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Seismic Response of Core Wall Building with Friction-Based Force-Limiting Connections

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Abstract: This paper presents preliminary results from earthquake numerical simulations of an eighteen-story building model with a reinforced concrete core wall seismic force-resisting system. Friction-based force-limiting connections with three types of force-displacement responses are used between the floors and the core wall. The first type of force-displacement response simulates a friction-based connection with constant limiting force (i.e., the Coulomb model). The second type of force-displacement response simulates a friction-based connection with linearly varying limiting force (i.e., constant positive post-elastic stiffness). The third type of force-displacement response simulates a friction-based connection with discrete variable limiting force. The preliminary seismic responses of the building models with friction-based force-limiting connections are compared with the seismic response of the building model with connections that simulate a monolithic connection between the floors and the core wall. The preliminary results show that the use of friction-based force-limiting connections reduces the seismic induced force and acceleration responses of the building. The use of friction-based force-limiting connections with discrete variable limiting force results in the smallest seismic induced displacement demand in the floors relative to the seismic induced displacement demand in the core wall compared to the use of friction-based force-limiting connections with constant or linearly varying limiting force.

Keywords: friction-based force-limiting connection; tall buildings; reinforced concrete core wall system; higher mode responses; floor accelerations.

1. Introduction

The reinforced concrete core wall system is a widely used seismic force-resisting system for tall buildings because of its high lateral stiffness and its capacity for dissipating energy [1]–[6]. In the core wall system, the wall piers are typically connected by reinforced concrete coupling beams along the height of the structure [7]. The core wall system is designed in a way that the nonlinear inelastic mechanism takes place at the coupling beams and at the base of the walls, with the rest of the structure remaining linear elastic [7]. The inelastic response at the wall base reduces the first mode response. However, the higher mode responses are not affected significantly by the inelastic response at the wall base and they can have large participation in the total dynamic response of tall buildings [8]. The large participation of higher mode response in the total dynamic response of core wall buildings leads to seismic amplification of story shear forces and floor accelerations.

Practical force-limiting connections between the floors and the vertical elements of seismic force-resisting systems (e.g., reinforced concrete planar walls and rocking steel braced frames) in earthquake-resistant buildings have been developed [9]–[16]. Fig. 1 shows a schematic example of a building with planar walls and force-limiting connections. The force-limiting connections consist of limited-strength load-carrying hysteretic components (friction devices or buckling-restrained braces) and low damping rubber bearings. The low damping rubber bearings provide out-of-plane stability to the planar walls of the seismic

force-resisting system and post-elastic stiffness to the force-limiting connections. The post-elastic stiffness in the force-limiting connections limits the seismic induced displacement of the floors relative to the planar walls of the seismic force-resisting system. The force-limiting connections are designed to accommodate the seismic induced three-dimensional kinematic requirements between floors and planar walls of seismic force-resisting systems. The use of force-limiting connections in these buildings (1) limits the seismic induced force and acceleration responses (2) reduces the variability in the force and acceleration responses due to the ground motion variability, and (3) mitigates the effects of higher mode responses on the dynamic response of buildings.

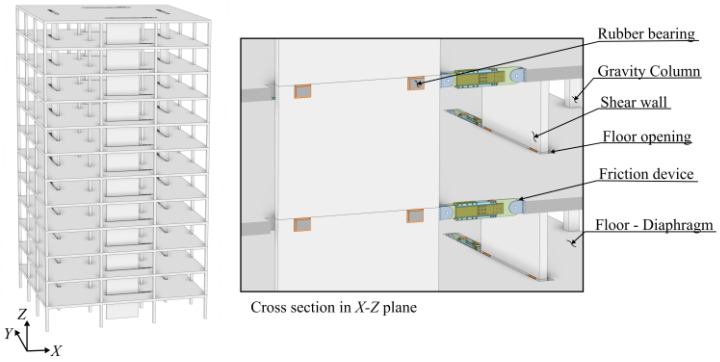


Fig. 1 - Schematic example of a building with planar walls and force-limiting connections.

