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Shake Table Testing of a Frame-Spine System with Force-Limiting Connections

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ABSTRACT

A novel structural system is being developed collaboratively by researchers from the United States and Japan 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 must be maintained. The development is focusing on new construction, but it also has potential for use in seismic retrofit of deficient existing buildings. 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

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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 FLC reduce higher-mode effects and provide supplemental energy dissipation. 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, validated the functionality of the structural system.

Introduction

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 braced frame or wall with a flexible moment-resisting frame (MRF), possess an elastic restoring force from the MRF that at least partially mitigates concentrated lateral drifts after inelastic response in the braced frame or wall [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 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 uneconomical or impractical proportioning of the spine and damage to acceleration-sensitive nonstructural components.

To mitigate floor-level 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 to achieve the above goals.

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 its contents and occupant injuries must be prevented.

Design 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) FLC 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 FLC limit the seismic forces transferred from the MRF to the spines, reducing the magnitude of the higher-mode acceleration demands compared to a Frame-Spine system without FLC.

Full-Scale Shake Table Test

To validate the concept of Frame-Spine-FLC System, full-scale shake table testing was performed for a building with the Frame-Spine-FLC System at the E-Defense shake-table facility, Hyogo Earthquake Engineering Research Center in Japan. 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 and spines. In the MRF-Spine-FLC tests, the same MRF was connected to the spines by a combination of slip-critical bolted connections and FLC.

A record from the Sepulveda Valley Hospital during the 1994 Northridge earthquake was selected as the primary ground motion input based on its large spectral pseudo-accelerations near the second-mode period [23]. It was used in both the MRF-Spine tests and the MRF-Spine-FLC tests to allow direct comparison between acceleration and drift results. The JMA Kobe record from the 1995 Kobe earthquake was used for the MRF-Spine-FLC tests to provide additional insight into the behavior of the Frame-Spine-FLC System for differing ground motion characteristics.

(a) (b) (c)

Figure 1. Shake-table test building: (a) overview, (b) FLC at Floor 1, and (c) FLC at Floor 3

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 [24,25]. The three-story building on its own with column bases fixed can represent a hospital building in Anaheim, California. However, to demonstrate the capability of spines in helping a deficient MRF form a uniform drift profile, the base isolators were removed and the MRF column bases were placed on clevises to induce a tendency to form a severe story mechanism.

At the predicted second modal period of the three-story pinned-base building, the spectral acceleration of the Northridge ground motion was near the peak value. Thus, with the addition of spines, the building becomes stiffer, the second modal period shorter, and the spectral acceleration lower, which does not represent the common case for buildings with more than three stories. To address this issue, it was determined that the mass of the roof of the three-story building should be increased, and a fourth floor with the same mass should be added onto the top of the original building. In this way, after adding spines, the spectral acceleration calculated using the second modal period approaches the peak value, and higher-mode effects can be fully excited, as shown in Fig. 2. This additional story was designed and fabricated in the U.S., shipped to Japan, and added to the existing three-story building at E-Defense.

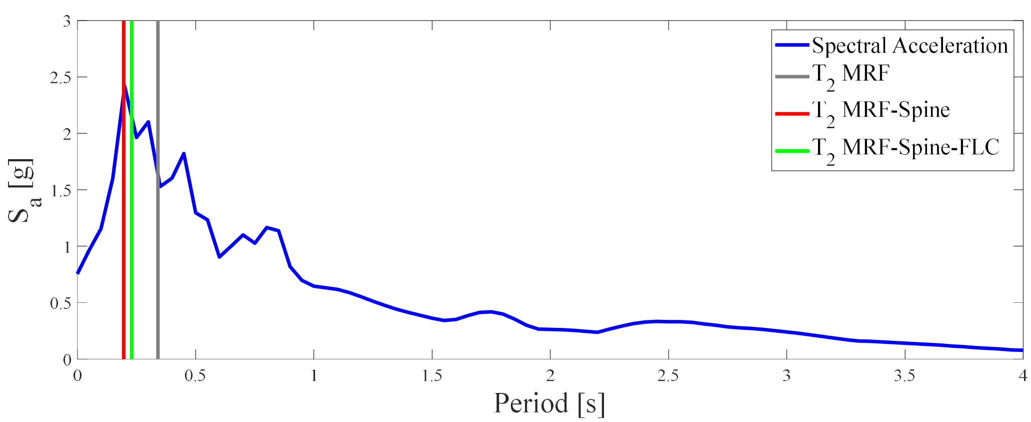

Figure 2. Spectral acceleration diagram of Northridge ground motion

As shake table testing was conducted along one primary building axis, spines were installed on only two sides of the building, as shown in Fig. 1. 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 (the roof level) by a slip-critical bolted connection. The FLC at Floor 1 consisted of a yielding T-shaped cantilever, bearing plates and ties, as shown in Fig. 1(b). 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. 1(c). 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 Corporation.

Preliminary Test Results

Table 1 presents the peak floor accelerations from the 100% Northridge excitation 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 [26]. Then, a sixth-order bi-directional Butterworth filter was used to remove high-frequency noise without causing phase distortion [27]. The acceleration records from two accelerometers on the same floor were averaged to approximately represent the acceleration at the center of each floor.

Table 1. Peak floor accelerations [g]

Configuration	Floor 1	Floor 2	Floor 3	Floor 4
MRF-Spine	1.66	1.98	1.05	1.14
MRF-Spine-FLC	1.35	1.38	0.91	0.90

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-Frame-Spine test with the same ground motion, the peak acceleration at Floor 2 significantly decreased. Similar, if not as significant, reductions in accelerations were observed at other floor levels.

Conclusions

A novel structural system that employs stiff, elastic spines and force-limiting connections (FLC) has been developed 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.

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