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REUSABLE FORCE-LIMITING CONNECTION WITH VARIABLE FRICTION FORCE FOR HIGH-PERFORMANCE BUILDINGS

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ABSTRACT

This paper presents a reusable force-limiting deformable connection with a discrete variable friction force for high-performance reinforced concrete core wall buildings. The connection is designed to limit the seismic-induced horizontal forces transferred from the floors to the core wall piers, control the relative displacement between the floors and the core wall piers, and accommodate the three-dimensional kinematics expected between the floors and the core wall piers. The connection is simple to manufacture and assemble. It is designed to withstand multiple earthquake events without damage. The components and the assembly of the friction-based force-limiting deformable connection are presented. The expected kinematics and the expected force-displacement response are discussed. Preliminary numerical simulation results are used to validate the expected cyclic force-displacement response of the connection. Limited results from preliminary earthquake numerical simulations of an eighteen-story reinforced concrete core wall building model are discussed. The numerical simulation results show that it is possible to design a reusable force-limiting connection with friction force that increases at target design displacement levels to limit the magnitude of the seismic responses in the eighteen-story reinforced concrete core wall building model and accommodate the three-dimensional kinematics expected between the floors and the core wall piers.

Keywords: friction-based force-limiting connection; structural component reusability; high-performance buildings; reinforced concrete core wall structure

INTRODUCTION

Practical force-limiting deformable connections between the floors and the vertical elements of seismic force-resisting systems (e.g., reinforced concrete planar structural walls and self-centering concentrically-braced steel frames) have been developed (Zhang et al. 2014; Tsampras 2016; Tsampras et al. 2016, 2017, 2018; Zhang et al. 2018; Tsampras and Sause 2022). Figure 1(a) shows a schematic example of a building with reinforced concrete planar structural walls and force-limiting connections. The force-limiting connections consist of buckling-restrained braces or friction devices and low-damping rubber bearings. The force-limiting connections allow relative displacement between the floors and the seismic force-resisting system and transfer the seismic-induced horizontal forces from the floors to the seismic force-resisting system. The compressive stiffness of the rubber bearings ensures the out-of-plane stability of the structural walls. The shear stiffness of the rubber bearings provides post-elastic stiffness to the force-limiting connections required to limit the inelastic deformation demands between the floors and the planar structural walls. Figure 1(b) shows a sketch of the friction device developed and tested by Tsampras et al. (2018). Results from earthquake numerical simulations showed that buildings with planar reinforced concrete structural walls and force-limiting connections have reduced magnitude and dispersion in the force and acceleration responses compared to conventional buildings (Tsampras et al. 2016, 2017, 2018).

Tall buildings commonly use a core wall or multiple core walls instead of planar structural walls to resist the seismic-induced horizontal forces. Lee et al. (2022) conducted a preliminary study to assess the seismic response of an eighteen-story building with a reinforced concrete core wall and friction-based force-limiting connections between the floors and the core wall piers. Lee et al. (2022) showed that it is not possible to use low-damping rubber bearings to add post-elastic stiffness in force-limiting

connections between floors and core wall piers since the compressive stiffness of the rubber bearings practically restrains the horizontal displacement of the floors relative to the core wall piers. To eliminate restraining the horizontal displacement of the floors relative to the core wall piers, Lee et al. (2022) assumed a modified force-limiting connection that consists of a friction device without low-damping rubber bearings. The force of the assumed modified friction-based force-limiting connection was designed to increase at predetermined displacement values resulting to a discrete variable friction force. The discrete variable friction force in the assumed modified friction-based force-limiting connection resulted in a non-zero effective post-elastic stiffness. Results from the preliminary earthquake numerical simulations of the eighteen-story core wall building model showed that it is possible to use the assumed modified friction-based force-limiting connection with discrete variable friction force to limit the magnitude of the force and acceleration responses while maintaining reasonable force-limiting connection deformation demand.

