DEFORMABLE CONNECTION FOR EARTHQUAKE-RESISTANT BUILDING SYSTEMS

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ABSTRACT: This paper presents a deformable connection that is used to connect each floor system of the flexible gravity load resisting system (GLRS) with the stiff lateral force resisting system (LFRS) of an earthquake-resistant building. The deformable connection limits the forces transferred from the GLRS to the LFRS, and reduces the floor accelerations and force responses of the structure. The deformable connection consists of a buckling restrained brace (BRB) or a friction device (FD) which acts as a limited-strength hysteretic component, in parallel with low damping laminated rubber bearings (RB) which provide out-of-plane stability to the LFRS, post-elastic in-plane stiffness, and help with partial re-centering. Preliminary numerical simulations of a twelve-story reinforced concrete wall building structure with deformable connections showed reduced structural responses compared to a building with rigid-elastic connections.

Key Words: floor accelerations, buckling restrained brace, low damping laminated rubber bearings, friction device

1. INTRODUCTION

In conventional earthquake-resistant building systems the gravity load resisting system (GLRS), in particular, the floor system, where most of the seismic mass is located, is rigidly attached to the lateral force resisting system (LFRS), which resists the seismic inertial force. The inertial force is transferred from the GLRS to the LFRS assuming a rigid connection between the floor system and the LFRS.

Skinner et al.[1)] sketched a building system with a separated tower and a moment-resisting frame connected by hysteretic dampers. This concept allows relative motion between the tower and the frame and the hysteretic dampers dissipate energy. Key[2)] performed a numerical study to assess the effect of using hysteretic dampers to link a stiff structure (shear wall) with a flexible structure (moment

resisting frame) to dissipate energy and improve the structural response. Luco and De Barros[3] studied the seismic response of a tall building modelled by two shear beams interconnected with stiff or flexible link elements. Mar and Tipping[4] presented structural details for a story isolation system that reduces the base shear and roof acceleration demands.

Crane[5] conducted shake table tests on two small-scale six-story buildings with energy dissipative connections between the floors and the LFRS. Triangular-plate added damping and stiffness devices were used as the connections. Reduced floor accelerations and base overturning moment were observed.

Based on this previous research, studies (Zhang et al.[6], Fleischman et al.[7], Tsampras et al.[8], Tsampras and Sause[9]) have been initiated on an earthquake-resistant building system that allows relative motion between the LFRS and GLRS with the use of deformable connections. The deformable connections can limit the forces transferred from the floor systems to the LFRS and reduce the floor accelerations and force responses.

2. DEFORMABLE CONNECTION CONFIGURATIONS

Figure 1(a) shows the plan view of a building structural system with the deformable connections in the undeformed condition. Figure 1(b) shows the elevation of the building system in a deformed condition. As seen in Figure 1(a), openings in the floor system are required to allow the relative motion between the LFRS and the floor system. The floor system is connected to the LFRS using a deformable connection that consists of two types of components. The limited-strength hysteretic component is required to transfer lateral forces in the plane of the LFRS from the floor system to the LFRS, and to provide stability to the flexible GLRS. The limited-strength hysteretic component will extend and retract due to the relative horizontal motion in the plane of the LFRS. The bearing components brace the LFRS in the out-of-plane direction. The bearing components must have high compressive stiffness and strength to transfer LFRS out-of-plane bracing forces without significant compressive deformation. To permit relative in-plane motion between the LFRS and the floor system, the bearing components should have low shear stiffness compared to their compressive stiffness. This shear stiffness provides post-elastic stiffness to the deformable connection in the in-plane direction. The close up views of the limited-strength hysteretic and bearing components in Figure 1(b) show the kinematic requirements for the deformable connection based on the expected seismic response of the building. These kinematic requirements are in-plane relative vertical and horizontal motions, and out-of-plane rotation of the LFRS relative to the floor system.

