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U.S.-JAPAN COLLABORATION FOR SHAKE TABLE TESTING OF A FRAME-SPINE SYSTEM WITH FORCE-LIMITING CONNECTIONS

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Abstract

Conventional lateral force-resisting systems can provide a stable, ductile response but also experience significant inelastic demands, rendering repairs impractical or uneconomical. Thus, there is a need for novel structural systems that protect structural and nonstructural components to reduce post-earthquake repairs and downtime. A U.S.-Japan research team – including three U.S. universities, two Japanese universities, and two major experimental research labs – is developing a structural solution to reduce peak drift and acceleration demands, thereby protecting buildings, their contents, and occupants during major earthquakes. The primary components of the system are: (1) steel base moment-resisting frames designed and detailed to behave in the inelastic range and dissipate energy, (2) stiff and strong elastic spines designed to remain essentially elastic to redistribute seismic demands more uniformly over the building height, and (3) force-limiting connections (FLC) that connect the frame to the spines to provide a yielding mechanism that limits acceleration demands. This economical earthquake-resilient system is intended to be used in essential facilities, such as hospitals, where damage to the buildings and contents and occupant injuries must be prevented and where continuity of operation is imperative. The system was recently tested at full scale at the E-Defense shake-table facility in Miki, Japan. This paper provides an overview of pre-test numerical simulations, shake-table test setup and instrumentation, and preliminary test results.

Keywords: shake table testing; steel-framed building; spine; force-limiting connection

1. Background and Research Motivation

Modern seismic lateral force-resisting systems (LFRS) are designed and detailed to exhibit stable, ductile response in the inelastic range under strong ground shaking. Although economical in terms of initial costs, a ductile LFRS can experience significant inelastic deformations and accumulate damage. The resulting degradation of strength and stiffness and residual deformations may necessitate repair, and, in some cases demolition. Moreover, even if properly designed, ductile LFRS are susceptible to concentrate lateral demands in a limited number of stories [1,2], potentially leading to story mechanisms. Story mechanisms not only cause damage to drift-sensitive structural and nonstructural components, rendering repairs impractical or infeasible, but they also can exacerbate P-Delta effects, possibly leading to building collapse.

Dual systems, which combine a relatively stiff ductile primary LFRS with a more flexible secondary moment-resisting frame (MRF), leverage the elastic restoring force of the MRF to limit story drift concentrations [3]. However, frame action in the MRF is an inefficient means of distributing inelastic demands to mitigate story mechanisms [4], and dual systems are still prone to concentrate lateral drifts and develop story mechanisms.

Instead, stiff elastic vertical structural components, or "spines", can be used jointly with a conventional ductile LFRS to impose a more uniform drift profile over the height of a building [5-11]. Spines are designed not to yield, thereby providing an elastic lateral load path to distribute demands more uniformly and delay or prevent story mechanisms. However, higher-mode story shear and acceleration demands in structural systems employing elastic spines are not well constrained by a nonlinear mechanism [12-17]. These higher-mode forces and accelerations can result in large and possibly impractical proportioning of the spine and damage to acceleration-sensitive nonstructural components.

To mitigate force demands, recent work has used deformable force-limiting connections (FLC) to link each floor of a flexible gravity load-resisting system to the stiff LFRS [18-22]. The deformable elements within the FLC allow relative motion between the gravity and lateral force-resisting systems, limiting the magnitude of the lateral forces transferred from each floor to the LFRS and resulting in reduced floor accelerations. Shake table tests and numerical simulations have validated the use of FLC with only modest relative deformation demands required for the FLC.

Herein, the benefits of the spine and FLC are combined to develop a practical lateral force-resisting system to control multi-modal seismic response and protect a building from damaging lateral drift and acceleration demands. The resulting Frame-Spine-FLC System is intended to provide enhanced building performance to protect structural and nonstructural components, especially those in essential facilities, such as hospitals, where damage to the building and contents and occupant injuries must be prevented.

This paper describes a full-scale shake-table testing program conducted at the E-Defense shake-table facility, National Research Institute for Earth Science and Disaster Resilience, in Japan. The research was conducted collaboratively by an international U.S.-Japan research team. An existing MRF specimen with a severe story mechanism tendency was supplemented with spines and FLC and tested under several levels of ground shaking. Two distinct structural conditions were tested: MRF-Spine and MRF-Spine-FLC. Pre-test numerical simulations were conducted for these two structural conditions in addition to the baseline case of the MRF with no supplementary elements, which was not tested due to collapse risk.

