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Application of frictional sliding fuse in infilled frames, fuse adjustment and influencing parameters

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Abstract. An experimental investigation is conducted here to study the effects of applying frictional sliding fuses (FSF) in concrete infilled steel frames. Firstly, the influences of some parameters on the behavior of the sliding fuse are studied: Methods of adjusting the FSF for a certain sliding strength are explained and influences of time duration, welding and corrosion are investigated as well. Based on the results, time duration does not significantly affect the FSF, however influences of welding and corrosion of the constitutive plates are substantial. Then, the results of testing two 1/3 scale single-storey single-bay concrete infilled steel frames having FSF are presented. The specimens were similar, except for different regulations of their fuses, tested by displacement controlled cyclic loading. The results demonstrate that applying FSF improves infill behaviors in both perpendicular directions. The infilled frames with FSF have more appropriate hysteresis cycles, higher ductility, much lower deteriorations in strength and stiffness in comparison with regular ones. Consequently, the infills, provided with FSF, can be regarded as an engineered element, however, special consideration should be taken into the affecting parameters of their fuses.

Keywords: steel frame; fibrous concrete; cyclic loads; ductility; retrofitting; damping; frictional sliding fuse; engineered infill.

1. Introduction

Infills are commonly used in low rise buildings of urban centers. Although considered non-structural elements, yet under seismic excitation, infill walls tend to interact with the surrounding frame and may result in different failure modes both to the frame and to the infill wall (El-Dakhakhni *et al.* 2004). It is proved that they have significant effects on both the strength and stiffness of buildings and should not be ignored in the analysis and design of structures (Abdel El Razik *et al.* 2006, FEMA-306 1998). Ignoring the frame-wall interaction is not always on the safe side, specially in seismic prone areas. The presence of infills can also have a significant effect on the energy dissipation capacity (Decanini *et al.* 2002).

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Some methods of structural seismic upgrading such as the addition of new frames or shear walls, have been proved to be impractical, they have been either too costly or restricted in use to certain types of structures. Structural frames with infill panels are typically providing an efficient method for bracing buildings (Jung *et al.* 2005). Thus the necessity of strengthening masonry infills has been recognized for a long time to raise the lateral strength of buildings.

The majority of researches on infilled frames conducted to date has been concentrating on the behavior infills of different types, including the influences of retrofitting or strengthening techniques, such as: using shear connectors (studs) at the interface of frames and infills (Saari *et al.* 2004), concrete covers (Moghadam *et al.* 2004), ferrocement (Zarnic *et al.* 1986), horizontal reinforcement (El Gawady *et al.* 2004), RC bond beam at mid-height of panel (Bertero *et al.* 1983) and Polymer composites (El Dakhakhni 2002). Infill walls, even retrofitted by one of the abovementioned techniques, are usually brittle with little or no ductility, and do not lead to an engineered infill panel. Among more than 60 years of researches on infill panels, a few ones, such as studies of Crisafulli *et al.* (2000), Sahota *et al.* (2001), Aref *et al.* (2003) and El-Dakhakhni *et al.* (2004), focused on how to achieve engineered infilled frames.

An engineered infilled frame is supposed to have sufficient ductility, comparable to other structural elements, well defined failure modes, stable postpeak behavior, low deterioration in stiffness and strength, high stability in out-of-plane direction during earthquakes. It should also be capable of being designed for a desired stiffness and strength.

To achieve an engineered infilled frame and specially to raise the ductility, Mohammadi (2007a), provided infills with two sliding surfaces. Two infilled frames with similar three ply infills-composed of 10 cm brick, 5 cm reinforced concrete and 10 cm brick, were tested in his research, in one of which two sliding surfaces were provided, shown in Fig. 1. The specimen with the sliding surfaces had two times higher deformation capacity. In addition, neither infill cracking nor corner crushing observed in the wall during the testing of this specimen up to 7.13% storey drift as shown in Fig. 1.

