavior ▪ Hysteretic force-deformation behavior based on experimental data

[a]Slip critical bolted connections
[b]T-shape and U-shape dampers

4 Design Spectrum and Initial Ground Motion Suite

A U.S. location in Oakland, CA was back-calculated from the strength of the modified four-story MRF; see Fig. 1(b). An existing suite of 40 scaled ground motion pairs [5], consistent with the Oakland site, was used to inform the influence of record-to-record variability on system response. Based on this suite of analyses, two ground motion records were selected to study the effects of different spectral characteristics near the first-mode and higher-mode periods: [a] unscaled Sepulveda Valley Hospital record from the 1994 Northridge earthquake with large pseudo-accelerations near the second-mode period and [b] unscaled JMA-NS record from the 1995 Kobe earthquake with large spectral displacements near the first-mode period.

5 Baseline Characterization of the Dynamic Response

The dynamic response of the Frame, Frame-Spine, and Frame-Spine-FLC was evaluated for the entire suite of ground motions using the simple baseline models. The peak story drift ratio and peak floor accelerations were collected as indicators of structural and non-structural damage respectively; see in Fig. 2 the 1) Frame, 2) Frame-Spine and 3) Frame-Spine-FLC response. Responses for the selected Northridge and JMA-Kobe ground motions are highlighted.

For more than half the ground motions, the baseline MRF with pinned column bases formed a story mechanism and, in many cases, exhibited "collapse", where drifts exceeded the valid range of the numerical model. In contrast, the addition of the spine results in reduced drifts due to more uniform demand distributions. However, floor accelerations increase due to the influence of the higher modes due to the elastic response of the spine. The magnitude of this influence strongly depended on the spectral characteristics of the ground motions; i.e., in some cases, the addition of the spine resulted in large higher-mode accelerations while others did not. Peak accelerations tended to reduce with inclusion of the FLCs at the cost of small increases in drift in most of the cases.

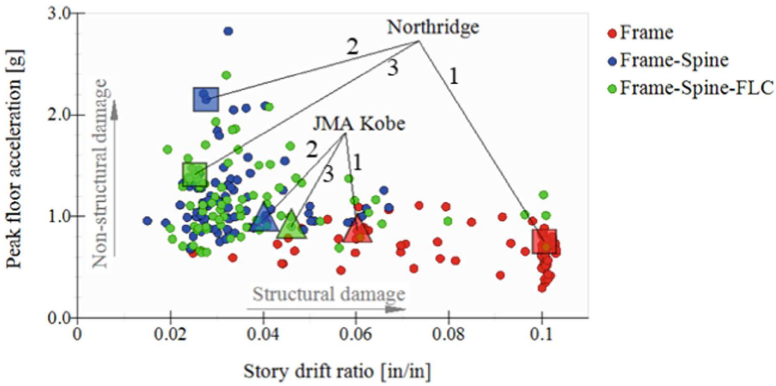

Fig. 2. Peak story drift ratio and peak floor acceleration for the ground motion suit, using simplified numerical models.

6 Prediction and Modeling Uncertainty

The sensitivity of the global responses to the modeling assumptions was studied. Different pre-test modeling variations were tested using the recorded table acceleration as the groun motion input. These ground motion inputs do somewhat vary with respect to the target ground acceleration records.

Figure 3 shows variations in peak drift and floor acceleration response for select modeling choices. Models FS-I and FLC-I refer to the simplified models. The other models account for refined modeling of the base MRF, including the beam composite action and panel zone nonlinearity. The Frame-Spine models, FS-II, FS-III, FS-IV, differ depending on the idealizations of the frame-to-spine connection at the first floor, including moment-released (FS-II), full moment transfer (FS-III), and moment-rotation estimated based on the stiffening beam capacity (FS-IV) to target yielding to the connection only. Model FS-V contains a moment-rotation relationship for every story, based on an assumed idealized behavior between the bolts and slots under rotation. The refined Frame-Spine-FLC model, FLC-II, estimates the force-deformation relation of the yielding components in the FLCs based on quasi-static experimental data.