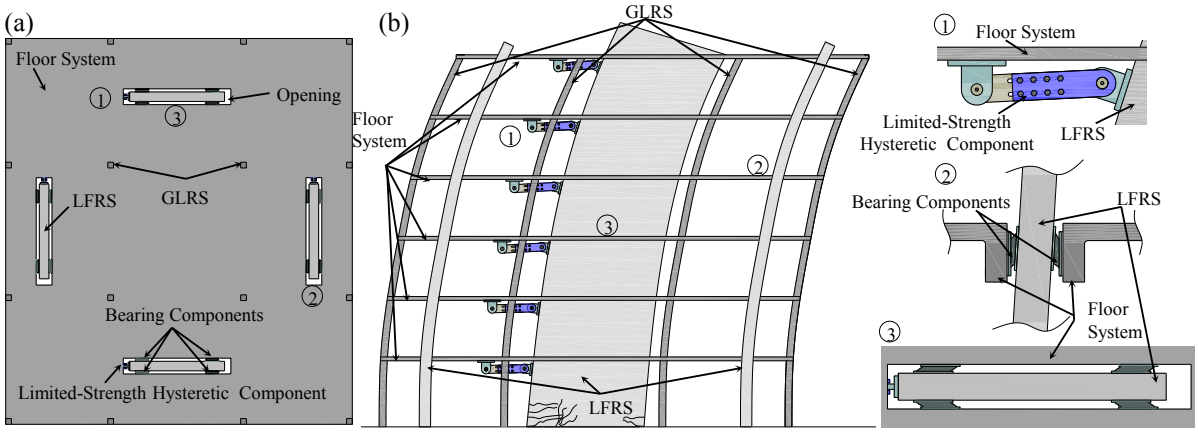


Fig. 1 Sketches of earthquake-resistant building system with deformable connections.

Two configurations of the deformable connection are presented in this paper. The first deformable connection configuration consists of a buckling restrained brace (BRB) and a set of low damping laminated rubber bearings. The second deformable connection configuration consists of a

friction device and a set of low damping laminated rubber bearings. Comparing the two configurations, the BRB is expected to have smaller elastic stiffness than the friction device designed for the same force demand. The force-deformation behavior of a BRB, is expected to exhibit isotropic hardening and non-zero post-elastic stiffness, which is not expected for a friction device. Finally, the length of the BRB will be greater than the length of the friction device designed for the same deformation demand.

Figure 2(a) shows an example friction device along with the clevis connections and the pins used to attach the friction device to the LFRS and the floor system. Spherical bearings are used at the end connections to ensure the accommodation of the expected kinematic requirements showed in Figure 1(b). Figure 2(b) shows the friction device installed in a building structure. Figure 2(c) shows the components of a BRB with pin end connections. Figure 2(d) shows a BRB attached to a LFRS and a floor system using clevis connections with spherical bearings. Similar attachments could be used for different types LFRS and floor systems.