To achieve a better engineered infilled frame, the infill and the fuse are improved here to avoid deficiencies of the previous research (Mohammadi 2007a). In this regard, an experimental study is

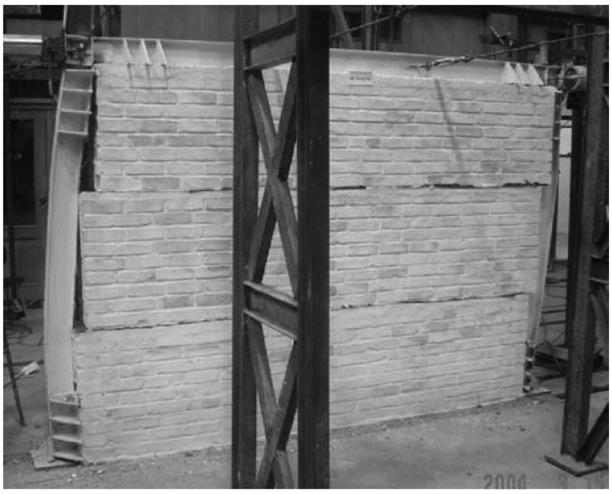


Fig. 1 Deformation of the specimen, with sliding surfaces, at the drift of 7.13%

conducted to study the effects of some influencing parameters on the behavior of the frictional sliding fuses. For this, the effects of three parameters, including time, welding and corrosion were considered and the obtained results are presented. In addition method of regulating FSF is explained.

Subsequently, two concrete infilled steel frame specimens having FSFS at their mid-heights were tested. According to the results, the engineered infill wall with the proposed configuration of this paper has high ductility, great damping ratio, and high stability in out of plane direction. Besides it is capable of being designed for a definite strength through FSF regulation.

2. Frictional Sliding Fuse (FSF)

In this study, the frictional Sliding Fuse (FSF) is composed of three steel plates, shown in Fig. 2: Two plates (A and B) are connected to each other by welding, on which the third one (plate C) can slide. To supply sufficient spacing for the bolt head (that move during fuse sliding), some elements with rectangular section, are applied between plates A and B as shown in Fig. 2. Plate C has normal holes but plate B is supplied by longitudinal slots, shown in Fig. 2, to restrain transversal sliding and improve wall stability in out of plane direction.

Six high strength N20 bolts connect plates B & C, which are used to regulate the FSF sliding strength. Seven L60 × 60 × 6 mm (each 50 mm) are also used on each of outer plates, A and C, to transfer shear forces.

2.1 Calibration fuses

To study the relation between FSF sliding strength and the bolts fastening torques, some calibration fuses were tested, by which the influence of duration, welding and corrosion are studied as well.

The calibration fuse, with similar mechanism of the main fuses, was composed of two plates (with 6 mm thickness), fastened by 2 pre-tensioned bolts by the same torque, shown in Fig. 3(a). The sliding strength of the calibration fuses were obtained by tensile loading tests, shown in Fig. 3(b). Force-displacement diagrams of testing calibration fuses are shown in Fig. 4(a), in which the bolt fastening torque of each specimen is shown by "T = ". Fig. 4(b) depicts the results briefly and shows that the fuse sliding strength and bolts' torques rise accordingly.

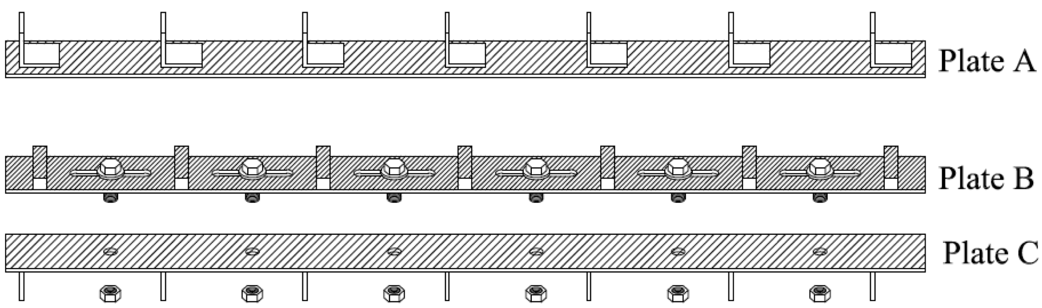
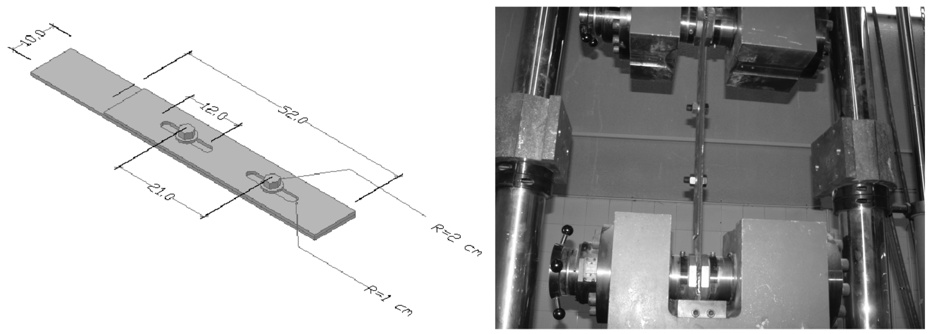
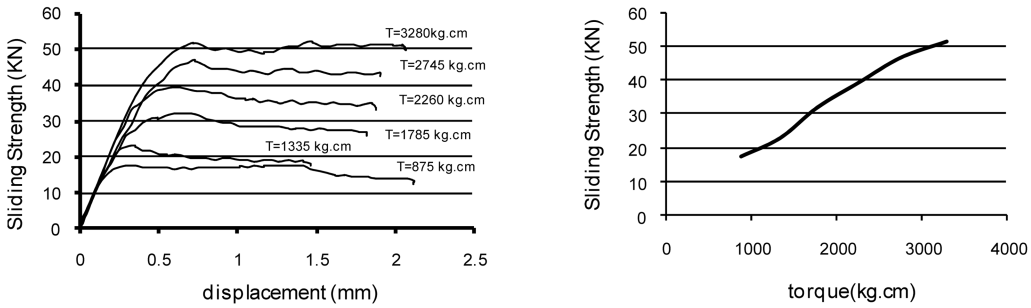