Force-limiting connections between floors and a core wall could be used to mitigate the higher mode effects on the dynamic response of tall buildings with core wall seismic force-resisting system. However, the force-limiting connections developed for buildings with planar walls cannot be used in buildings with core walls. The three-dimensional kinematic requirements in force-limiting connections between the floors and the core wall are different from the three-dimensional kinematic requirements in force-limiting connections between floors and planar walls. For example, the wall piers of a core wall can maintain their out-of-plane stability without the use of rubber bearings. In addition, the high stiffness of the rubber bearings under compression constrains the relative movement between the floors and the core wall, making the force-limiting connection ineffective, as shown in Fig. 2. Thus, the force-limiting connection between the floors and the core wall should be modified to eliminate the use of low damping rubber bearings without increasing the post-elastic displacement demand in the floors relative to the core wall.

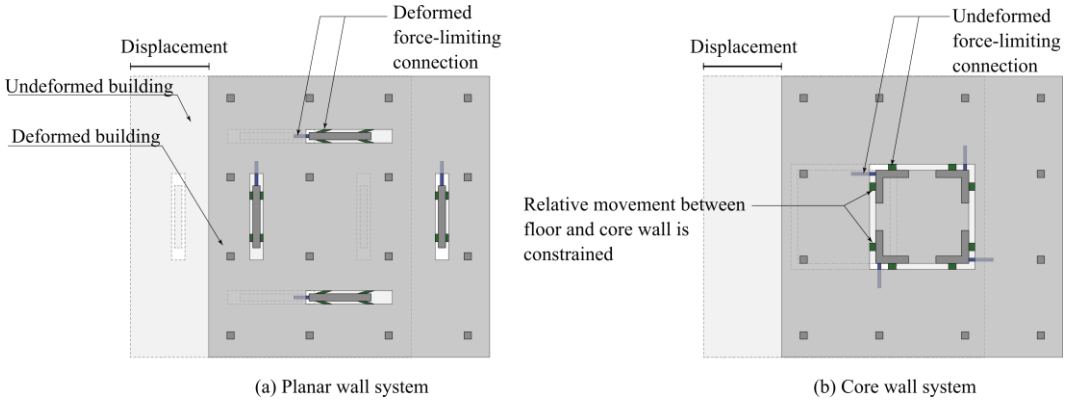


Fig. 2 - In contrast with the planar wall system, the relative movement between the floors and the core wall system is constrained by the rubber bearings. The planar wall system is shown in (a) and the core wall system is shown in (b).

Numerical earthquake simulations are required to understand the effect of the force-displacement response of the force-limiting connections in the seismic response of

earthquake resistant reinforced concrete core wall buildings. This paper presents preliminary results from earthquake numerical simulations of an eighteen-story building model with a reinforced concrete core wall seismic force-resisting system subjected to the scaled ground acceleration record from the 1987 Superstition Hill event. Friction-based force-limiting connections with three types of force-displacement responses are considered between the floors and the core wall. The first type of force-displacement response simulates a friction-based connection with a constant limiting force. A limiting force at a given floor (F_{Lx}) is the force at which the force-limiting connections transition from linear elastic to post-elastic force-displacement response. This force-displacement response is possible using a friction device [14]. The second type of force-displacement response simulates a friction-based connection with linearly varying limiting force. This force-displacement is possible using a friction device in parallel with a linear elastic component that provides positive post-elastic stiffness, similar to the low damping rubber bearings. Adding positive post-elastic stiffness in the force-displacement response potentially reduces the post-elastic deformation demand in the force-limiting connection. The third type of force-displacement response simulates a friction-based connection with discrete variable limiting force. A modified version of the friction devices studied in past research [14] is currently under development to achieve this type of force-displacement response. The force-displacement response of the modified friction device can potentially reduce the post-elastic deformation demand in the force-limiting connection, without the need for low damping rubber bearings. The preliminary seismic responses of the building models with friction-based force-limiting connections of the three types of force-displacement responses are compared with the seismic response of the building model with connections that simulate a monolithic connection between the floors and the core wall.