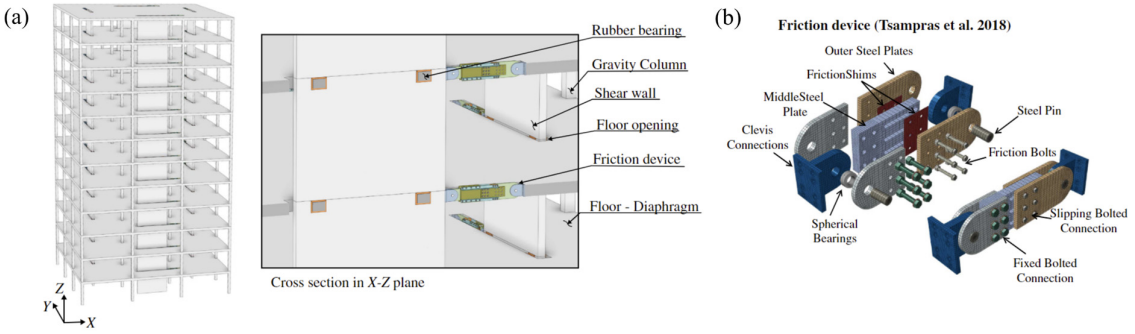


Figure 1 (a) Schematic example of a building with reinforced concrete planar structural walls and force-limiting connections. (b) Sketch of the friction device developed by Tsampras et al. (2018).

In this paper, the preliminary physical embodiment of a reusable force-limiting connection with discrete variable friction force is presented. The connection is termed Modified Friction Device (Modified FD) in this paper. The term Modified is used to indicate that a non-zero effective post-elastic stiffness is achieved through the discrete variable friction force. The components and the assembly of the Modified FD are discussed. Results from preliminary numerical simulations are used to validate the expected kinematics and the expected force-displacement response of the Modified FD. Limited preliminary earthquake numerical simulation results are used to compare the seismic response of an eighteen-story reinforced concrete core wall building model with Modified FDs with the seismic response of the building model with assumed monolithic connections between the floors and the core wall piers.

REUSABLE FRICTION-BASED FORCE-LIMITING CONNECTION

Components

Figure 2 shows a sketch of the components, the exploded view, the assembly, and the front view of the Modified FD. The Modified FD consists of an internal plate, two external plates, four curved edge plates, four rectangular friction shims, four curved edge friction shims, ten structural bolts with flat washers and nuts, and a spherical bearing. The end clevises used to attach a Modified FD on a floor and a core wall pier are not shown in Figure 2. Pretension load is applied to the bolts to clamp the external plates, the curved edge plates, the friction shims, and the internal plate. The bolted components create the assembly of the Modified FD. Friction interfaces are established in the contact surfaces between the internal plate and the friction shims. The rectangular friction shims are not expected to move relative to the external plates. The curved edge friction shims are not expected to move relative to the curved edge plates. The slots in the internal plate allow the longitudinal motion of the friction shims, the external plates, and the curved edge plates relative to the internal plate. The curved edge plates and the curved edge friction shims are positioned within slots in the external plates, and they are not expected to move relative to the internal plate until the curved edges of the friction shims and the plates are in contact with

the external plates. The gap between the curved edge plates and the short slots in the external plates is termed D_1, and the gap between the curved edge plates and the long slots in the external plates is termed D_2, as shown in Figure 2(d). The spherical bearings at the ends of the Modified FD allow the rotational motions and restrain the translational motions within the plane of the plates. As a result, the Modified FD is expected to develop axial load along its longitudinal direction and zero moments at the ends.