2. Frame-Spine-FLC System Concept

The Frame-Spine-FLC System has several potential variations, and the configuration currently being studied consists of three primary components: (1) base steel MRFs, (2) stiff and strong elastic steel spines, and (3) force-limiting connections (FLC) that connect the spines to the MRFs. The steel MRFs resist a portion of the lateral load and dissipate energy through ductile inelastic response. The spines are pinned at their bases and are designed to remain elastic, enforcing a nearly uniform story drift profile over the height of the MRF. The spines can mobilize the energy dissipation capacity of every story of the MRF, even an MRF with a severe tendency to form a story mechanism. The FLC limit the seismic forces transferred from the MRF to the spines, reducing the magnitude of the higher-mode acceleration demands.

3. Shake Table Test Setup

Between December 14, 2020 and December 17, 2020, full-scale shake table testing was performed with the Frame-Spine-FLC System at the E-Defense facility, National Research Institute for Earth Science and Disaster Resilience, in Japan. The goal of testing was to validate the concept of the Frame-Spine-FLC System. Two sets of testing were performed, namely MRF-Spine tests and MRF-Spine-FLC tests. In the MRF-Spine tests, an MRF was connected to the spines by slip-critical bolted connections – thereby not restricting the shear transferred between the MRF building and spines. In the MRF-Spine-FLC tests, the same MRF building was connected to the spines by FLC. The same ground motion and scale factors were used in the MRF-Spine tests and the MRF-Spine-FLC tests to provide direct comparison between acceleration and drift responses. An additional ground motion was used for the final stage of the MRF-Spine-FLC tests to provide additional insight into the behavior of the Frame-Spine-FLC System for differing ground motion characteristics.

3.1 Test building configuration

The base MRF was adapted from an existing three-story building that was tested previously as base-isolated, and thus not damaged, for the Holistic Assessment of Seismic Damage in Medical Facilities portion of the Japanese project Enhancement of Resilience for Tokyo Metropolitan Area [23,24]. This three-story building included standard concrete slabs except for at the top where the slab was thickened to add mass. To investigate higher mode response, an additional story of steel framing was designed and fabricated in the U.S., shipped to Japan, and added to the existing three-story building, along with a standard concrete slab and supplemental steel plates to add mass. The original MRF was designed to remain elastic and adopted a typical Japanese beam-column moment connection, which tends to sustain substantial plastic rotation. However, per ANSI/AISC341-16, the MRF did not satsify the strong-column-weak-beam criterion and seismic compactness requirements, and it had weak panel zones. To study the influence of the elastic spines, the base isolators were removed from the original 3-story building and the MRF column bases were placed on clevises to induce a tendency to form a severe story mechanism. As shake table testing was conducted along one primary building axis, spines were installed on two sides of the building, as shown in Fig. 1.

Fig. 1 – Test building on shake table

Each spine was attached to the MRF at all four levels by slip-critical bolted connections for the MRF-Spine tests and by a combination of FLC and slip-critical bolted connections for the MRF-Spine-FLC tests. These MRF-Spine connections were facilitated by stiffening beams (oriented with the web in the horizontal plane) with one flange bolted to the MRF beam web and the other flange available for FLC attachment. In the MRF-Spine tests, each spine was attached at all four floors, Floors 1-4, by slip-critical bolted connections. In the MRF-Spine-FLC tests, each spine was attached to Floors 1, 2 and 3 by FLC, and attached to Floor 4 (Roof) by a slip-critical bolted connection. A FLC is made up of three components: a yielding element that is designed

to limit the horizontal force (F_h) transferred to the spine, and slide bearings and ties. The slide bearings and ties were designed to resist the moment (M) about the vertical axis due to the eccentricity of the spine with respect to the flange of the stiffening beam and to provide torsional bracing to the spine, where the bearings and ties resist compression and tension, respectively. Fig. 2 illustrates the FLC design, showing F_h and M. The FLC at Floor 1 consisted of a yielding T-shaped cantilever, bearing plates and ties, as shown in Fig. 3(a). The FLC at Floor 2 consisted of bearing plates and ties only with no yielding element as the horizontal force transferred to the spine at this floor was intended to be zero. The FLC at Floor 3 consisted of two yielding U-shaped bars, bearing plates and ties, as shown in Fig. 3(b). The T-shaped cantilevers were customized elements developed at Lehigh University, and the U-shaped bars were standard NSUD40 elements produced by Nippon Steel Engineering.

Table 1 – Test building data

Floor or Story #	Column	Beam	Spine	Frame-Spine Connection	Weight (kN)
4	W10×100	W16×40	W30×148	Slip-critical bolted connection	556
3	□-250×250×9	H-400×200×8×13	W30×148	Slip-critical bolted connection or FLC	528
2	□-250×250×9	H-400×200×8×13	W30×148	Slip-critical bolted connection or FLC	160
1	□-250×250×9	H-400×200×8×13	W30×148	Slip-critical bolted connection or FLC	256