Fig. 2 Detail of a Frictional Sliding Fuse (FSF)



(a) Configuration (all dimensions are in mm) (b) Picture of a tensile testing

Fig. 3 A calibration fuse



(a) Test results (b) Summary of calibration fuse tests

Fig. 4 Results of tensile tests on calibration fuses

The FSF can be similarly regulated for a desired sliding load, based on the results of Fig. 4(b), regarding that the sliding strength of the FSF (having 6 bolts) is triple of the calibration fuse (with 2 bolts), if the same torque are applied to bolts of main and calibration fuses.

3. Influencing parameters of FSF

Regarding the frictional nature of the FSF, many parameters may affect the fuse behavior (including pre-tensioned loads of the bolts that explained previously). Among them influences of time duration, welding and corrosion of the constitutive plates are investigated here by experimental testing.

3.1 Time duration

Time between fuse installation and earthquake occurrence may be long, during which the fuse should remain adjusted. However, this time may change the pre-tensioned load of the bolts, caused by plastic deformation of their threads. In this regard, three calibration fuses, adapted for different sliding strengths, placed in lab for two month (the maximum time duration that was possible in this project). The sliding strengths of these fuses were measured and compared with ones of the fuses

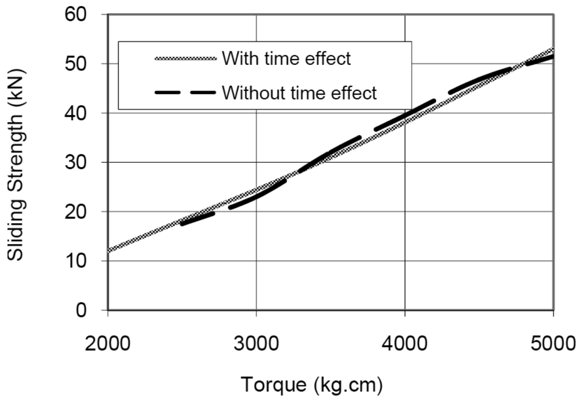


Fig. 5 Effect of two month duration on the Sliding strength of the FSF

that were regulated just before testing. The results are shown in Fig. 5, in which the sliding strength is plotted via the fastening torque of the bolts. According to this figure, the deviation of the fuse sliding strength in time is insignificant.

3.2 Welding

One of the advantages of the engineered infill panels is that they can be re-adjusted for a new strength by re-adapting their fuse bolts. This is a valuable capability to comply the building for new seismic code requirements. In this regard, the nut should be welded to Plate C of the fuse, Fig. 2, and a new torque be applied to the bolt heads, through the gap between plates A & B. To investigate effects of the welding on the fuse sliding strength, six experimental investigations were conducted in two groups. In the first one, the plates of the calibration fuse is separated before welding the nut to the plate. In the second group, the welding is performed while the calibration fuse is assembled. The results are compared with ones of a normal calibration fuse, shown in Fig. 6. As depicted in this figure, the welding raises the sliding strength of the calibration fuse of both groups of specimens. The rise is higher when the welding is done after installation of the fuse plates.