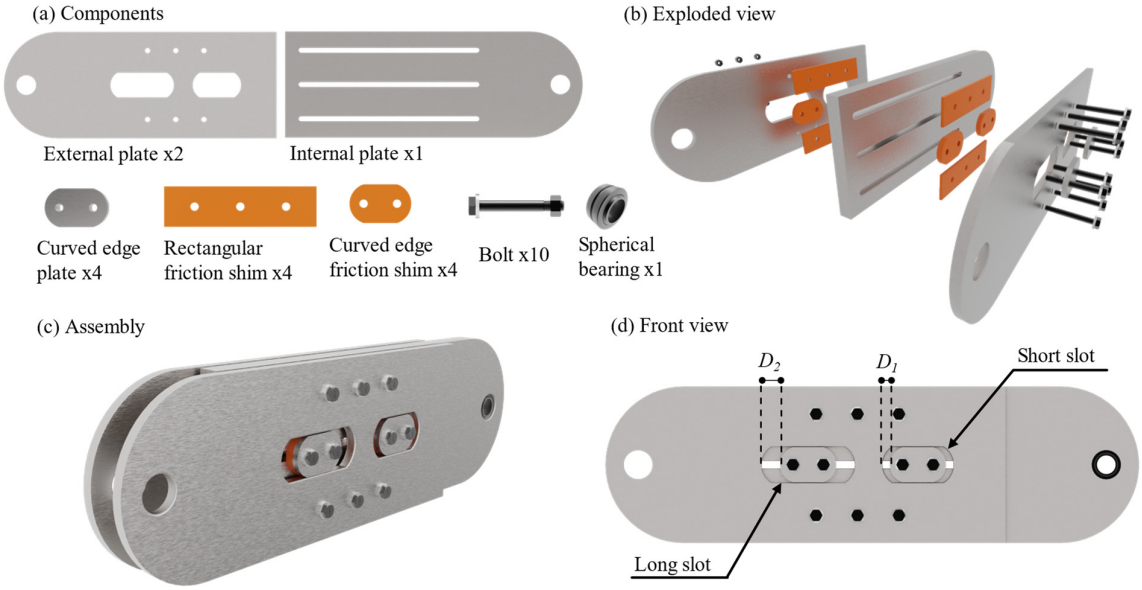


Figure 2 Modified FD (a) components, (b) exploded view, (c) assembly, and (d) front view with initial gap dimensions D1 and D2 between the curved edge plates and the slots in the external plates.

Expected kinematics and expected force-displacement response

Figure 3 shows the expected kinematics and the expected force-displacement response of the Modified FD. The term "expected" is used in this paper because the kinematics and force-displacement response have not been validated through experimental testing yet. The following parameters define the expected kinematics and the expected force-displacement response: the initial gap between the curved edge plates and the short slot in each external plate, D_1; the initial gap between the curved edge plates and the long slot in each external plate, D_2; the friction force generated by the frictional interface between the internal plate and the rectangular friction shims, F_1; the friction force generated by the frictional interface between the internal plate and the curved edge friction shims in the short slot of the external plates, F_2; the friction force generated by the frictional interface between the internal plate and the curved edge friction shims in the long slot of the external plates, F_3; and the values of the elastic stiffnesses K_1, K_2, and K_3. Six phases define the expected kinematics of the Modified FD that result to the expected force-displacement response. The expected kinematics and the expected force-displacement response described below assume that the translational motion of the internal plate is restrained (i.e., pinned condition at the end of the internal plate) and that a displacement along the longitudinal direction of the Modified FD is applied at the ends of the external plates. Positive displacement results in axial compression in the Modified FD and negative displacement results in axial tension in the Modified FD. The following section presents the six phases. In this paper, the discussion of the kinematics in the six phases ignores the elastic deformations F_1/K_1, F_2/K_2, and F_3/K_3 assuming $K_1=K_2=K_3 \cong \infty$. Thus, the rigid body kinematics of the Modified FD components are considered.

Phase 1 – Sliding along the positive direction of motion with friction force F_1: The increase of the imposed displacement in the Modified FD results in increasing force with stiffness K_1. When the force in the Modified FD becomes equal to F_1 the rectangular friction shims and the external plates start moving relative to the internal plate. The sliding at the frictional interface between the internal plate and the rectangular friction shims results to F_1. F_1 can be estimated using Coulomb theory, $F_1 = n_{s1}N_1\mu_{s1}$,

where $n_{s1} = 2$ is the number of friction interfaces; N_1 is the total load from the six bolts acting normal to the friction interfaces between the rectangular friction shims and the internal plate; μ_{s1} is the coefficient of friction in the friction interfaces between the rectangular friction shims and the internal plate.