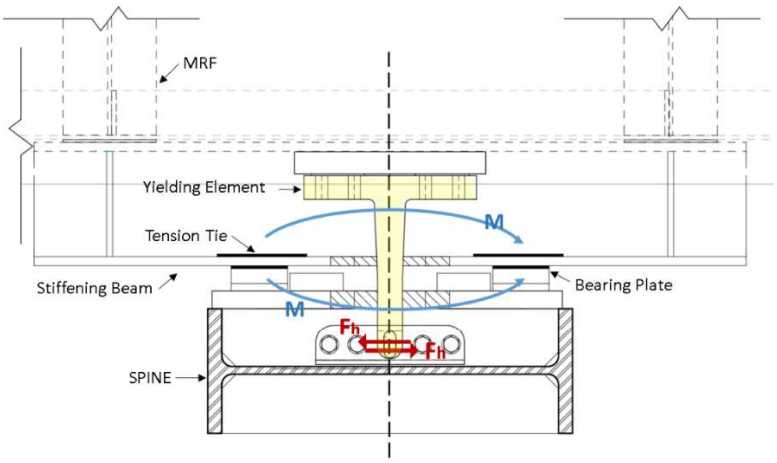
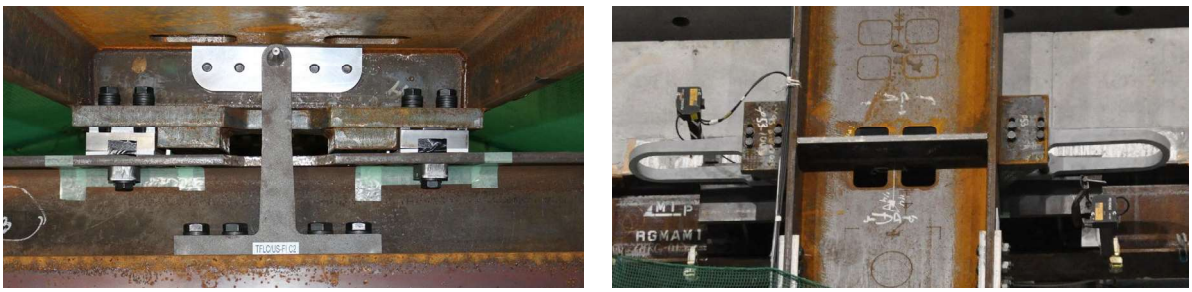


Fig. 2 – Simplified FLC configuration with design forces



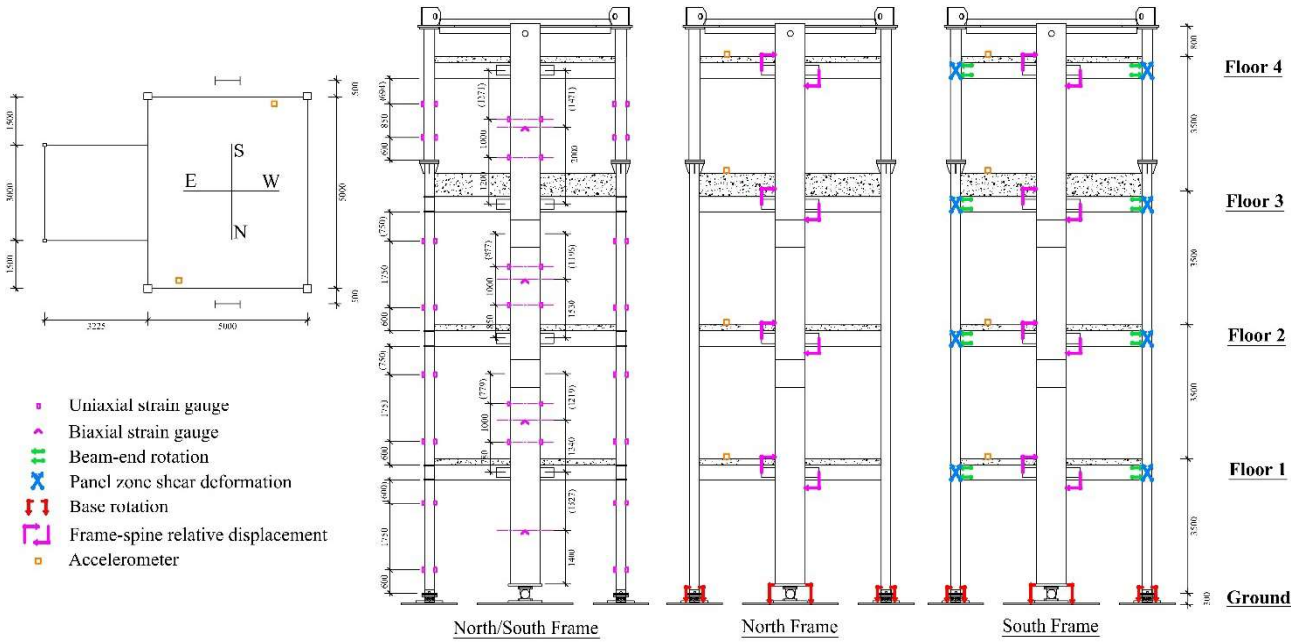
(a) (b)