2. Building model

An eighteen-story core wall structure from Tauberg et al. (2018) [4] is used for the preliminary earthquake numerical simulations. The structure is a typical core wall structure with four L-shaped wall piers connected by coupling beams along the height, as shown in Fig. 3. The typical story height is 3048mm (10ft), the length of the wall is 2743mm (9ft), the aspect ratio of the coupling beam is 3.0 with a length of 2286mm (7.5ft) and a height of 762mm (30in). The slab is 203mm (8in) thick with a 1829mm (6ft) cantilever slab overhang. Twelve gravity columns are located along the edge of the slab with a 9144mm (30ft) distance. The structure is designed for Seismic Design Category (SDC) D_{max} as defined in FEMA P695 [17].

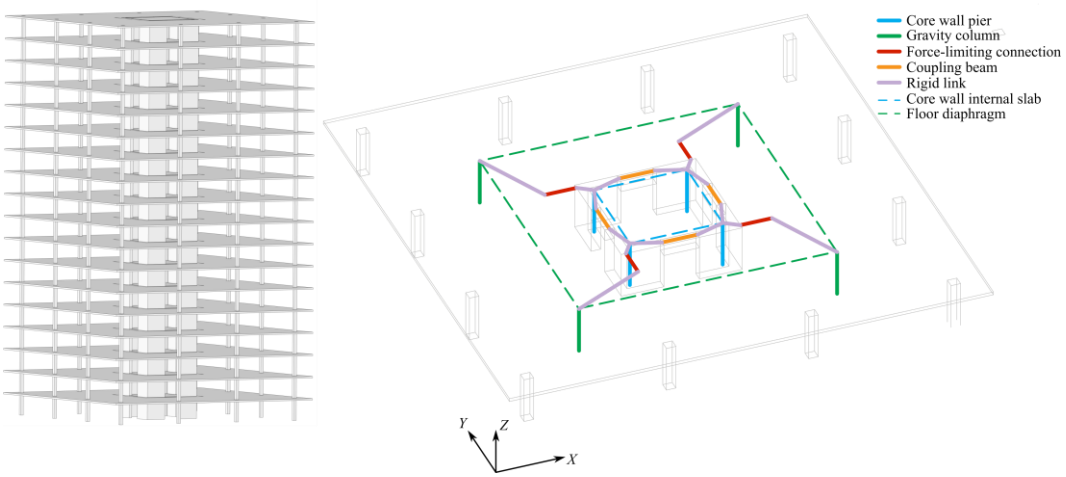


Fig. 3 - Schematic of the building and the elements of a typical floor in the building model.

A numerical model of the eighteen-story core wall structure was developed in Opensees [18]. Fig. 3 shows the elements of a typical floor in the building model of the eighteen-story core wall structure. The four wall piers of the core wall in each story of the building model are simulated using force-based nonlinear elements with fiber sections. The gravity columns are simulated with four linear elastic beam elements. The wall pier elements are connected by a series of elements that simulate the inelastic response of coupling beams. The floor diaphragm and the core wall internal slab are simulated using elements with high in-plane flexural stiffness (i.e., diaphragm action) and low out-of-plane flexural stiffness (i.e., assuming cracked section). The core wall internal slab elements have low axial stiffness to represent voids inside the core whereas the floor diaphragm elements have high axial stiffness (i.e., diaphragm action). Each floor is connected to the core wall using four truss elements that simulate the inelastic force-displacement response of the force-limiting connections. Two elements are used along the global *X* direction and two elements are used along the global *Y* direction.

3. Analysis cases

In this preliminary study, numerical earthquake simulations of the eighteen-story core wall structure are conducted to compare the seismic response of the building model considering four types of connections between the floors and the core wall.

The first analysis case assumes Rigid Elastic (RE) connections to simulate monolithic connections between floors and the core wall. The second analysis case assumes friction-based force-limiting connections with constant limiting force (FD connections), as shown in Fig. 4(a). The third analysis case assumes friction-based force-limiting connections with linearly varying limiting force (FD+RB connections), similar to the ones proposed in Tsampras et al. [11] for buildings with planar walls, as shown in Fig. 4(b). The fourth analysis case assumes friction-based force-limiting connections with discrete variable limiting force (Modified FD connections), as shown in Fig. 4(c).

