Full-Scale Seismic Stability Evaluation of a Frame-Spine System with Force-Limiting Connections

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Abstract

A new seismic-resilient structural system is being developed to protect buildings, their contents, and occupants during major earthquakes. This economical system is intended for 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 primary components of the Frame-Spine-FLC 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. An international team, including three U.S. universities, two Japanese universities and two major experimental research labs, is collaborating on this project and recently conducted full-scale shake-table testing at the E-Defense facility in Miki, Japan. The test building represents a hospital facility and includes realistic nonstructural components and medical equipment. This paper provides an overview of the shake-table testing program and presents preliminary results that demonstrate the seismic stability response of the Frame-Spine-FLC System and the overall viability of the new concept.

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1. Background and Introduction

Conventional ductile seismic steel systems for buildings are economical but are designed to be damaged in the design-basis earthquake (DBE). In addition, these systems tend to develop concentrated lateral drift in individual stories, leading to single-story failure mechanisms (Lignos et al. 2011, Suita et al. 2008) with significant potential for damage to drift-sensitive non-structural systems and collapse.

To prevent story mechanisms, systems that combine conventional ductile frame behavior with a stiff and strong spine were developed (Grigorian and Grigorian 2016, Laghi et al. 2017, Pollino et al. 2017, Qu et al. 2012, Simpson and Mahin 2018, Takeuchi et al. 2015, Tremblay and Poncet 2007). A properly-designed spine helps control lateral story drifts and eliminate single-story mechanisms. However, 20 years of research show that lateral-force resisting systems (LFRS) with spine-like behavior (i.e., with a true pinned base or with a base-moment-yielding mechanism and elastic response over the height) develop large seismic forces (and corresponding floor accelerations) compared to conventional ductile frame systems (Chen et al. 2019, Eberhard and Sozen 1993, Kurama et al. 2002, Priestley 2003, Roke et al. 2008, Sause et al. 2010). These large forces arise because spine-like systems do not have a nonlinear mechanism for controlling the higher-mode response. These large forces decrease the potential for the spine to remain elastic at DBE and maximum considered earthquake (MCE) intensities. Large floor accelerations also increase the potential for damage to acceleration-sensitive non-structural systems and building contents.

Recent work has used deformable force-limiting connections (FLC) to control the forces transferred between each floor of an earthquake-resistant building and its stiff LFRS (Tsampras 2016, Tsampras et al. 2016 and 2017, 2018, Zhang 2018). Shake table tests and numerical simulations have shown significant reductions in the seismic forces and floor accelerations.

Herein, the benefits of the spine and FLC are combined to develop a practical LFRS that controls multi-modal seismic response and protects 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.

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 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.

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. Preliminary results that demonstrate the seismic stability response of the frame-spine-FLC system and the overall viability of the new concept are presented.

2. Shake Table Test Setup

Between December 14, 2020 and December 17, 2020, full-scale shake table testing was performed on 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. To control residual drifts of the test building, for Tests 7 and 9, ground motions were applied in the opposite direction compared to the previous tests. The test building data is shown in Table 1, and the test sequence is shown in Table 2. A total of 14 tests were conducted, and the tests not listed in Table 2 were broadband white noise excitation to assess structural parameters.

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

Table 2 – Test sequence

Earthquake #	Test #	Ground Motion	Intensity	FLC Condition
1	2	Northridge_SepulvedaVA	+40%	Restrained
2	4	Northridge_SepulvedaVA	+100%	Restrained
3	7	Northridge_SepulvedaVA	-40%	Active
4	9	Northridge_SepulvedaVA	-100%	Active
5	11	JMA Kobe	+50%	Active
6	13	JMA Kobe	+100%	Active

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 (Kawamata et al. 2021, Kurata et al. 2021). 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 satisfy 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

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.

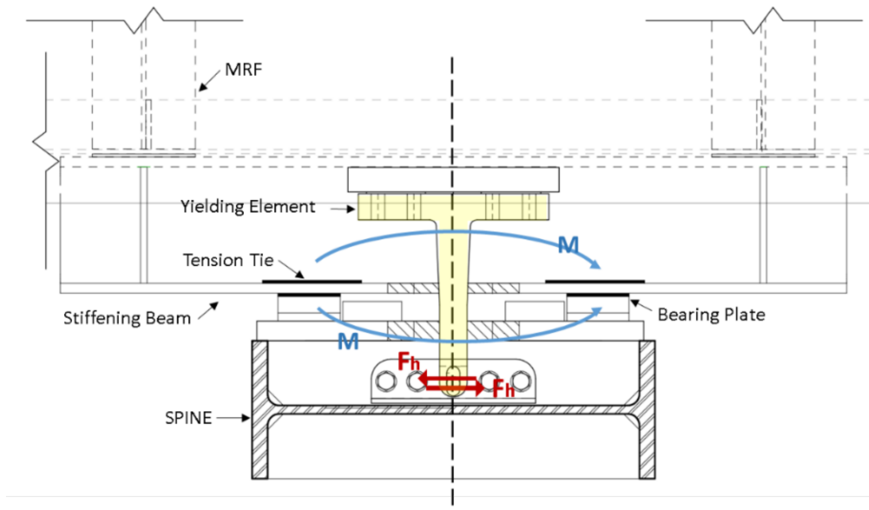


Fig. 2 – Simplified FLC with design forces

(a) (b)

Fig. 3 – Force-limiting connections with yielding elements

3. Preliminary Test Results

Fig. 4 presents the acceleration response histories of Floor 2 for Tests 4 and 9. Unrealistic spikes in the original acceleration records were identified and removed based on the jerk plots (Boore and Bommer 2005). Then, a sixth-order bi-directional Butterworth filter was used to remove high-frequency noise without causing phase distortion (Seo and Sause 2013). The acceleration records from two accelerometers on the same floor were averaged to approximately represent the acceleration at the center of each floor.