Fig. 3 – Test building FLC with yielding elements

3.2 Instrumentation

3.2.1 Strain gauges

Fig. 4(a) shows the locations of all strain gauges, which were placed at sections expected to remain elastic and used to calculate internal forces in the columns and spines. Sixty-four uniaxial gauges were used for four columns and 24 uniaxial gauges were used for the two spines in conjunction with 8 biaxial gauges. The strain gauges were not bridged but directly connected to the data acquisition system, occupying 104 total channels. Each column was instrumented with uniaxial strain gauges at two sections at each story. At each section, a pair of uniaxial gauges, one at each flange, was placed at the middle of the flange along the longitudinal direction. Similarly, for the Story 2-4, each spine was instrumented with uniaxial strain gauges at two sections with two gauges per section. For each spine at midheight of each story, one biaxial strain gauge rosette was placed.



(a) (b) (c)

Fig. 4 – Location of instruments

3.2.2 Displacement transducers

Fig. 4(b) and 4(c) show the locations for all displacement transducers, which occupied 60 total channels. Displacement transducers were used to measure local deformations of the specimen, including (a) frame-spine relative displacements, (b) beam-end rotations, (c) panel-zone shear deformations, and (d) column/spine base rotations. Frame-spine relative displacements were measured at all occurrences, i.e., two frames at four floors, totaling eight locations. At each location, a pair of laser transducers was attached to the top and bottom flanges of the stiffening beam. These measurements can be used to calculate the horizontal relative displacement at the center of the connection and the relative rotation between the MRF and spine. Column and spine base rotations were measured by using a pair of laser transducers at all six occurrences. Pairs of displacement transducers were used to measure the panel zone deformations and beam-end rotations at the south frame at four floors and two ends, totaling eight monitoried connection regions.

3.2.3 Load cells

A pair of load cells was located at each clevis at the base of the spines to measure the horizontal and vertical components of the column base forces, occupying four total channels. The measured shear forces can be used to calibrate the shear forces calculated from strain gauge measurements at the first story.

3.2.4 Accelerometers

Accelerometers were placed at the northeast and southwest corners of each floor to record acceleration time series, occupying 24 total channels. At each location, the accelerometer recorded the x-, y-, and z-components of the accelerations. The test specimen was only excited in the east-west building direction (y-direction of the accelerometers). By comparing the accelerograms obtained from two accelerometers on the same floor, potential torsional response of the structure can be assessed.

4. Pre-Test Numerical Models

This section describes the numerical simulations used to support the experimental design. Numerical models were developed using the OpenSees framework [25]. Two-dimensional models were developed to represent the south frame of the specimen, including the base MRF, spine, and the FLC as shown in Fig. 5(a).

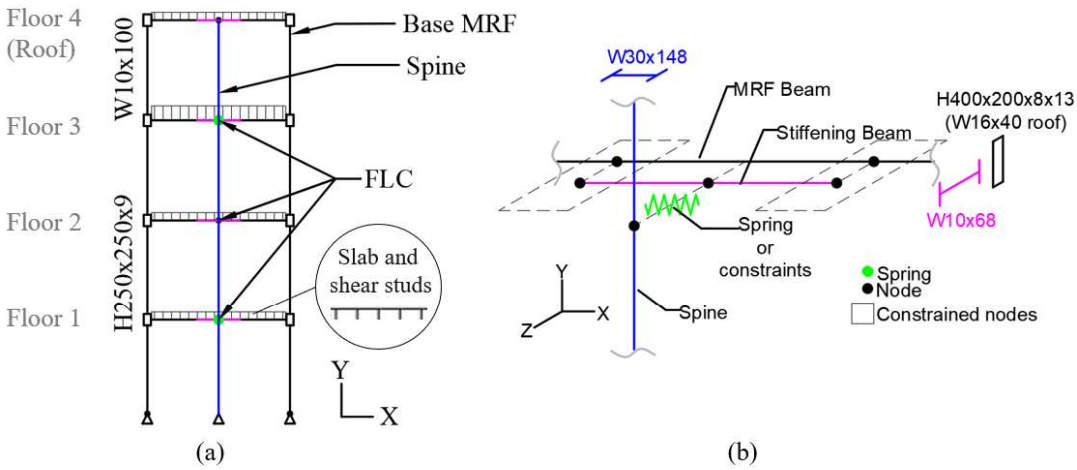


Fig. 5 – (a) Schematic of the OpenSees model, and (b) MRF-Spine connection region

4.1 Numerical Modeling

The MRF was modeled with force-based beam-column elements connecting nodes located at the workpoints of the beam-column intersections. Fiber sections, discretized with five fibers across the web depth and flange thickness of the section, were distributed along each element using a five-point Gauss-Lobatto integration scheme. The beams and columns used corotational and P-Delta transformations, respectively. The panel zone was modeled using a parallelogram configuration with stiff, elastic elements connected with pins at each corner [26]. A rotational spring at one corner of the panel zone used a trilinear force-deformation constitutive relation to represent the shear strength of a joint with square columns and wide-flange beams [27]. At the end of the beams and columns, elastic elements of half the section depth shifted the location of the integration points away from the edge of the beam-column joint to better represent locations of flexural yielding and the stiffness of the frame in the inelastic range.