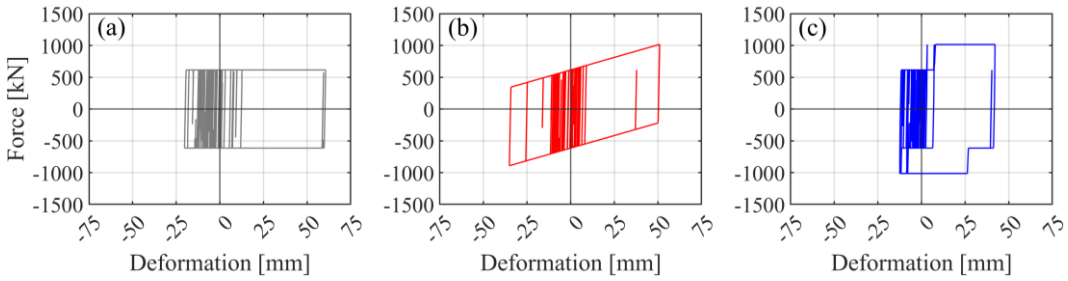


Fig. 4 - Force-displacement response of friction-based force-limiting (a) FD connection, (b) FD+RB connection, and (c) Modified FD connection considered in this preliminary study.

The limiting force at a given floor (F_{Lx}) is computed using a force-based design method [16] and is the same for FD connection, FD+RB connection, and Modified FD connection. The calculated values of F_{Lx} are 614.57 kN (138.16 kips), 722.57 kN (162.44 kips), 902.50 kN (202.89 kips), 1082.43 kN (243.34 kips), and 1262.41 kN (283.80 kips) for floors 1 to 14, floor 15, floor 16, floor 17, and floor 18, respectively.

4. Earthquake ground motion

The earthquake ground motion selected for this preliminary study is from the 1987 Superstition Hill event recorded at Peo Road with a scale factor of 2.0. The scaled ground acceleration of the two horizontal components B-POE270 (H1) and B-POE360 (H2) are shown in Fig. 5(a) and Fig. 5(b), respectively. Fig. 5(c) shows the response spectra of the scaled ground acceleration and the design spectrum. H1 and H2 are applied at the base of the model along the global *X* and *Y* direction, respectively.

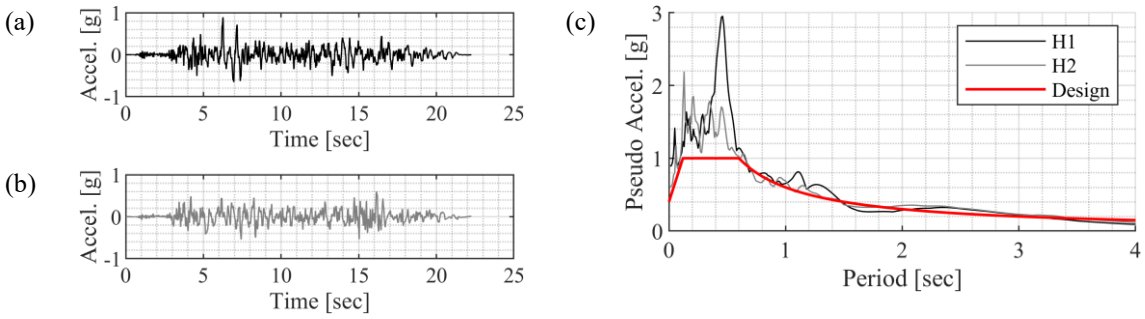


Fig. 5 - Scaled ground acceleration of the two horizontal components (a) B-POE270 (H1) and (b) B-POE360 (H2), and (c) pseudo acceleration response spectra of scaled ground motions and design spectrum with a 5% damping ratio.

5. Numerical simulation results

Fig. 6 shows the maximum responses at each floor or story of the building models subjected to H1 and H2.