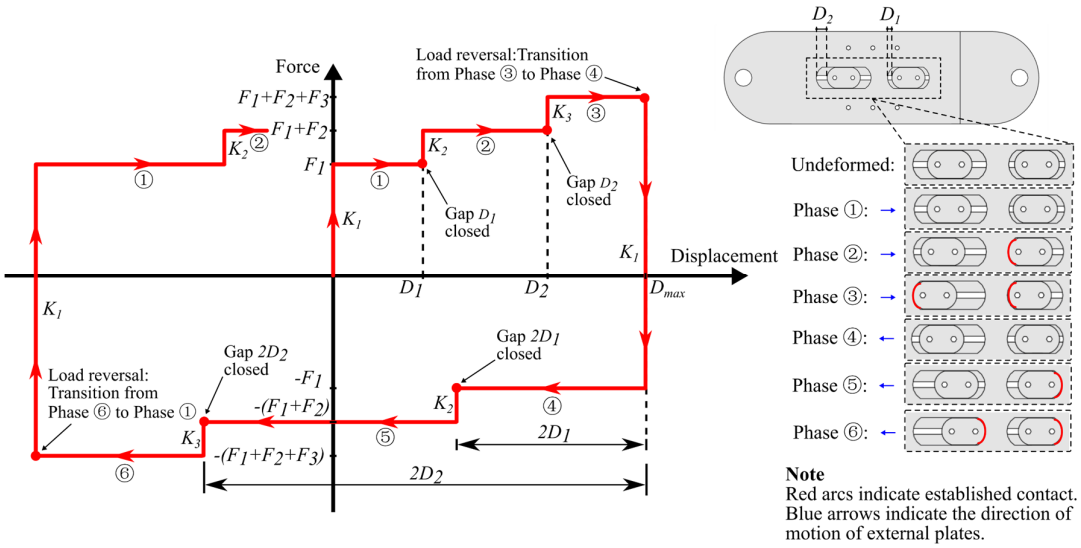


Figure 3 Expected kinematics and expected force-displacement response of Modified FD.

Phase 2 – Sliding along the positive direction of motion with friction force F_1+F_2: Assuming that the elastic deformations are negligible, once the value of displacement reaches D_1, the external plates contact the curved edge plates located in the short slots. As the displacement in the Modified FD increases, the force in the Modified FD increases with stiffness K_2. When the force in the Modified FD becomes equal to F_1+F_2, the curved edge plates and the curved edge friction shims in the short slots start moving relative to the internal plate. The sliding at the frictional interface between the internal plate and the curved edge friction shims in the short slots results to F_2. F_2 can be estimated using Coulomb theory, $F_2 = n_{s2}N_2\mu_{s2}$, where $n_{s2} = 2$ is the number of friction interfaces; N_2 is the total load from the two bolts acting normal to the friction interfaces between the curved edge friction shims in the short slots and the internal plate; μ_{s2} is the coefficient of friction in the friction interfaces between the curved edge friction shims in the short slot and the internal plate. The total force in the Modified FD during this phase is F_1+F_2.