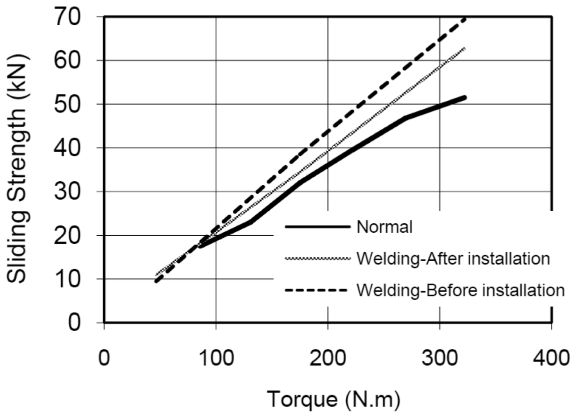
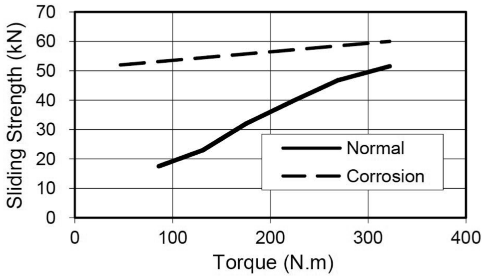


Fig. 6 Influence of welding on the behavior of calibration fuses

(a) A corroded specimen



(b) Behavior of the corroded specimen

Fig. 7 Influence of corrosion on the behavior of calibration fuses

3.3 Corrosion

Two calibration fuse specimens were tested to consider corrosion, caused by environmental parameters, e.g., humidity and temperature. To accelerate corrosion, the specimens were put in salt water having lime for two months. A corroded specimen is shown in Fig. 7(a). According to the results, shown in Fig. 7(b), behavior of the fuse is highly affected by corrosion. Therefore, a cathode protection should be provided for fuses made of steel plates, or other materials that are resistant to corrosion should be used.

4. Engineered infilled frames, having FSF

Two 1/3 scale (1.5 × 1.0 m) single-storey single-bay steel frames were tested under cyclic lateral in-plane loading. Each specimen has a Frictional Sliding Fuses (FSF) at the infill mid-height. One of the specimens was also loaded in out of plane direction after failure by in plane loading.

The cryptogram for identification of each specimen is *EIF-i*, where *EIF* stands for Engineered Infilled Frame and *i* is an index to identify the number of wall sequentially tested. Infills of the specimens, EIF-1 and EIF-2, were composed of 74 mm thick reinforced fibrous concrete with 1% standard steel angular fibers. They had standard compressive strengths of 17 and 15 MPa, respectively. The infills had also a reinforced mesh of Φ8 mm bars with 15 cm horizontal and 10 cm vertical spacings. Modulus of elasticity, yielding and ultimate strengths of the bars were measured as 171.67 GPa, 314 MPa and 581 MPa, respectively. The infill was (30 mm) chamfered in its corners near the fuse, shown in Fig. 8, in order to prevent infill from contacting the frame, which may produce a shear dominated area in columns.

Seven shear connectors (each a 50 mm of L60 × 60 × 6 mm) with a spacing of 18 cm were used on beams and each side of the *FSF* to transfer shear forces, shown in Fig. 8.

The specimens EIF-1 and EIF-2 have the same features, regarding the frame, infill and dimensions, except for their fuses that were regulated for sliding strength of 51 and 73 kN respectively. For regulation, torques of 87.5 and 140.0 N.m were applied to each bolt of their fuses, respectively, based on the results of calibration fuse testing, shown in Fig. 4.

Beams and columns of the specimens are made of single standard IPE-120 and IPE-140, respectively, shown in Fig. 8, with the measured average modulus of elasticity, yielding strength and ultimate strength of 192.7 GPa, 311 MPa and 433 MPa, respectively, based on ASTM, E 8M-89b (2000). The beam-column connection is rigid.

