Experimental and Analytical Studies on the Infilled Frames with Frictional Sliding Fuses

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ABSTRACT

Experimental and analytical investigations have been conducted on a new type of infilled frames with Frictional Sliding Fuses (FSF). The results show that these infilled frames have adjustable strength and high ductility similar to other structural elements. Furthermore, the ultimate strengths and deformation capacities of such infills are much more than regular similar fuse-less infilled frames. To study the behavior of such infilled frames in out of plane direction, a specimen was loaded transversally after being failed by in-plane loadings and having the experience of 6% drift in this direction. The results reveal that the infill has sufficient strength against out of plane components of regular earthquakes. The infill with the proposed configuration of this study is modeled by finite element method, in ABAQUS, to study the influence of the fuse sliding strength on its ultimate strength. It is shown that the ultimate strength is raised linearly by increasing the sliding strength of the fuse. In summary, the results confirms that such infilled frames can be regarded engineered for their high ductility as well as the capability of being adjusted for a desired strength.

Keywords:
Engineered infill;
Steel frame;
Frictional Sliding Fuse (FSF); Out of plane;
Strength

1. Introduction

Infills are commonly used in buildings for architectural reasons. 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 [1-2]. Structural frames with infill panels typically provide an efficient method for bracing buildings [3]. The presence of infills can also have a significant effect on the energy dissipation capacity [4].

The necessity of strengthening masonry infills has been recognized for a long time to raise the lateral strength of buildings. Various techniques have been used so far for strengthening masonry infill panels such as: using shear connectors (studs) at the interface of frames and infills [5], concrete covers [6], ferrocement [7], horizontal reinforcement [8], *RC* bond beam at the mid-height of panel [9], and Polymer composites [10].

The above mentioned studies are rather concentrated on techniques to increase stiffness and strength of infill panels. Some methods were also researched to achieve engineered infills, in which undesirable behaviors and failure modes are eliminated and the infills are supposed to have well defined strengths, as well as sufficient ductilities, comparable to other structural engineered elements. In this regard, Aref and Jung [11] proposed a new infill panel composed of Polymer Matrix Composite (*PMC*) material. The *PMC* infill consisted of two fiber-reinforced polymer laminates with an infill of vinyl sheet foam. It was shown that introduction of a *PMC* infill wall panel in a semi-rigidly connected steel frame produces significant enhancements to stiffness, strength and energy dissipation.

Sahota and Riddington [12] showed that using coppertellurium lead layer increases the cracking load of infill, but does not change the ultimate strength so much. It also does not have any adverse effect on the racking performance of the infilled frame. In this study, the lead layer was attached to the underside of the top beam of the frame, using a contact adhesive prior to the construction of the infill. Crisafulli et al [13] proposed an approach for ductile cantilever infilled frames, in which the masonry panels were prevented from suffering severe damage. In this study, the ductile behavior was achieved by controlled yielding of the columns subjected to tensile axial forces. Another method was suggested for masonry infill panels by Moghadam [14]. In this method, strength and ductility of masonry infills were increased by adding concrete covers to both sides of the wall.

Each of the above mentioned studies was a step forward, however more investigations are still required to achieve engineered infilled frames. Therefore, the authors of the present study have conducted a research on a new configuration of infilled frames which can be considered engineered. These infills are called Engineered Infilled Frames hereafter and are referred as *EIF*. For this purpose, a horizontal layer is supplied in the infill, named "Frictional Sliding Fuse (*FSF*)", which slides before infill crushing. The *FSF* capacity can be adjusted in such a way not to permit infill crushing. In this research, two engineered infilled steel frames are tested by in-plane loading. The results, presented briefly here, confirm the efficiency of the proposed method to achieve engineered infilled frames, with adjustable in-plane strengths and high ductilities [15].

This paper is focused on the out of plane strength of the engineered infilled frames as well as the relation between ulimate strength of *EIF* and its *FSF* sliding strength. For this, one of the specimens returned back to the normal position (zero drift) and loaded in out of plane direction.