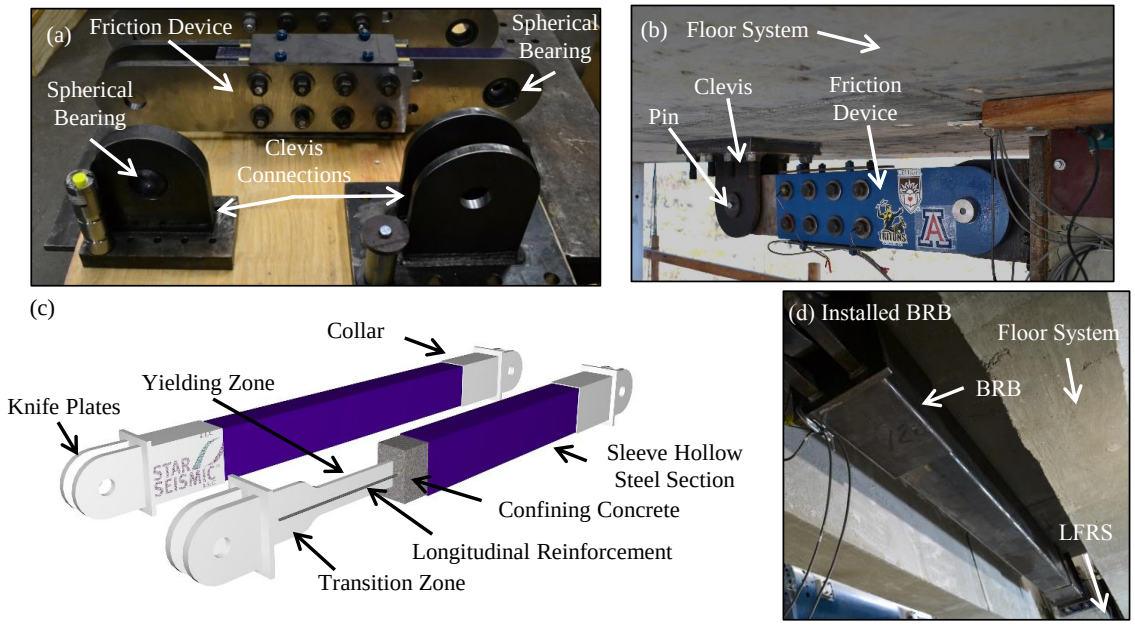


Fig. 2 (a) Friction device and clevis connections. (b) Installed friction device. (c) BRB components. (d) Installed BRB.

The use of spherical bearings at the end connections allows also the accommodations of the potential construction errors. Figure 3(a) and (b) shows two different clevis connections attached to steel plates embedded in a LFRS without and with construction error, respectively.

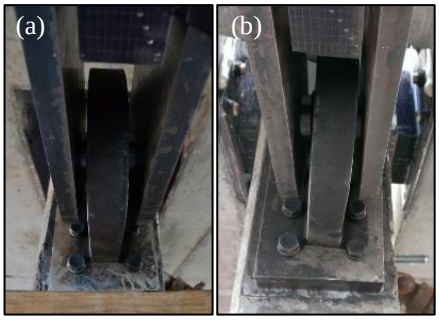


Fig. 3 Clevis connections (a) without and (b) with construction error.

Low damping laminated rubber bearings were used because of their essentially elastic response under large shear deformation with modest energy dissipation (Constantinou et al.[10], Naeim and Kelly[11], Kelly and Takhirov[12]). Their shear force-deformation response can be approximated with linear elastic models (Huang et al.[13]) and their compressive stiffness is significantly higher compared to their shear stiffness. Their mechanical properties are not expected to be shear deformation rate depended (Naeim and Kelly[11]).

Figure 4 shows an overview and a close-up view of a low damping laminated rubber bearing installed between a concrete LFRS and a concrete floor system. The rubber bearing consisted of laminated rubber layers that created a rubber pad which was bonded on two external steel end-plates. The low damping laminated rubber bearings were pre-compressed against the LFRS using wooden edges and grout was poured to maintain the pre-compression.

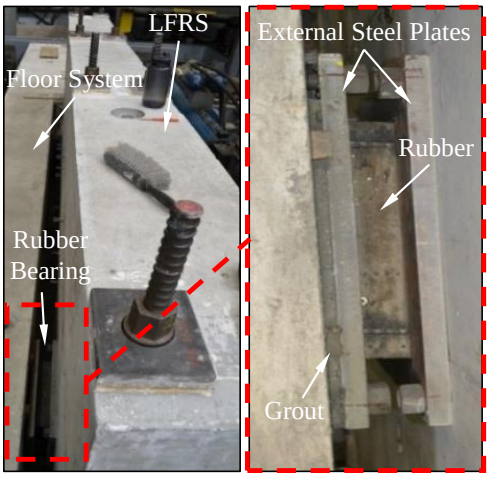


Fig. 4 Example of installed low damping laminated rubber bearings.