Phase 3 – Sliding along the positive direction of motion with friction force $F_1+F_2+F_3$: Assuming that the elastic deformations are negligible, once the value of the displacement reaches D_2, the external plates contact the curved edge plates located in the long slots. As the displacement in the Modified FD increases, the force in the Modified FD increases with stiffness K_3. When the force in the Modified FD becomes equal to $F_1+F_2+F_3$, the curved edge plates and the curved edge friction shims in the long slots start moving relative to the internal plate. The sliding at the frictional interface between the internal plate and the curved edge friction shims in the long slots results to F_3. F_3 can be estimated using Coulomb theory, $F_3 = n_{s3}N_3\mu_{s3}$, where $n_{s3} = 2$ is the number of friction interfaces; N_3 is the total load from the two bolts acting normal to the friction interfaces between the curved edge friction shims in the long slot and the internal plate; μ_{s3} is the coefficient of friction in the friction interfaces between the curved edge friction shims in the long slots and the internal plate. The total force in the Modified FD during this phase is $F_1+F_2+F_3$. The motion continues until the Modified FD reaches the maximum imposed displacement D_{max}.

Phase 4 – Sliding along the negative direction of motion with friction force $-F_1$: The reversal of the imposed displacement reduces the force in the Modified FD with elastic stiffness K_1. When the force in the Modified FD becomes equal to $-F_1$ the external plates start moving relative to the internal plate along the negative direction. The curved edge friction shims are not expected to move relative to the internal

plate during this phase. The rectangular friction shims and the external plates move relative to the internal plate resulting to a force with magnitude equal to F_1.

Phase 5 – Sliding along the negative direction of motion with friction force $-(F_1+F_2)$: Assuming that the elastic deformations are negligible, once the value of displacement reaches D_{max} - $2D_1$, the external plates contact the curved edge plates located in the short slots. As the displacement in the Modified FD decreases, the force in the Modified FD decreases with stiffness K_2. When the force in the Modified FD becomes equal to $-(F_1+F_2)$, the curved edge plates and the curved edge friction shims in the short slots start moving relative to the internal plate. The sliding at the frictional interface between the internal plate and the curved edge friction shims in the short slots results to a force with magnitude equal to F_2. The total force in the Modified FD during this phase is $-(F_1+F_2)$.

Phase 6 – Sliding along the negative direction of motion with friction force $-(F_1+F_2+F_3)$: Assuming that the elastic deformations are negligible, once the value of displacement reaches D_{max} - $2D_2$, the external plates contact the curved edge plates located in the long slots. As the displacement in the Modified FD decreases, the force in the Modified FD decreases with stiffness K_3. When the force in the Modified FD becomes equal to $-(F_1+F_2+F_3)$, the curved edge plates and the curved edge friction shims in the long slots start moving relative to the internal plate. The sliding at the frictional interface between the internal plate and the curved edge friction shims in the long slots results to a force with magnitude equal to F_3. The total force in the Modified FD during this phase is $-(F_1+F_2+F_3)$.

Preliminary numerical force-displacement response

The development of the Modified FD requires experimental characterization of its kinematics and its force-displacement response. However, finite element analysis can be used for the preliminary assessment and the rapid digital prototyping of the Modified FD.

Preliminary numerical simulations with two types of finite element models are conducted to validate numerically the expected force-displacement response of the Modified FD. The first model uses solid finite elements, and it is termed *Solid Model* in this paper. The Solid Model simulates explicitly the internal plate, the external plates, the curved edge plates, and the friction shims. The Solid Model simulates explicitly the contact interfaces between the modeled components of the Modified FD. The second model simulates the expected force-displacement response of the Modified FD at a macroscopic level using a truss finite element model. The second model is termed *Truss Model* in this paper. The Truss Model is used to simulate the force-displacement response of the Modified FD in earthquake numerical simulations of buildings. The Solid Model and the Truss model assume D_1 = 2 cm (i.e., 0.8 in.); D_2 = 5 cm (i.e., 2 in.); F_1 = 596 kN (i.e., 134 kips). $F_2 = F_3$ = 222.4 kN (i.e., 50 kips). A pseudo-static sinusoidal axial displacement loading history is applied to the Modified FD models. The maximum applied displacement is equal to 6.35 cm (i.e., 2.5 in). Figure 4 shows the force-displacement response computed from the numerical simulations. The Solid Model confirmed the expected kinematics and the expected force-displacement response in the Modified FD. The Truss Model approximated reasonably well the force-displacement response computed using the Solid Model.