2. Specimens' Properties

Two engineered infilled steel frame specimens, called *EIF*-0.35 and *EIF*-0.5, are tested by in-plane cyclic loads. In each, a Frictional Sliding Fuse (*FSF*) is applied to improve their behaviors and to adjust their strengths. *FSF* is an instrument with adjustable sliding strength, applied at the mid-height of infills, which will be explained later in detail. The fuse sliding strengths of *EIF*-0.35 and *EIF*-0.5 are 51 and 73*kN*, respectively (which are 0.35 and 0.50 of the ultimate strength of a similar fuse-less infill panel, calculated by Mainstone formula [2]).

As shown in Figure (1), the beams and columns of the specimens are made of single standard *IPE*-120 and *IPE*-140, respectively. The material properties of these sections are listed in Table (1). The frame is a 1/3 scaled of a true three-bay four-storey building, designed for a high seismicity zone on the basis of the Iranian Standard National Code [16]. The beam-column connections are rigid and the measured stiffness of the bare frame is 6.72*kN/mm*. The frame is 1.5*m* high and 1.0*m* long, in which three $126.2 \times 30 \times 0.6 mm$ stiffeners are welded at each connection to each side of the column web, in order to prevent the buckling in high lateral loads. An *FSF* element is applied at the mid-height of each specimen. Seven shear connectors ($L60 \times 60 \times 6mm$

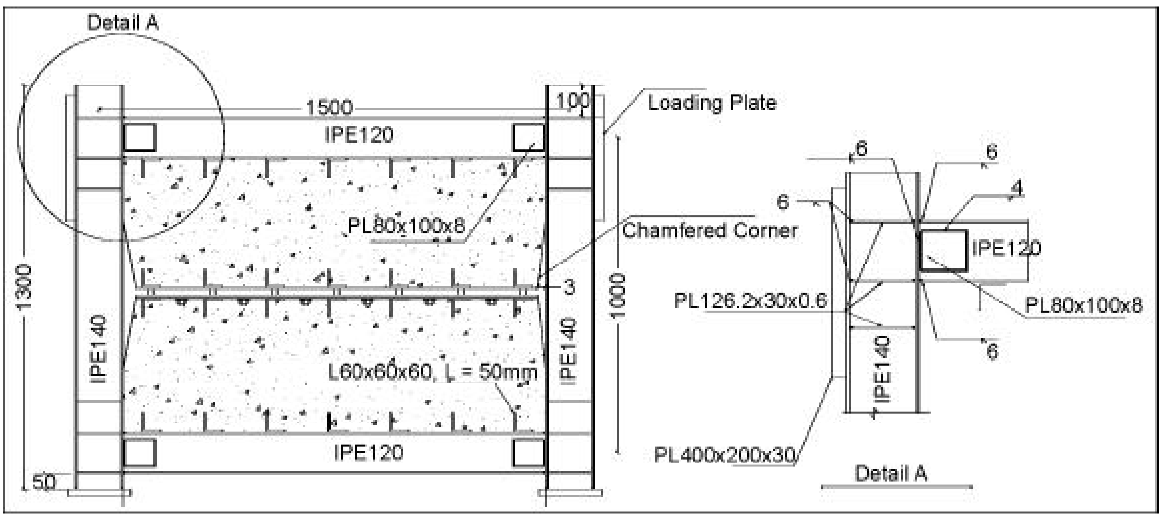


Figure 1. Details of the specimens' frame (dimensions in mm).

with the length of 50*mm*) of 18*cm* spacing are used on beams and each sides of *FSF* to transfer shear forces.

The thickness of the infill is 74*mm*, equal to the width of the column flanges. The average standard cylindrical compressive strengths of the infill material are listed in Table (2).