Solid concrete slabs were used at all four floor levels with a typical thickness of 150 mm except for a thicker slab (610 mm) at Floor 3. To represent the effects of the slab, it was explicitly modeled with force-beam-column elements and connected to the beams using elastic elements at the shear stud locations. The shear studs were modeled with the same moment of inertia and area of the connecting beam. Gravity loads were applied as nodal loads at each shear stud location along the MRF beam, except for Floor 4 (Roof), where loads were applied to the columns directly based on the expected load path in the specimen. Lumped masses were located at the same location of the gravity loads. The total weights for Floors 1-4 were 331, 229, 510, and 510 kN, respectively; half of these values were used in the model. These preliminary values do not agree with the more accurate values shown in Table 1, but they are maintained as these analyses were completed before the experimental phase and they are presented here as true predictions (no model updating based on test results).

The spine was modeled as elastic; analyses showed that the spine remained well in the elastic range for the selected ground motions. The stiffening beam at each floor was modeled with a force-based beam-column element attached at its ends to the MRF beam. Zero-length elements representing the FLC or other imposed conditions (i.e., multi-point constraints) were used to model the connection of the spine to the middle of the stiffening beam attached to the MRF; see Fig. 5(b). These MRF-Spine connection conditions at the different floors resulted in three numerical models: [i] MRF case where the spine and FLC were not included in the model, [ii] MRF-Spine case where the spine was connected directly to the MRF and [iii] MRF-Spine-FLC case where the MRF-Spine connections were modeled with FLC.

For model [i], the spine, and FLC were neglected. This case was only studied numerically (i.e., it was not tested experimentally) and represented the baseline reference case. For model [ii], stiff elements were used to connect the spine to the MRF at all floors. Herein, results for model [ii] are presented with the rotational degrees of freedom released at the MRF-Spine connections (i.e., pinned conditions), but other connection conditions were also considered [28]. For model [iii], the force-deformation response for the FLC yielding components was based on experimental data. Characterization tests for the T-shaped yielding components used at Floor 1 were conducted at Lehigh University (Fig. 6) and hysteretic response for the U-shaped yielding components (NSUD40) used at Floor 3 was provided by Nippon Steel Engineering. No in-plane force transfer was modeled between the spine and the stiffening beam at Floor 2. At Floor 4 (Roof) the connection was pinned.

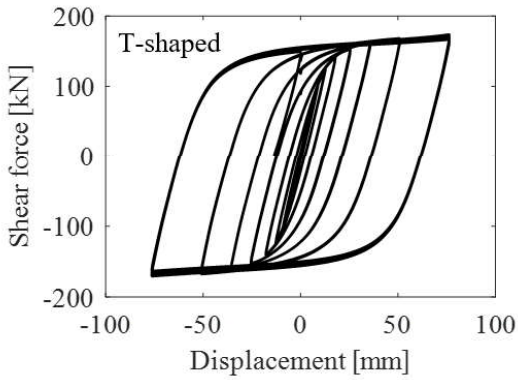


Fig. 6 – Force-deformation response of T-shaped yielding components

Based on the low damping expected for the experimental tests, the target damping ratio was set to 0.5% at $1.5T_1$ and T_3 using Rayleigh damping. Table 3 shows the fundamental periods corresponding to the lateral modes for the different models.

Table 3 – Model fundamental periods (seconds)

Model Cases	T_1	T_2	T_3	T_4
MRF	1.520	0.340	0.169	0.116
MRF-Spine	1.247	0.196	0.085	0.039
MRF-Spine-FLC	1.255	0.230	0.152	0.113

4.2 Ground motion input

The recording from the Sepulveda Valley Hospital during the 1994 Northridge earthquake was selected as a ground motion record based on its large spectral pseudo-accelerations near the second-mode period (Fig. 7). In addition, the JMA-Kobe NS ground motion record was selected to study the effects of different spectral responses near the first-mode and higher-mode periods. The analysis of the peak drifts and floor acceleration responses under a larger number of ground motion inputs can be found in [28].