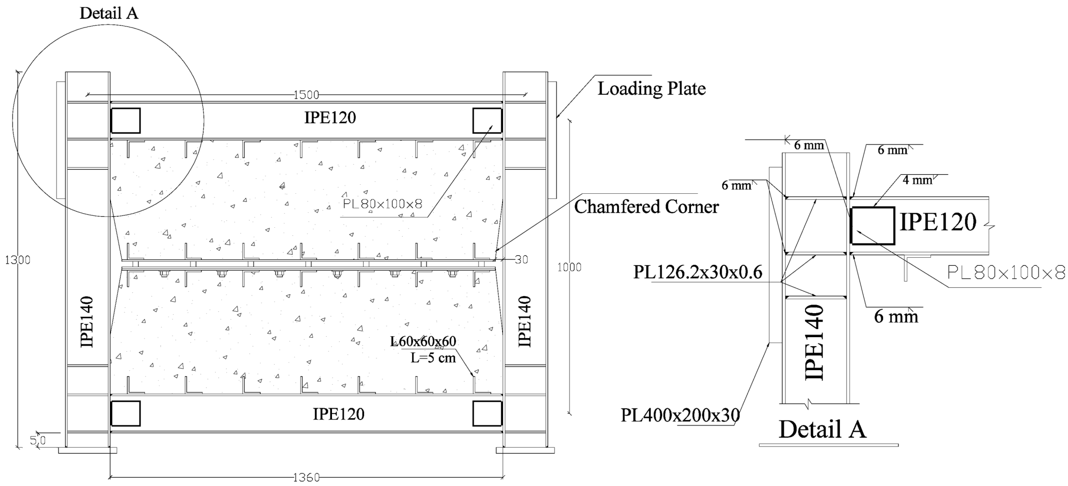


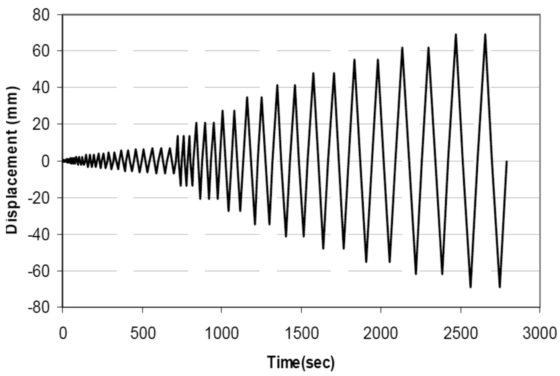
Fig. 8 Details of the specimens' frame (all dimensions in mm)

5. Displacement protocol and instrumentation of EIFs

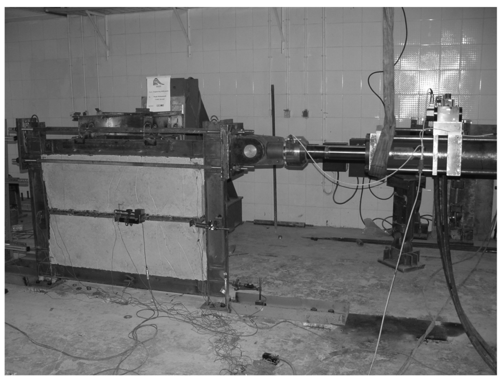
A displacement controlled loading was applied to the specimens, EIF-1 and EIF-2. Amplitudes, number of cycles and loading rates, shown in Fig. 9(a), were calculated in such a way to detect FSF sliding and frame yielding, based on ATC-24 criteria (1992). The specimens were loaded only in longitudinal direction without applying any vertical loads.

A hydraulic jack, installed in one side of the specimen, applied the loads through loading plates, shown in Fig. 9(b): compressive loads were applied directly to the specimen, and tensile forces were applied through four Φ24 rods connecting to a loading plate on the opposite side.

To prevent out of plane movements of the frame, lateral supports were provided at two points of the upper beam.