The preliminary results demonstrate the capability of FLC in controlling floor accelerations. During the MRF-Spine test with the 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.

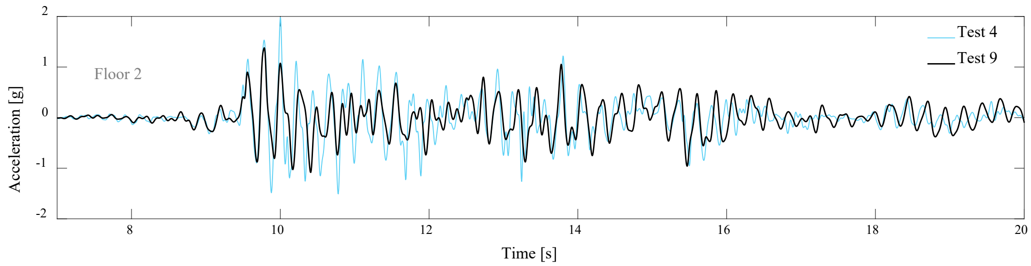
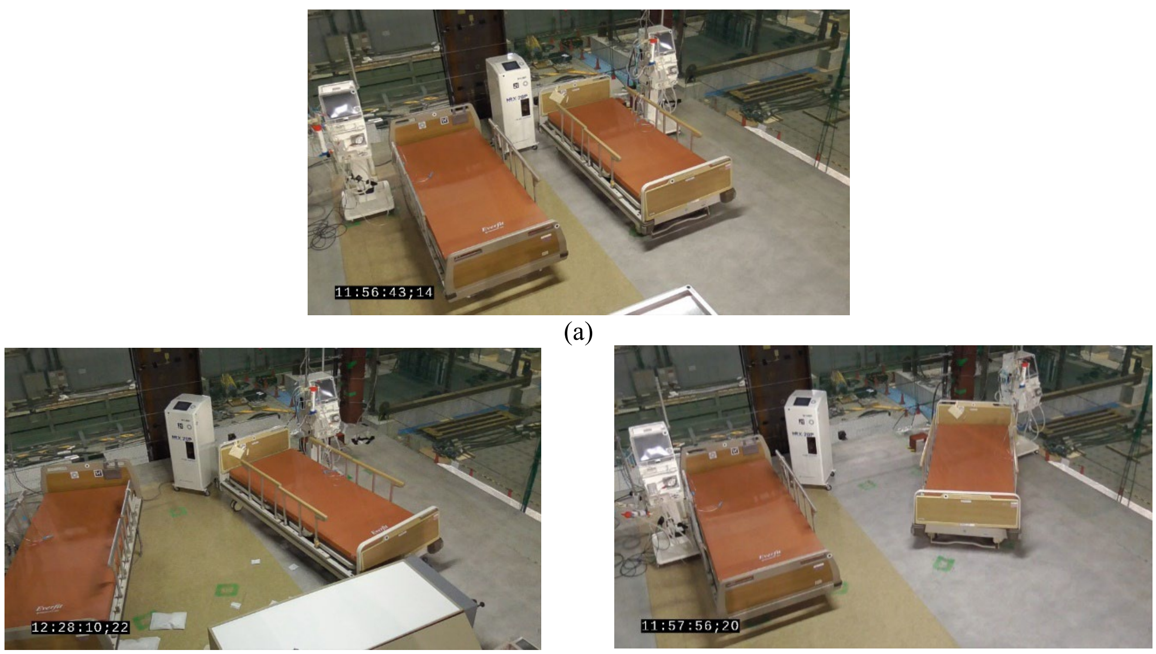


Fig. 3 – Average floor accelerations of Floor 2

Fig. 4 shows the position of hospital contents before and after Tests 4 and 9 on Floor 2. Although the accelerations of the contents were not directly measured, they can be qualitatively assessed through the behavior of the contents. After Test 4, a cabinet fell onto the floor due to the large inertial force that caused tipping. In contrast, after Test 9, the furniture movement was more modest, and the large cabinet did not tip. Although the response of nonstructural components requires more thorough investigation, the initial anecdotal observations provide qualitative support for the efficacy of floor acceleration reduction through FLC.



(a)

(b) (c)

Fig. 4 – Hospital contents on Floor 2: (a) original, (b) after Test 4, and (c) after Test 9

4. 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 reliable seismic stability and enhanced building performance that protects 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 a 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. Preliminary shake table test results show 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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