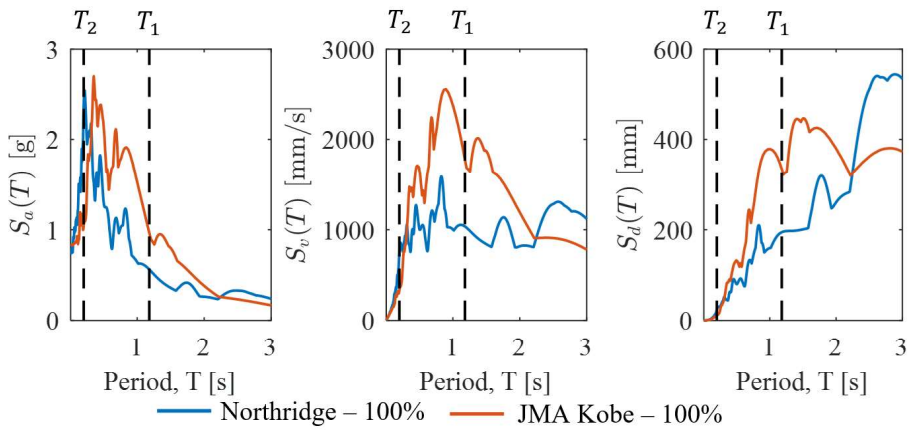


Fig. 7 - Spectral response: (a) pseudo-acceleration S_a, (b) pseudo-velocity S_v, and (c) displacement S_d

4.3 Numerical simulations

The peak response profiles from the nonlinear dynamic analyses are shown in Fig. 8 for the Northridge and JMA-Kobe records scaled to 100% of their original intensity. Drift ratios higher than 5% are not shown. Model [i] exhibited concentrations of story drifts in the first story, indicative of a severe first-story mechanism that limited the magnitude of the floor accelerations. In contrast, models [ii], MRF-Spine, and [iii], MRF-Spine-FLC, exhibited smaller, more uniform drift distributions. The addition of the FLC in model [iii] resulted in reduced peak acceleration demands compared to the results from model [ii], MRF-Spine, for the Northridge record. However, this reduction and the higher-mode accelerations induced by the elastic spine depend on the characteristics of the ground motion input, i.e., larger higher-mode pseudo-accelerations for the Northridge record compared to the JMA-Kobe record resulted in larger acceleration demands, as shown in Fig. 8.

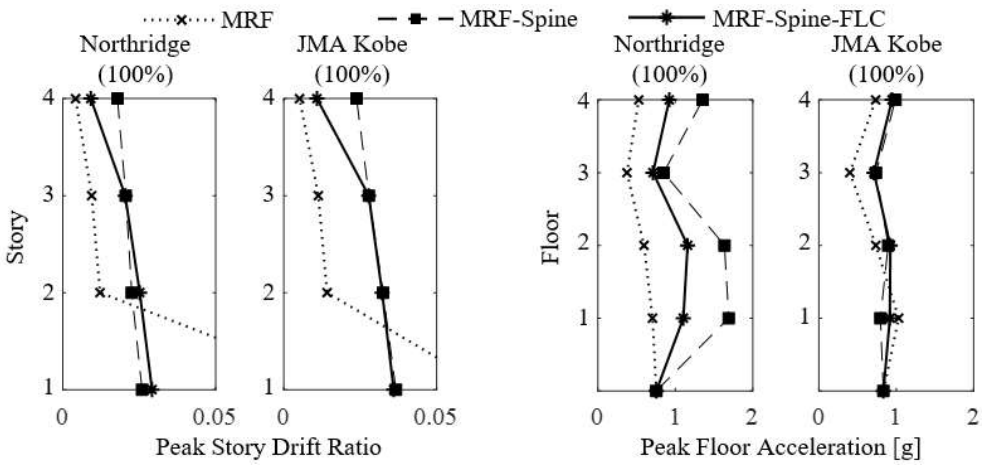


Fig. 8 - Peak demands profile for Northridge and JMA-Kobe ground motions

To compare and select of scale factors for the shake-table testing plan, the maxima of the peak story drift ratios and absolute floor acceleration responses were collected for several scale factors; see Fig. 9. Based on these analyses, certain scale factors were selected for full-scale experimental testing, namely: Northridge scaled to 40% and 100% of the original intensity and JMA-Kobe scaled to 50% and 100% of the original intensity. The scale factors for the Northridge record corresponded to intensities when the FLC first yielded and the original record intensity when the FLC in model [iii] behaved in the inelastic range, respectively. The scale factors for the JMA-Kobe record correspond to design-level spectral intensities near the first-mode period and a very intense, rare event, respectively. The MRF-Spine test setup was only subjected to the Northridge ground motion; the MRF-Spine-FLC test setup was subjected to both the Northridge and JMA-Kobe records.