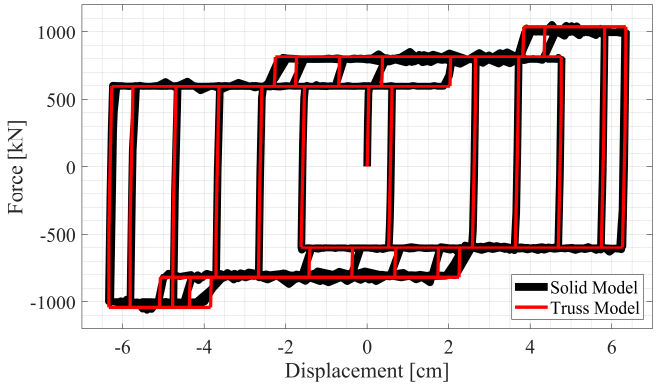


Figure 4 Preliminary numerical simulation results.

PRELIMINARY EARTHQUAKE NUMERICAL SIMULATIONS

Preliminary earthquake numerical simulations of an eighteen-story reinforced concrete core wall building are conducted to compare the seismic response of a building model with Modified FDs to the seismic response of a building model with monolithic connections between the floors and the core wall piers. This study uses a building model developed by Lee et al. (2022).

The building model was subjected to a ground motion recorded at Shin-Osaka station during the 1995 earthquake in Kobe, Japan. Figure 5(a) and Figure 5(b) show the scaled ground acceleration time histories of the two horizontal components SHI000 (H1) and SHI090 (H2), respectively. Figure 5(c) shows the response spectra of the scaled ground motion and the design spectrum. H1 and H2 are applied at the base of the model along the global X and Y direction, respectively.

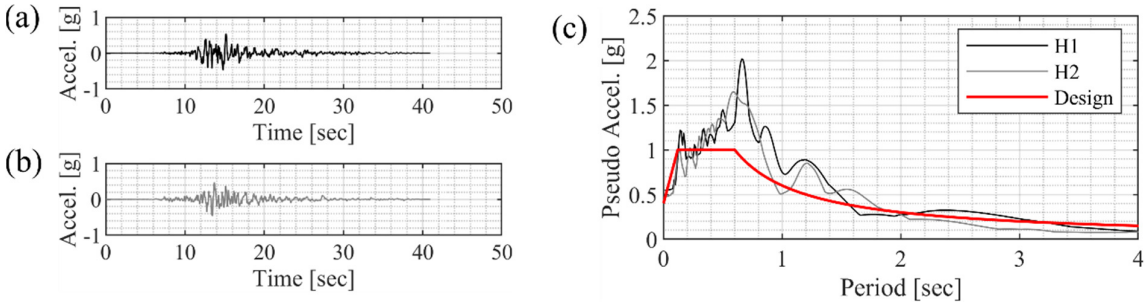


Figure 5 Scaled ground acceleration of the two horizontal components (a) SHI000 (H1) and (b) SHI090 (H2), and (c) pseudo acceleration response spectra of scaled ground motions and design spectrum with a 5% damping ratio.

Figure 6 shows the time history response of the roof total acceleration of the building model with the monolithic connections and with the Modified FD. The use of the Modified FD reduces the roof total acceleration. There is a 38% and 27% reduction in the peak total acceleration in global X-direction and in global Y-direction, respectively.

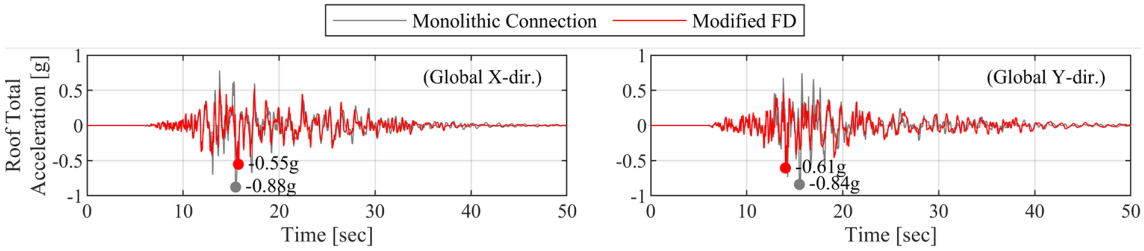


Figure 6 Time history response of the roof total acceleration.

