Frame-Spine System with Force-Limiting Connections for Low-Damage Seismic-Resilient Buildings

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Abstract. A novel structural system is being investigated collaboratively – by an international team including three U.S. universities, two Japanese universities and two major experimental research labs – as a means to protect essential facilities, such as hospitals, where damage to the building and its contents and occupant injuries must be prevented and where continuity of operation is imperative during large earthquakes. The new system employs practical structural components, including (1) flexible steel moment frames, (2) stiff steel elastic spines and (3) force-limiting connections (FLC) that connect the frames to the spines, to economically control building response and prevent damaging levels of displacement and acceleration. The moment frames serve as the economical primary element of the system to resist a significant proportion of the lateral load, dissipate energy through controlled nonlinear response and provide persistent positive lateral stiffness. The spines distribute response evenly over the height of the building and prevent story mechanisms, and the FLCs reduce higher-mode effects and provide supplemental energy dissipation. The Frame-Spine-FLC System development is focusing on new construction, but it also has potential for use in seismic retrofit of deficient existing buildings. This paper provides an overview of the ongoing research project, including selected FLC cyclic test results and a description of the full-scale shake-table testing of a building with the Frame-Spine-FLC System, which represents a hospital facility and includes realistic nonstructural components and medical equipment.

Keywords: Shake table testing · Steel-Framed Building · Spine · Force-limiting connection

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1 Background and Design Concept

Modern seismic lateral force-resisting systems (LFRS) are designed and detailed to exhibit stable and ductile response under strong earthquakes. However, the inelastic deformations and damage accumulated in such scenarios can lead to degraded stiffness and strength of the LFRS. In addition, a properly designed LRFS is still susceptible to lateral demands concentrated in a limited number of stories and story mechanisms [1, 2]. These effects can cause damage to drift-sensitive structural and nonstructural components, render repairs impractical, and even lead to building collapse.

Dual systems, combining a stiff LRFS with a flexible moment-resisting frame (MRF), are designed to rely on the MRF's elastic restoring force to mitigate concentrated lateral drifts [3], but the frame action of the MRF is insufficient in distributing inelastic demands [4], and dual systems are still prone to developing story mechanisms. Instead, stiff elastic vertical structural components, or "spines", can be combined 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, due to the lack of a nonlinear mechanism, higher-mode story shear and acceleration demands in such systems are not well constrained [12–17], and they can result in uneconomic or 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 a stiff LFRS [18–22]. The deformable elements within the FLC allow relative motion between the gravity system and LFRS, 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 and economical LFRS 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.

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) FLCs that connect the spines to the MRFs. The steel MRFs resist a portion of the lateral load and dissipate energy through ductile 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 FLCs limit the seismic forces transferred from the MRF to the spines, reducing the magnitude of the higher-mode acceleration demands.

2 Shake Table Test Setup

Between December 14, 2020 and December 17, 2020, full-scale shake table testing was performed for 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 tests were performed, namely MRF-Spine tests and MRF-Spine-FLC tests.

2.1 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 at E-Defense, 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 effectiveness 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.

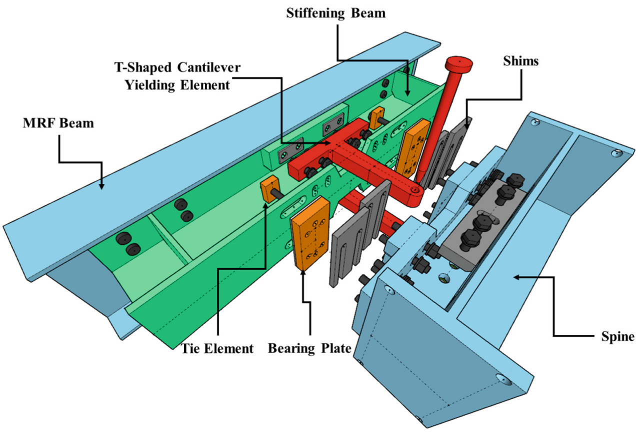
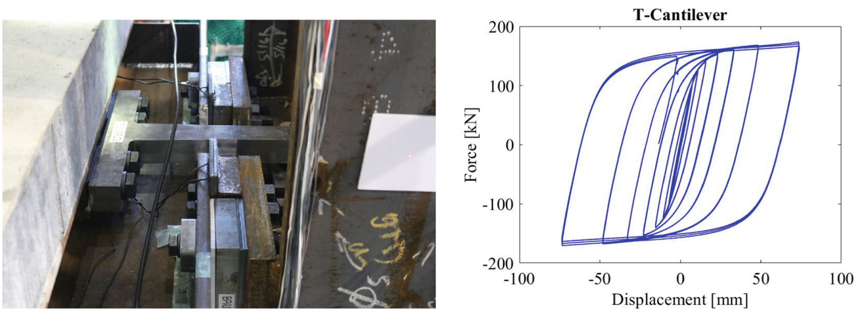