The infill is divided in two parts by *FSF*, each composed of fibrous concrete and a reinforced mesh of 8*mm* bars with 15*cm* horizontal and 10*cm* vertical spacing. The measured modulus of elasticity, yielding and ultimate strength of the bars is 171675, 314 and 581*MPa*, respectively. 1% steel angular fibers, made of 0.6*mm* steel with the length of 3*cm* are used for the fibrous concrete. The infill is chamfered in its corners near the fuse by the maximum distant of 3*cm* between the fuse and column in order for the infill corners (close to *FSF*) not to contact the frame after fuse sliding, see Figure (1).

Table 1. Material properties of IPE-120 and IPE-140.

Section	Modulus of Elasticity (Mpa)	Yielding Stress (MPa)	Ultimate Stress (MPa)
IPE-120	187549	300	416
IPE-140	197927	322	450

Table 2. Standard compressive strength of infill material.

Specimens	f_c' (MPa)
EIF-0.35	17
EIF-0.5	15

3. FSF of the Specimens

FSF is composed of three steel plates, shown in Figure (2): Two plates (*A* and *B*) are fixed to each other by welding, on which the third one (Plate *C*) can slide. Six high strength *N*20 bolts connect plate *B* to *C*. Plate *B* has slots, shown in Figure (2), which makes sliding possible in longitudinal direction but restrain transversal movement to supply out of plane stability of infill walls. *FSF* sliding strength and the bolts' compressive forces are increased accordingly; therefore the fuse sliding strength can be regulated to desired values by the bolts.

4. Loading Protocol

Displacement controlled loading is applied to the specimens by a hydraulic jack, controlled by a computer, shown in Figure (3a). The specimens are

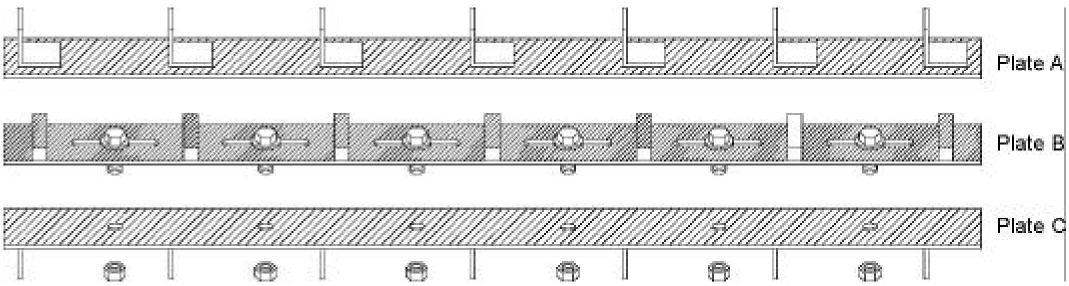
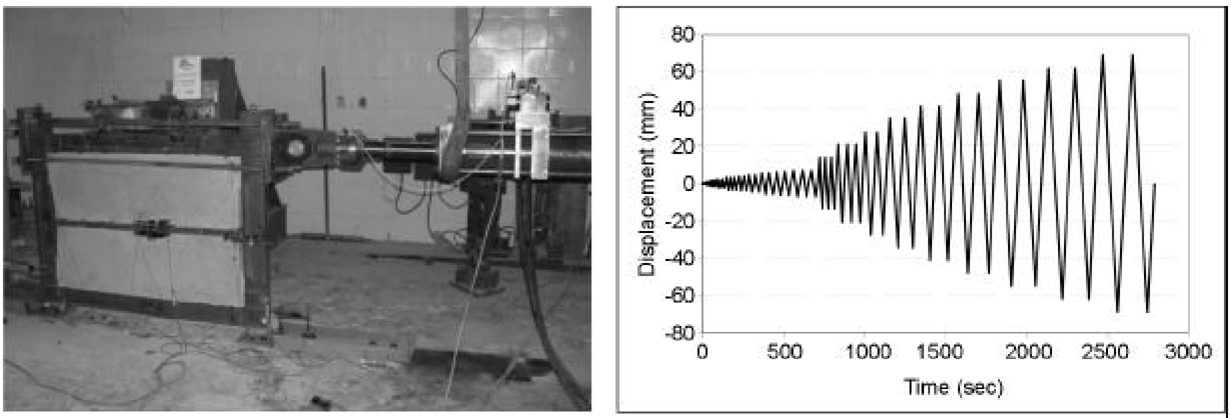