(a) Displacement history



(b) Loading setup

Fig. 9 Loading setup and displacement history of the specimens

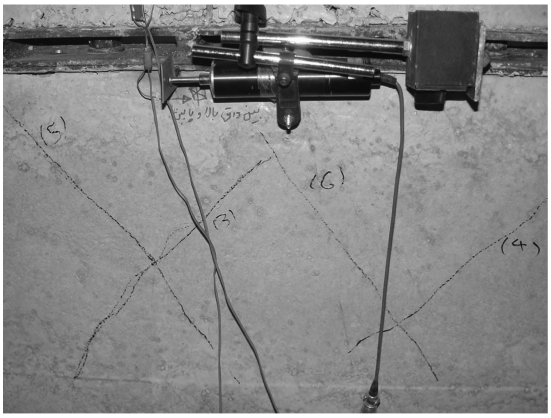


Fig. 10 Inclined cracks in the infill of EIF-1

6. Behaviors of the specimens

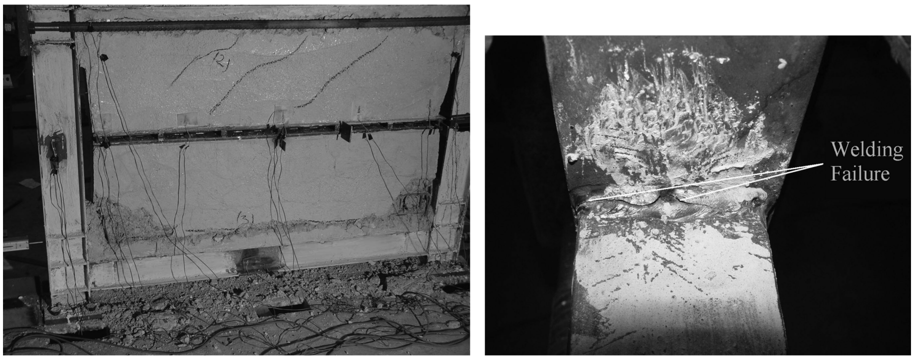
During the testing of EIF-1, cracking of infill-frame interface occurred initially, at the lateral load and drift of 30 kN and 0.15%. Then 45^o inclined cracks initiated in the infill near the shear connectors, shown in Fig. 10. FSF sliding started in cycle 17 at the load and drift of 80.28 kN and 0.389%, respectively.

For EIF-2, which had similar behavior, interface cracking observed at the load and drift of 25 kN and 0.13%, and FSF sliding occurred in 30th cycle at the load and drift of 136.9 kN and 0.53%, respectively. In both specimens, EIF-1 and EIF-2, as the rest of the cycles continued, the infill suffered corner crushing, followed by horizontal shear failure near the upper beams (Fig. 11(a)). Drift and load at the beginning of the corner crushing were 1.8% and 243 kN for EIF-1 and 2.4% and 275 kN for EIF-2. Subsequently, two plastic hinges or connection failure occurred at two ends of the upper beam (Fig. 11(b)). It is worth mentioning that nearly 6% lateral drift were applied to the specimens, which rarely happens in earthquakes.

Test results of the specimens are listed in Table 1, including their initial stiffnesses, strengths and drifts of interface cracking, infill cracking and ultimate case. Comparison of the results of EIF-1 and EIF-2 shows that sliding and ultimate strengths of the specimens rise in accordance with FSF sliding strength. This shows that the ultimate strength of EIF can be regulated by FSF, which is easily adjusted by some bolts. It is worth noting that the FSF of the specimens were regulated before their installation in the wall, however they could also be adapted in situ (after installation), as explained before in Part 3.2 of this paper. This provides a very valuable capability for the building to comply with new seismic code requirements.

For the secondary effect of the frame which increased the normal load on the fuse, the sliding strengths of the specimens (column 3 of Table 1) are practically greater than the adjusted ones (51 kN and 73 kN for EIF-1 and EIF-2, respectively).

Cyclic load-displacement plots of the specimens EIF-1 and EIF-2 are generated, Fig. 12 and their envelops are shown in Fig. 13. As a general trend, the hysteretic loops are symmetric in both loading directions, except for minor differences in the ultimate load capacities. The degradation of the stiffness and strength of the specimens with respect to increasing drift angle is ignorable.