Figure 7 shows the distribution of the strain demand at the base section of the core wall piers at the time when the moment reaction is equal to the absolute maximum value of the moment reactions from the four core wall piers. The use of the Modified FD reduced the absolute values of the maximum and minimum strain in the core wall base section by approximately 49% and 54%, respectively, compared to the use of monolithic connections. The reduction in the magnitude of the strain demands indicates a potential reduction in the expected structural damage in the core wall piers.

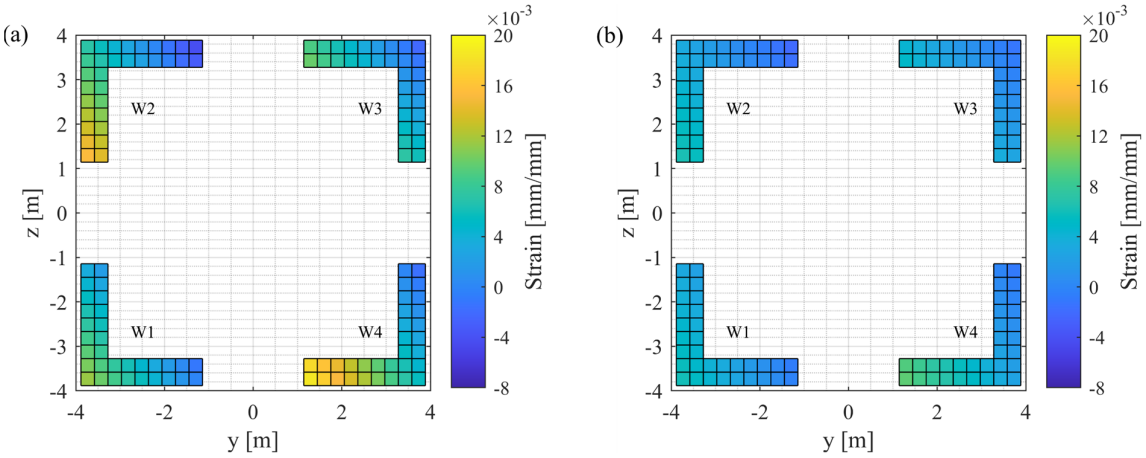


Figure 7 Strain distribution at the base of the core wall piers for the case with (a) monolithic connections and (b) Modified FDs.

CONCLUSIONS

This paper presented a reusable force-limiting deformable connection with a discrete variable friction force for high-performance reinforced concrete core wall buildings. The force-limiting connection was termed Modified FD. The Modified FD aims to limit the seismic-induced horizontal forces transferred from the floors to the core wall piers of reinforced concrete core wall buildings, control the relative displacement between the floors and the core wall piers, and accommodate the three-dimensional kinematics expected between the floors and the core wall piers. The expected kinematics and the expected force-displacement response of the Modified FD were discussed. Preliminary finite element analyses conducted for the preliminary assessment of the kinematics and the force-displacement response of the Modified FD. Limited earthquake numerical simulation results show that the use of Modified FDs between the floors and the core wall piers in an eighteen-story reinforced concrete core wall building model reduces the magnitude of the roof total acceleration and the strain at the core wall base compared to a model of a conventional core wall building. The results indicated that the use of the Modified FD could potentially limit the residual damage in core wall structures.

Parametric earthquake numerical simulations are required to determine the values of the design parameters of the Modified FD that result to acceptable seismic performance of core wall buildings. Experimental characterization of the kinematics and the force-displacement response of the Modified FD is required.

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