Figure 2. Detail of FSF elements.



a) Loading Setup

b) Loading Protocol

Figure 3. Loading setup and history of the specimens.

subjected to some loading cycles, shown in Figure (3b): the amplitudes, number of cycles and loading rates are calculated in such a way to detect both *FSF* sliding and frame yielding, based on *ATC*-24 criteria [17]. The loading rate is 0.5 and 1.5*mm/sec* before and after yielding of the frame connections, respectively.

To prevent out of plane movements, lateral supports are also provided at two points of the upper beam of specimens.

5. Test Results

During the testing of the specimens, *EIF*-0.35 and *EIF*-0.5, the infill-frame interface cracking occurred initially. Then inclined cracking started near the shear connectors and spread throughout the top and bottom parts of the wall at an angle of 45, as shown for *EIF*-0.35 in Figure (4a).

In *EIF*-0.35, the *FSF* sliding started in cycles 17, in the lateral load and drift of 80.28*kN* and 0.389%, respectively. For *EIF*-0.5, the fuse sliding occurred in 30th cycle in the load and drift of 136.9*kN* and 0.53%, respectively. Then, the corner crushing occurred in the infill, followed by infill horizontal shear failure near the beams, see Figure (4a). Subsequently, plastic hinges or connection failure occurred at two ends of the upper beam, see Figure (4b).

Test results of the specimens are listed in Table (3), including initial stiffness, as well as the strengths and drifts of interface cracking, infill cracking and ultimate case. Based on the results, for each specimen, the load in which the *FSF* slides (column 4 of Table (3)) is practically greater than the adjusted one (column 2). That is because *FSF* sliding strength depends on two parameters: 1- *FSF* adjusted sliding strength 2- normal loads on *FSF*; the second of which rises by increasing lateral drift of specimens, although the first one is constant.

Based on the results, in both fused specimens, the strengths of *FSF* sliding as well as the ultimate cases raise by increasing the *FSF* strength. However, the strengths of interface cracking or infill cracking do not correlate with the *FSF* strength.

Hysteresis diagrams of the specimens and their envelopes are shown in Figures (5) and (6), respectively. Strength deterioration of the specimens by cycles is very slight and can be neglected. It is worth noting that the degradation is generally considerable in ordinary infill panels [18].

The results show that the ultimate strengths of the specimens have improved considerably in comparison to a similar ordinary infilled frame. The

(a) Infill Cracking and Crushing (b) Plastic Hinge in Top Beam

Figure 4. Failure modes of the specimens.

Table 3. Properties and results of the experimental tests.

Specimen	Adjusted FSF Sliding Strength (kN)	Initial Stiffness (kN/mm)	FSF Sliding		Interface Cracking		Infill Cracking		Ultimate	
			Strength (kN)	Drift (%)	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)
EIF-0.35	51	24.30	80.3	0.39	30	0.15	50	0.21	270.8	2.51
EIF-0.5	73	31.86	136.9	0.53	25	0.13	60	0.2	314.9	3.50

ultimate strength for an ordinary infill panel with the same materials and dimensions of the studied specimens is 145kN, calculated by Mainstone Equation [2] which is verified by many experimental results [19]. However, based on the results of the present study, see Table (3), the strengths of the specimens are more than 267.7. This means that the ultimate strength of a fused infilled frame is at least 1.84 times that of an ordinary similar one. Application of *FSF* raises deformation capacities of infilled frames as well. For normal and fibrous concrete infills, the corresponding drift of the ultimate strength is 0.32% and 0.5%, respectively [19]. However, for the specimens of this study, it is more than 2.5%, which means that the deformation capacity of a fused infilled frame is more than five times that of similar ordinary one.