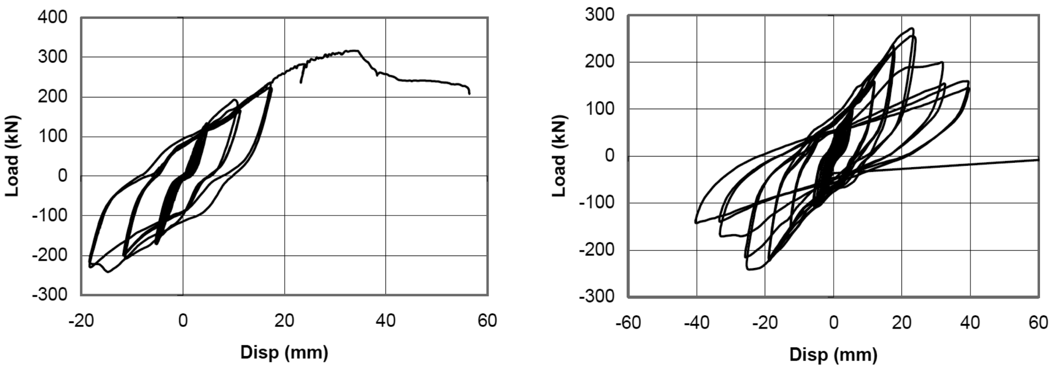


(a) Infill damages (b) Welding failures

Fig. 11 Infill and connection damages of EIF-1 after testing

Table 1 Results of the experimental tests

Specimen	Initial Stiffness (kN/mm)	FSF Sliding		Interface Cracking		Infill Cracking		Ultimate	
		Strength (kN)	Drift (%)	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)
EIF-1	24.30	80.3	0.39	30	0.15	50	0.21	267.6	2.51
EIF-2	31.86	136.9	0.53	25	0.13	60	0.2	314.7	3.50



(a) EIF-1 (b) EIF-2

Fig. 12 Cyclic load-displacement diagrams of the specimens

Viscous damping ratios of the specimens are obtained and shown in Fig. 14 by calculating the dissipated and strain energies for each cycle of the load-displacement diagrams (Chopra 2008). As shown, damping ratios of the specimens increase considerably after FSF sliding, occurred in cycles 17 and 30, respectively; For EIF-1 the damping ratio rises from 7% to 15% and for EIF-2 it rises from 5% to 20%, after fuse sliding.

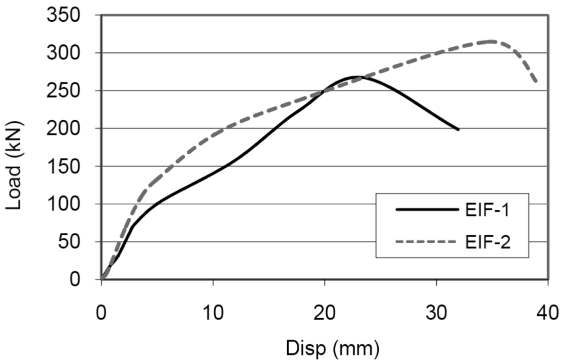


Fig. 13 Envelopes of the load-displacement behaviors of specimens

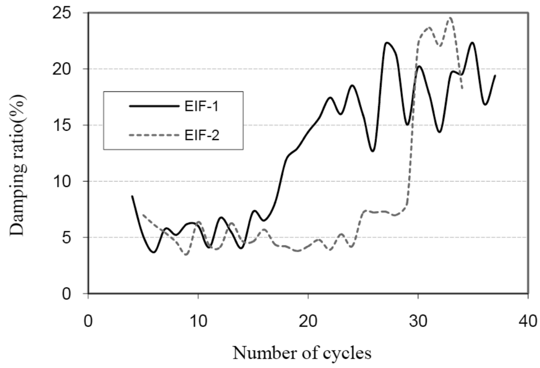


Fig. 14 Damping ratios of the specimens

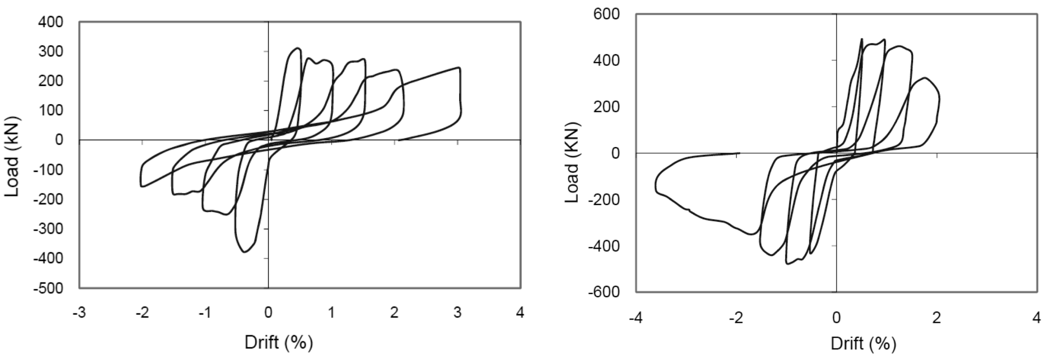
7. Out of plane loading test

Many researches have been conducted for out of plane strength of infill panels (Flanagan *et al.* 1999). However, the author of the present study believes that most of them ignore the worst case, with the minimum integrity between frame and the infill. This occurs after some in-plane vibrations, when the frame returns back to its normal position - zero drift (Mohammadi 2008).