The use of force-limiting connections reduces the maximum floor total accelerations compared to the use of RE connections. The use of Modified FD connections results in equal or higher floor total accelerations compared to the use of FD connections and FD+RB connections. At displacements smaller than 50 mm, the Modified FD connection in this preliminary study is designed to result in higher force compared to FD connection and FD+RB connection which explains the observed higher floor total accelerations.

The use of force-limiting connections reduces the maximum shear force at the base of the core wall compared to the use of RE connections. The wall base shear is similar when FD connections, FD+RB connections, or Modified FD connections are considered.

The maximum story drift in the core wall along the global *X* direction is smaller when force-limiting connections are used compared to RE connections. The maximum story drift in the core wall along the global *Y* direction is larger when force-limiting connections are used compared to RE connections. The maximum deformation in the force-limiting connections varies from 25 mm to 75 mm. The Modified FD connections result in the smallest maximum deformation demands in the force-limiting connections.

Fig. 7 shows the time history of the displacement at the top of the core wall divided by the total height of the building (i.e., wall roof drift ratio). The peak wall roof drift ratio is similar in all analysis cases. The maximum residual wall roof drift ratio in the global *X* direction is reduced approximately by 50% when force-limiting connections are used compared to when RE connections are used. The maximum residual wall drift ratio in the global *Y* direction is approximately 55% larger when force-limiting connections are used compared to when RE connections are used.

6. Conclusions

The preliminary study showed that the use of force-limiting connections between floors and a core wall can improve the seismic response of the eighteen-story core wall building. A force-limiting connection with the force-displacement response of the Modified FD can be used in the eighteen-story core wall building to potentially limit the floor total accelerations and the core wall base shear while reducing the maximum deformation demand in the force-limiting connection.

Further numerical studies are required to determine the design of the Modified FD force-limiting connection that will result in improved seismic performance of the eighteen-story core wall building considering the effect of the variability in the ground motion

characteristics. Further numerical studies will also assist the development of the physical embodiment of the Modified FD force-limiting connection. Experimental tests are required to validate the force-displacement response of the Modified FD force-limiting connection and to validate that the three-dimensional kinematic requirements between the floors and the core wall can be accommodated.