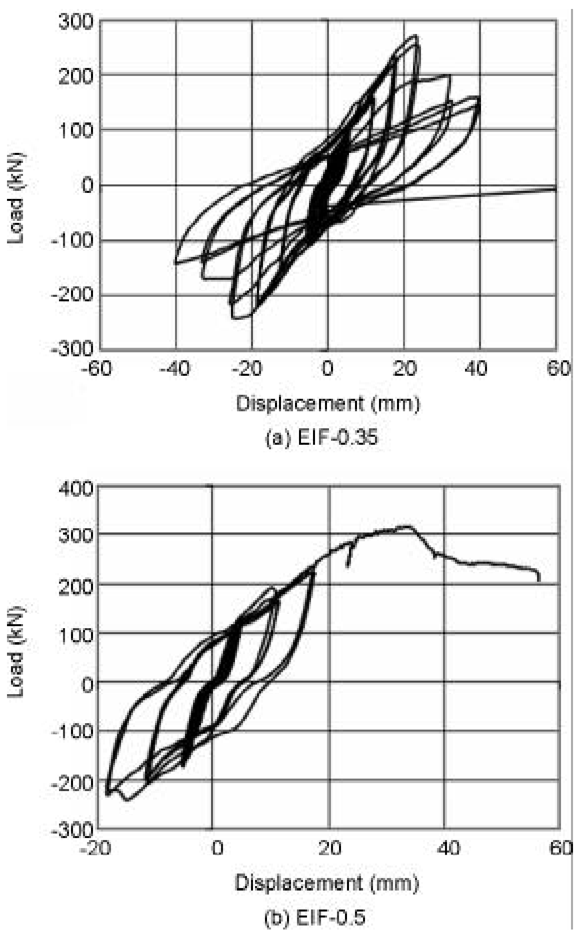


Figure 5. Hysteresis diagrams of the specimens.

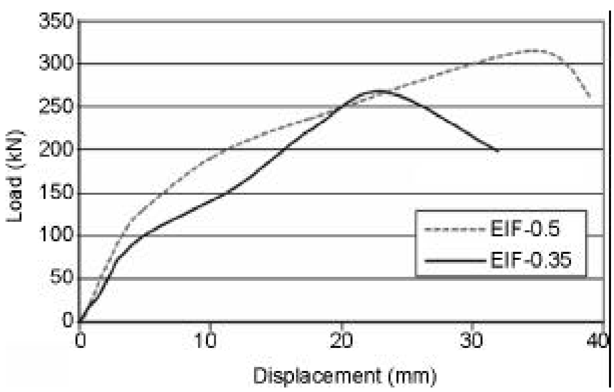


Figure 6. Envelopes of hysteresis behaviors of the specimens.

Furthermore, the strength of *EIF* can be raised by increasing *FSF* sliding strength: *EIF*-0.5 with greater *FSF* sliding strength has higher ultimate strength than *EIF*-0.35. This shows that the strength of such infilled frame can be adjusted for a desired value. The relation between *FSF* sliding strength and the ultimate strength of the engineered infilled frame is studied by finite element analysis method and will be explained later in this paper.

6. Out of Plane Loading Test

Based on the previous studies on regular infill panels, *X* pattern of cracks, resulting from in-plane forces is similar to the crack pattern for a panel subjected to out of plane forces. It implies that the transverse strength can be substantially weakened by in-plane cracking [20].

The authors believe that out of plane strength of regular infills are less than those calculated by formulas of last researches, since the relations do not consider the worst case with the minimum integrity between frame and the infill [21]. This case happens where an infill is loaded in an in-plane direction and returns back to its normal position-zero drift [22]. In other words, the infill out of plane strength is related directly to the wall-frame integration and the wall should be stable for out of plane loads in the critical case with the minimum integration. This occurs where the maximum infill-frame interface cracking has occurred by in-plane drifts and the wall is returned back to the normal position.