Fig. 2. FLC exploded view



(a) (b)

Fig. 3. T-shaped cantilever yielding element: (a) photo in test building; (b) hysteretic response

Figure 2 illustrates the exploded view of a typical FLC. 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. 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. Cyclic test results for the T-shaped cantilevers are shown in Fig. 3(b), and representative cyclic test data for the U-shaped bars are provided in a Nippon Steel Technical Report [25].

2.2 Ground Motion Input and Testing Plan

The ground motion record from the Sepulveda Valley Hospital during the 1994 Northridge earthquake was selected based on its large spectral pseudo-accelerations near the estimated second-mode period. In addition, the JMA-Kobe NS ground motion record was selected to provide additional insight into the behavior of the Frame-Spine-FLC System for differing ground motion characteristics. The analysis of the peak drifts and floor acceleration responses under a larger number of ground motion inputs can be found in [26].

40% and 100% Northridge records were used in both the MRF-Spine tests and the MRF-Spine-FLC tests to provide direct comparison between acceleration and drift responses. However, for the MRF-Spine-FLC tests, the Northridge records were used in the direction opposite to the previous tests to counteract accumulated residual drifts and to allow the continuation of the testing plan for the remaining 50% and 100% JMA Kobe records. A total of 14 tests were conducted, and the tests not listed in Table 1 were broadband white noise excitations to assess structural modal periods.

Table 1. Test sequence

Earthquake	Test	Ground motion	Scale	FLC condition
1	2	Northridge_SepulvedaVA	+40%	Restrained
2	4	Northridge_SepulvedaVA	+100%	Restrained
3	7	Northridge_SepulvedaVA	−40%	Activated
4	9	Northridge_SepulvedaVA	−100%	Activated
5	11	JMA Kobe NS	+50%	Activated
6	13	JMA Kobe NS	+100%	Activated

3 Preliminary Test Results

Figure 4 presents the MRF column base shear, spine base shear and total base shear response histories for Test 13. A sixth-order bi-directional Butterworth filter was used to remove high-frequency noise without causing phase distortion [27]. This response data illustrates the significant increase in base shear capacity that the spines introduce as they prevent a first-story mechanism from developing in the deficient MRF. Figure 5 presents the acceleration response histories of Floor 2 for Tests 4 and 9. Spurious spikes in the original acceleration records were identified and removed based on the jerk plots [28], and a sixth-order bi-directional Butterworth filter was used [27]. 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.

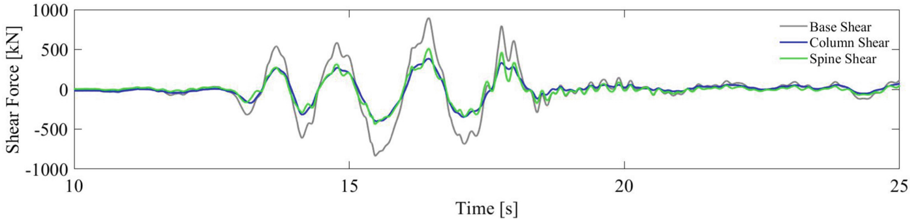


Fig. 4. Column base shear, spine base shear and total base shear for Test 13

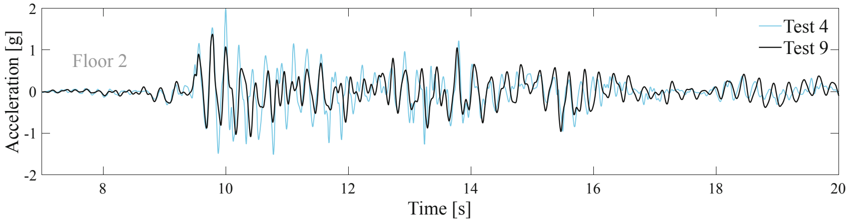


Fig. 5. Average floor accelerations of Floor 2

4 Summary

This paper presents a novel structural system that employs stiff, elastic spines and force-limiting connections (FLC) to provide resilient response in a deficient base moment-resisting frame (MRF) building. Shake-table test results indicate that a more uniform story drift profile can be achieved in a MRF when elastic spines are added, and that increased floor accelerations from adding elastic spines can be reduced by implementing FLC. The ongoing project is exploring a broad range of Frame-Spine-FLC Systems and will develop a design framework for implementation in practice.

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