3. PRELIMINARY NUMERICAL SIMULATIONS

Preliminary numerical simulations were conducted. The structural response of a building structure with rigid-elastic connections was compared with the structural response of the same building structure with deformable connections. The open source software OpenSEES (McKenna et al.[14]) was used to develop the numerical model shown in Figure 5. The building structure was a twelve-story special reinforced concrete shear wall structure with plan dimensions 30.48 m x 54.86 m (100 ft. x 180 ft.). It was designed using ASCE7-10[15] (R = 5, Ωo = 2.5, Cd = 5). The Friuli 1976 earthquake ground motion component TMZ000 was used in the analysis. The ground acceleration was scaled by 2.77 to match its spectral acceleration with the design spectral acceleration (ASCE 2010) near the first mode period of the structure. The twelfth floor acceleration time histories in Figure 6(a) show that the absolute peak floor acceleration is reduced by nearly 50% (from 1.3g to 0.7g) using the deformable connection. In Figure 6(b) the Fourier amplitude spectra of the twelfth floor acceleration histories shows that the deformable connection reduced the Fourier amplitude near the second (4Hz) and third (11Hz) mode frequencies of the structure. Thus, it is possible to reduce the higher mode contributions to the total structural response. It was observed that the reduction of the floor acceleration is not the same at every floor of the structure. The twelfth floor deformable connection force-deformation response is shown in Figure 7(a). Figure 7(b) shows that the use of the deformable connection reduced the LFRS twelfth peak story shear by about 85% (from 14,000kN to 2000kN).

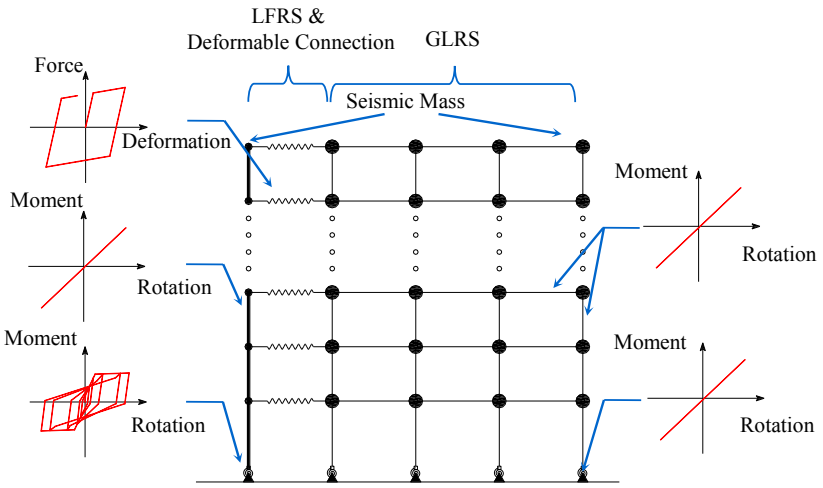


Fig. 5 Numerical model of twelve-story structure.

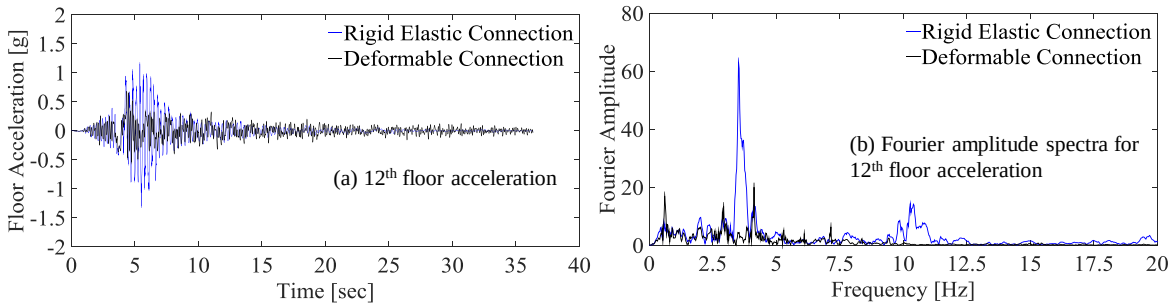


Fig. 6 12th floor acceleration time history and Fourier amplitude spectra.