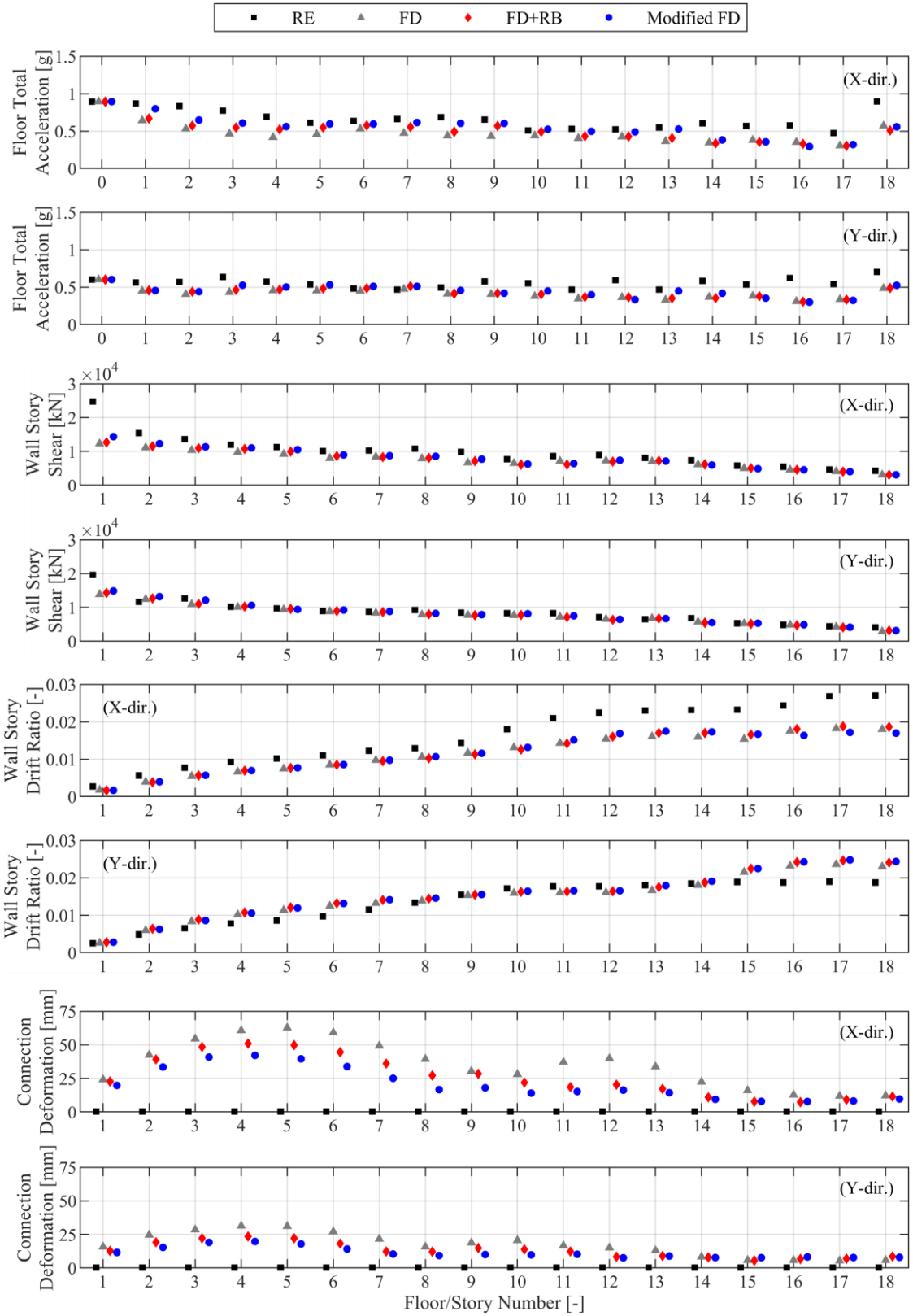


Fig. 6 - Maximum responses of the building models.

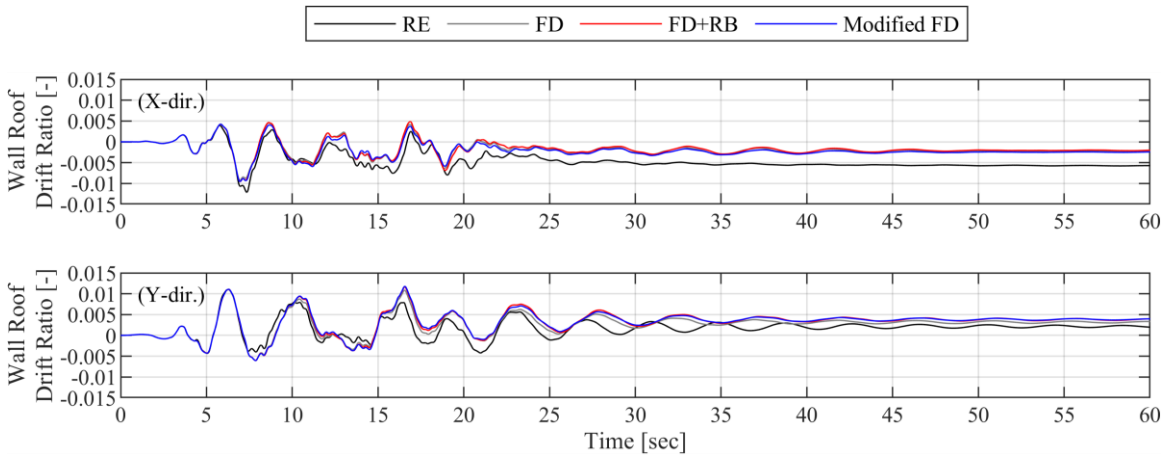


Fig. 7 - Time histories of the wall roof drift ratio.

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