In this regard, EIF-2 was loaded in out of plane direction, after being failed during the in plane testing (with a maximum drift of 6%) and returning back to its normal position. The transversal load was applied through a U-shape plate at the infill center by a manual jack. The corresponding displacement of the specimen was measured by a transducer, shown in Fig. 15(a). The maximum load and displacement were 9.24 kN and 22.9 mm, respectively. After that, the strength dropped down but the wall remained stable and did not fall out, shown in Fig. 15(b). This shows that the out of plane strength of the engineered infill panel is greater than 4.5 g (g: ground acceleration), regarding that the total mass of infill is 206.65 kg (including masses of the wall and fuse). This guarantees the out of plane stability of the engineered infilled frames in earthquakes, even after the wall having been damaged by in-plane loadings. The resistance is evidently originated from the integration of shear connectors with the wall.

(a) Out of plane loading (b) Deformation

Fig. 15 Out of plane loading and deformation of the specimen EIF-2



(a) Normal concrete infill (b) Fibrous concrete infill

Fig. 16 Load- displacement behavior of regular concrete infill panels

8. Comparing the EIF with ordinary infills

Comparison of the specimens of the present study with ordinary infilled frames shows that applying FSF in infilled frames raises their deformation capacities to more than five times: Previous study of the first author (Mohammadi 2007b) showed that for normal and fibrous concrete infills (with the height, length and thickness of 2 m, 3 m and 100 mm, respectively) the corresponding drift of the ultimate strength was 0.32% and 0.5%, respectively, shown in Fig. 16. Other properties of these specimens can be read in related paper, Mohammadi (2007b). For precast concrete infilled steel frames with window openings, the drift is less than 1.5% (Teeuwen *et al.* 2010). However, for EIFs of the present study, the corresponding drift of the ultimate strength, which is an indicator of the infill ductility, is more than 2.5%. Other priority of the engineered infills is that they can be designed or re-adjusted for definite strengths, by regulating their FSFs. This capability provides a quick, free of charge, solution to conform to more restrict emerging seismic codes requirements.

Furthermore, based to the obtained results of this study, the degradation of the stiffness and strength for the fused specimens with respect to increasing drift angle is nearly ignorable; however it is entirely considerable for ordinary infill panels (Moghadam *et al.* 2006), as can also be seen in Fig. 16 for infills made of ordinary and fibrous concrete infills.

The engineered infill panels, as opposed to ordinary infills, have high strength in out of plane direction, which is true even after the wall having been damaged by in-plane loadings. This guarantees the out of plane stability of the engineered infilled frames even in sever earthquakes.

9. Conclusions

This paper presents an experimental investigation to achieve engineered infilled frames.

For this a sliding device, called Frictional Sliding Fuse-FSF, is applied at the mid-height of the infill. The FSF is composed of three steel plates, restricted in transversal direction but capable of sliding longitudinally in a regulated load. To study the influences of some parameters on the behavior of the sliding fuses, some calibration fuses were tested. In this regard, influences of time duration, welding and corrosion of the constitutive plates are investigated and methods of adjusting the FSF for a certain sliding strength are explained as well. Based on the results, the fuse properties do not change considerably in time, however corrosion or welding on the constitutive plates highly affects the fuse behavior.

Two Infill specimens, having FSF, are presented; they had similar reinforced fibrous concrete infills and frictional sliding fuses (FSF), regulated for different sliding strengths. Based on the results, the infills with the proposed configuration of this study are five times more ductile than regular infill panels. They have a well defined failure modes and negligible degradation in stiffness and strength. Other advantage of the fused infill is that they can be designed or re-adjusted for definite strengths; therefore buildings with EIFs can be easily complied with new seismic code requirements with no charge, by re-adapting the FSFs of the infills. Having high resistance in transversal direction, even after being collapsed by in-plane loadings, prevents the engineered infill panels from tipping off or falling out of the frames. It makes the walls stable in this direction even in sever earthquakes.

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