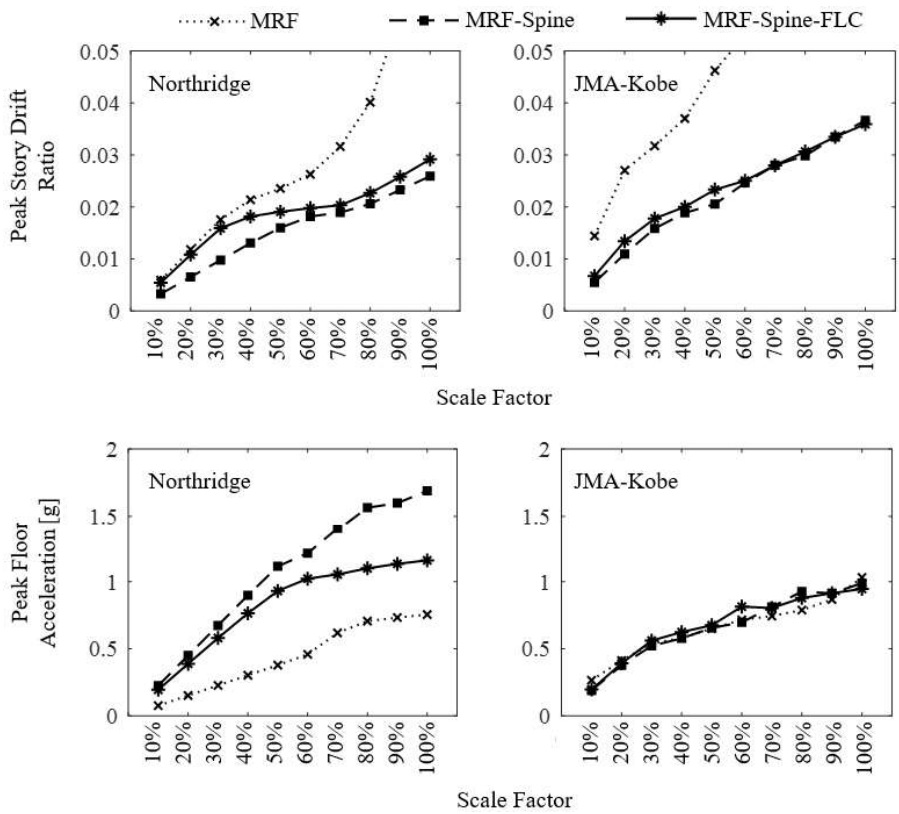


Fig. 9 - Peak demands among all stories/floors for different intensities of Northridge and JMA-Kobe ground motions

4.3.1 Simulation of the testing plan

Simulations were conducted sequentially to account for possible effects of residual damage in the experimental tests; see Fig. 10(a) for the drift ratio response history for the six tests executed in series. Note, the third and fourth tests used a reversed ground motion input (i.e., imposed in the opposite direction, with a flipped sign). Reversing the ground motion counteracted accumulated residual drifts and allowed the continuation of the testing plan for the JMA Kobe record.

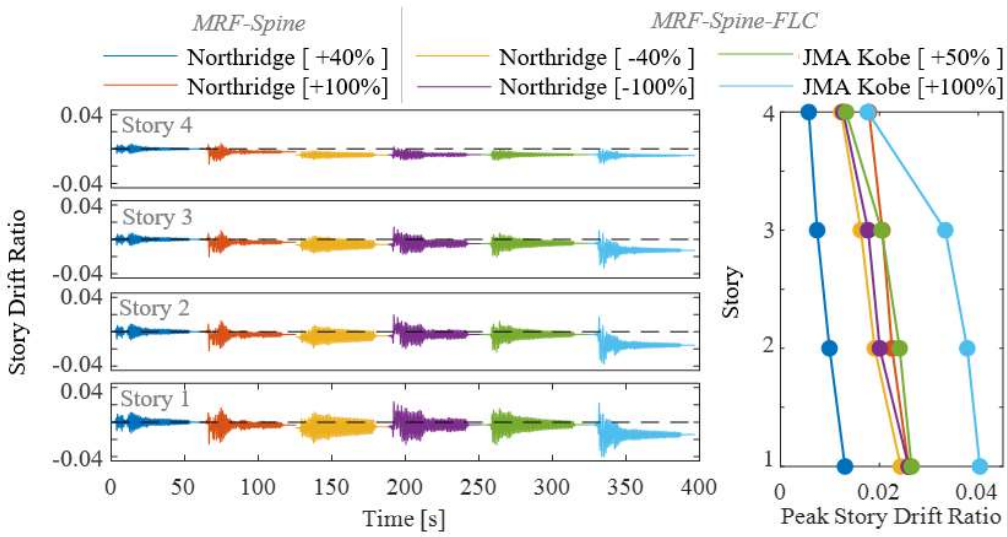


Fig. 10 - Sequential analysis: (a) story drift-ratio response-history, and (b) peak demands

These analyses supported decision-making after each experimental test. The first two time series represent the 40% and 100% Northridge excitations for the MRF-Spine case. The remaining time series correspond to the MRF-Spine-FLC case for the 40% and 100% Northridge excitations followed by the 50% and 100% JMA-Kobe excitations. Fig. 10(b) shows the expected peak story drift-ratio response from the numerical model with the sequential loading.