The numerical models show that the addition of the spine resulted in reduced peak drift response and a more uniform distribution of inelastic demands across all stories. Force and acceleration demands were observed to be highly influenced by higher-mode contributions, particularly for ground motions with high spectral acceleration in higher-mode periods. Simulations also showed that the addition of the FLCs slightly increased the story drift response.

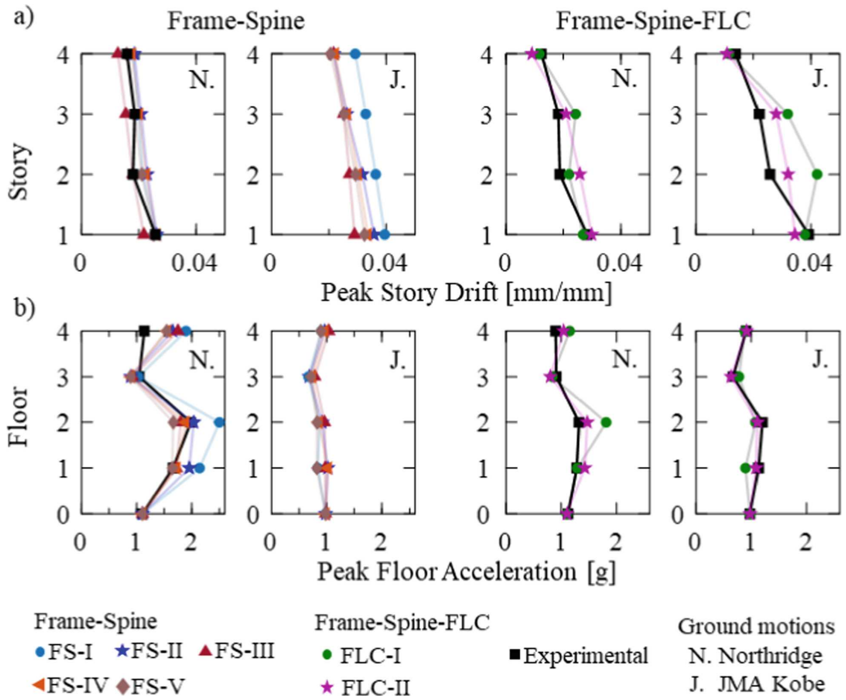

Fig. 3. a) Peak story drift ratio, and b) peak floor acceleration profile for different modeling choices and experimental data.

7 Summary and Conclusions

Numerical modeling provides insight into the dynamic behavior of structures. However, uncertainties in the behavior and modeling of the system components can lead to a broad range of expected response. This uncertainty plays an important role in the development and supervision of experimental tests, as well as in the participation of blind prediction contests. This paper presented some of the modeling challenges and the dynamic results for a wide spectrum of modeling choices. These numerical analyses supported the experimental tests of a Frame-Spine-FLC system at the E-Defense shaking table facility in Japan. Main findings and recommendations include:

- Simple numerical models are able to predict the global behavior of the structure, which facilitates internal validation of more complex models, which could be more prone to implementation errors. However, the response at the element level and the sequence of yielding may vary depending on the model's simplicity.
- Although the modeling choices led to different peak values, general trends were reasonably captured. From the analysis of other models, not presented in this study, the acceleration in the Frame-Spine-FLC is more sensitive to changes in mass and stiffness.
- In general, modeling of the spine to MRF connection (i.e., without FLCs) affects estimates of the peak floor accelerations. The model with moment-released connections exhibited the largest floor acceleration demands.
- Peak story drift ratios and floor accelerations were predicted well using the pre-test numerical models for the Frame-Spine and Frame-Spine-FLC cases. For all models including the spine, story mechanisms were mitigated, regardless of the frame-spine connection model.
- Behavior and modeling uncertainty of elements can be addressed by considering a finite number of scenarios selected based on engineering judgment that led to different modeling choices. Analysis and comparison of various modeling choices and assumptions allow for a more robust prediction of the specimen response.

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