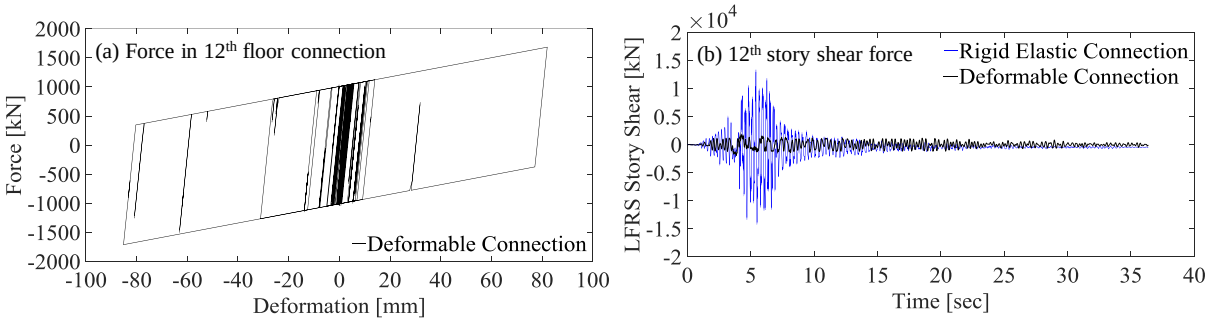


Fig. 7 12th floor/story response.

4. EXPERIMENTAL RESULTS

To validate the response of the two configurations of the deformable connection, an experimental program was conducted using the NEES@Lehigh equipment site at the Advanced Technology for Large Structural Systems (ATLSS) Engineering Research Center. The experimental set up included a portion of the twelfth floor of the twelve-story reinforced concrete shear wall structure used in the numerical simulations. As shown in Figure 8(a), part of the floor and part of the reinforced concrete shear wall were built in the laboratory. The components of the deformable connection were attached to these parts of the wall and floor. The objectives of the experimental program were to demonstrate the feasibility of the deformable connection for full-scale seismic demands from the twelve-story building

structure, to assess the process for installing the components of the deformable connection and to validate the performance of the deformable connection under sinusoidal displacement histories at various frequencies and amplitudes and also under displacement histories that represent expected seismic deformation demands. Figure 8(b) shows the test setup and specimen for the first deformable connection configuration (BRB+RB), including the wall and floor (without the concrete), the buckling restrained brace (from Star Seismic® LLC), and a set of steel reinforced low damping laminated rubber bearings. Figure 8(c) shows the second deformable connection configuration (FD+RB) including the friction device (developed at Lehigh University) and a set of carbon fiber reinforced low damping laminated rubber bearings (from DYMAT™, INC).

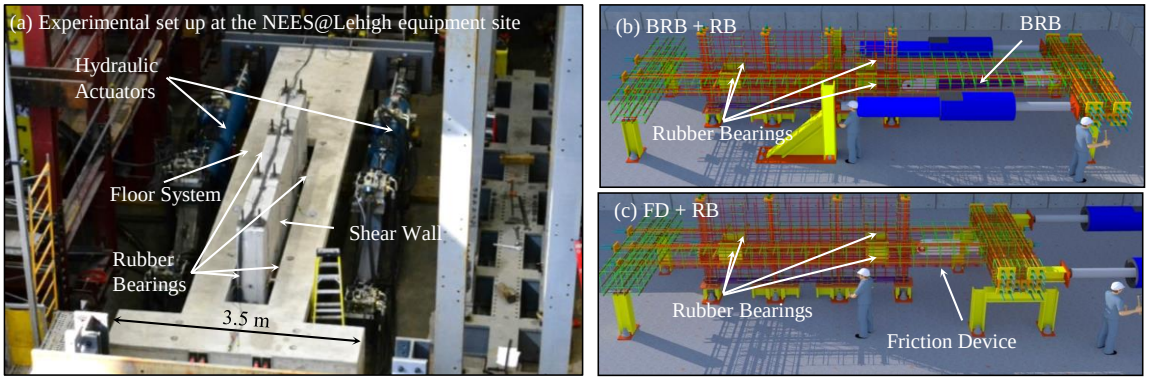


Fig. 8 Experimental set up at NEES@Lehigh equipment site.