5. Preliminary Testing Results

Fig. 11 presents the acceleration response histories from the 100% Northridge excitation of four floors for the MRF-Spine and MRF-Spine-FLC tests. Unrealistic spikes in the original acceleration records were identified and removed based on the plots of the first derivative of the acceleration with respect to time; i.e., the jerk [29]. Then, a sixth-order bi-directional Butterworth filter was used to remove high-frequency noise without causing phase distortion [30]. The acceleration records from two accelerometers on the same floor were averaged to approximately represent the acceleration at the center of each floor.

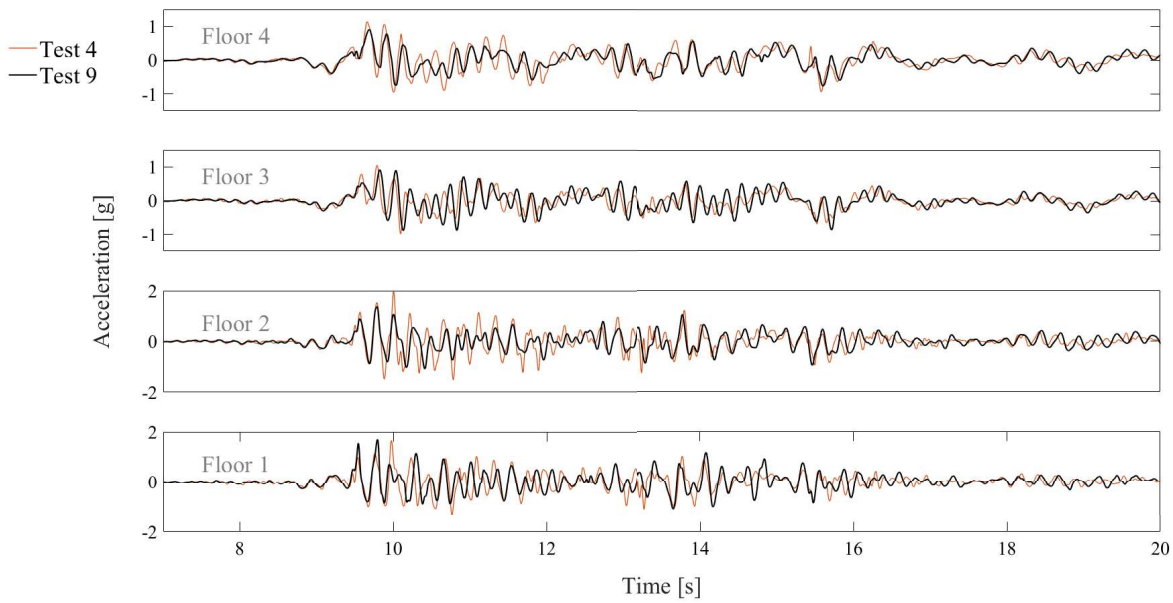


Fig. 11 – Average floor accelerations

The preliminary results demonstrate the capability of FLC in controlling floor accelerations. During the MRF-Spine test with 100% Northridge ground motion, accelerations were measured approaching 2g at Floor 2, which are large enough to cause damage to acceleration-sensitive nonstructural components. In the MRF-Spine-FLC test with the same ground motion, the peak acceleration at Floor 2 was significantly decreased. Similar, although not as significant, reductions in accelerations were observed at other floors.

6. Summary and Conclusions

This paper presented a novel system employing a base frame that has spines attached using force-limiting connections (FLC). The resulting Frame-Spine-FLC System is designed to provide enhanced building performance to protect structural and nonstructural components, especially those in essential facilities, such as hospitals, where damage to the building and contents and occupant injuries must be prevented. A full-scale shake-table testing program was conducted collaboratively by an international U.S.-Japan research team. An existing MRF building, which represented a hospital including realistic contents, with a severe story mechanism tendency was supplemented with spines and FLC and tested under several levels of ground shaking. Two distinct structural conditions were tested: MRF-Spine and MRF-Spine-FLC. Pre-test numerical simulations were conducted for these two structural conditions in addition to the baseline case of the MRF with no supplementary elements, which was not tested due to collapse risk. The numerical simulations confirm

the collapse vulnerability of the MRF alone and the need for supplemental measures to control seismic response. Preliminary shake table test results show – and are corroborated by numerical test predictions – that elastic spines added to a deficient MRF can enforce a more uniform drift profile, and that increased floor accelerations arising from addition of the elastic spines can be reduced by employing FLC. The research team is using these promising preliminary results as a foundation for more comprehensive study of the Frame-Spine-FLC System, including design methodologies that can be translated into practice in both the U.S. and Japan.

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