The results from the experimental program showed that the design of the two deformable connection configurations are feasible. Figure 9(a) and (b) shows the experimental force-deformation response of the first deformable connection configuration (BRB+RB) subjected to an earthquake and a sinusoidal quasi-static displacement history, respectively. Similarly, Figure 9(c) and (d) shows the experimental force-deformation response of the second deformable connection configuration (FD+RB) subjected to an earthquake and a sinusoidal quasi-static displacement history, respectively. The deformable connection hysteretic responses were stable under large deformations. The use of low damping laminated rubber bearings increased the deformable connection post-elastic stiffness. The attachments of the deformable connections to the wall and floor behaved as expected.

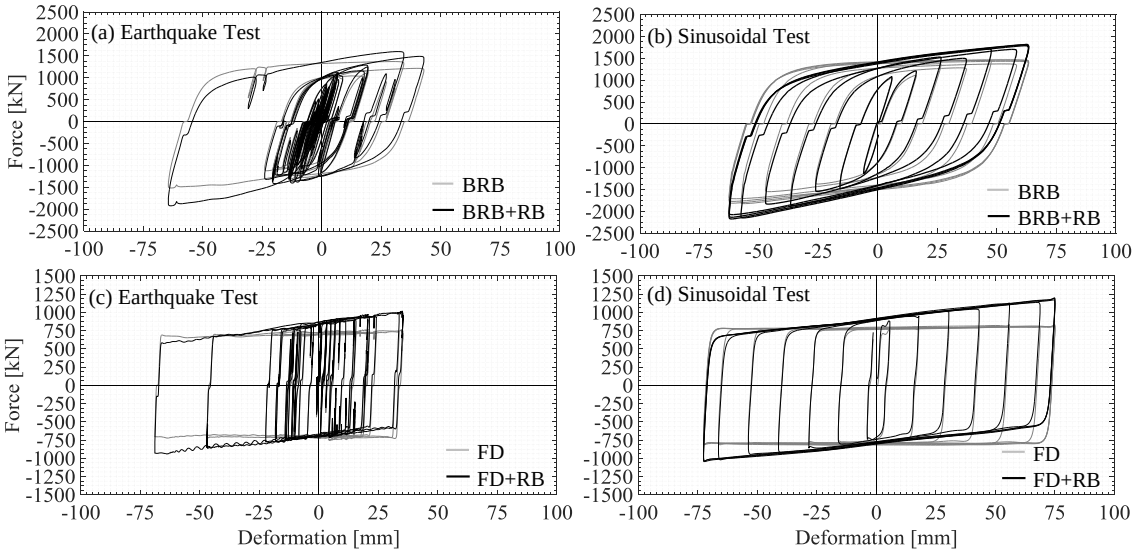


Fig. 9 Experimental results of the two configurations of the deformable connection.

4. SUMMARY AND CONCLUSIONS

Two configurations of deformable connections used to connect the floor systems in the gravity load resisting system (GLRS) with the lateral force resisting system (LFRS) of an earthquake-resistant building system have been presented. Deformable connections could be used to limit the forces transferred from the floor systems to the LFRS, reduce the floor accelerations, reduce the higher-mode contribution to the structural response, and reduce the forces develop in the LFRS. Details of two configurations of the deformable connection were presented. Experimental results showed that the design of two deformable connection configurations with stable hysteretic response is feasible.

ACKNOWLEDGMENTS

This paper is based upon work supported by grants from National Science Foundation, Award No. CMMI-1135033 in the George E. Brown, Jr. Network for Earthquake Engineering Simulation Research (NEESR) program, and Award No. CMMI-0402490 for the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) consortium operations. The authors are grateful for additional financial support provided by the Gerondelis Foundation, Yen Fellowship, and Lehigh University. The contributions of Joe Maffei, David Mar, Zhi Zhang, Ulina Shakya, Arpit Nema and the NEES@Lehigh and ATLSS Center staff are acknowledged. The authors appreciate the contributions of the companies DYMAT™ and Star Seismic® and Scan-Pac Mfg., Inc. Any opinions, findings, and conclusions expressed in this report are those of the authors and do not necessarily reflect the views of the National Science Foundation or others acknowledged here.

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