Therefore, in order to evaluate *EIF*-0.5 strength in out of plane direction, the specimen was loaded in this direction, after being failed during in-plane testing. The specimen had the experience of 6% drift during in-plane loading test, which would rarely happen in earthquakes.

The transversal load was locally applied at the wall center, through a U-shape plate by a manual jack. The corresponding displacement of the specimen was also measured by a transducer, shown in Figure (7). The load-displacement behavior is shown in Figure (8). The maximum load and displacement

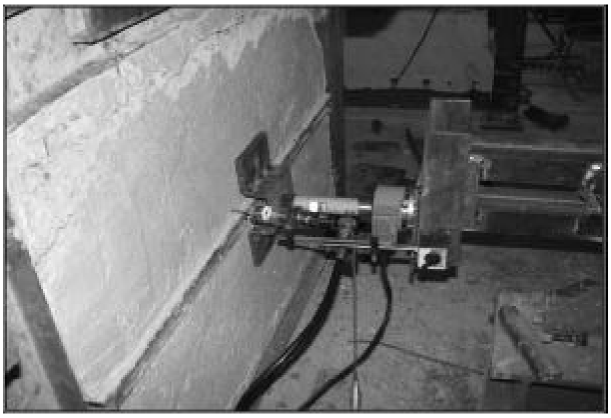


Figure 7. Out of plane loading test of EIF-0.5.

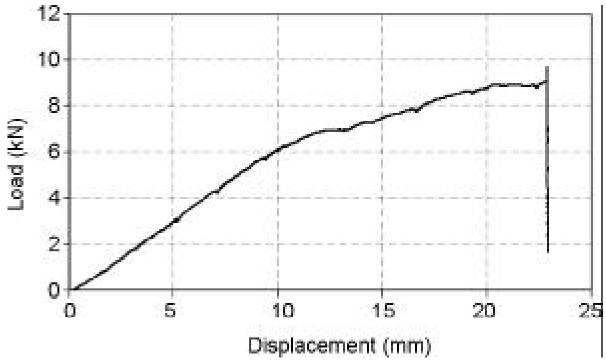


Figure 8. Out of plane load-displacement behavior of EIF-0.5.

are 9.24*kN* and 22.9*mm*, respectively.

It can be expected that the out of plane strength of the engineered infill panel is always more than the obtained value, 9.24*kN*. It is because the seismic transversal load is applied uniformly on the wall surface, but simulated here by a concentrated load, applying at the wall center. The obtained strength, 9.24*kN*, is equal to 4.5*g* in acceleration (*g*: ground acceleration), regarding that the total mass of infill is 206.65*kg*, including masses of the wall and fuse. After achieving this strength, the wall still remained stable in the frame and did not jump out, shown in Figure (9), but its resistance dropped down suddenly. Having the resistance of more than 4.5*g* guarantees the out of plane stability of the engineered infilled frames in earthquakes, even after the wall having been damaged by in-plane loading. This high resistance is originated from the integration of the shear connectors and the wall.

In *EIFs*, the relative displacement between the wall and beams are negligible as opposed to normal infill panels, therefore the out of plane resistance can be raised by welding the wall reinforcement to the shear connectors.

Figure 9. Out of plane deformation of EIF-0.5.

7. Modelling EIF by Finite Element Method

The engineered infilled frame with the proposed configuration of the present study is modelled by finite element method in *ABAQUS* 6.8.1. In this part, the relation between sliding strength of the fuse and the ultimate strength of the infilled frame are presented as well as the details of the modelling by finite element method.

Each part of the infill, top or bottom of the fuse, is modelled by 4-node tetrahedral elements- called *C*3*D*4, shown in Figure (10a). The frame is modelled by 8-node brick elements, *C*3*D*8*R*, illustrated in Figure (10b). The fuse is modelled by two contacting

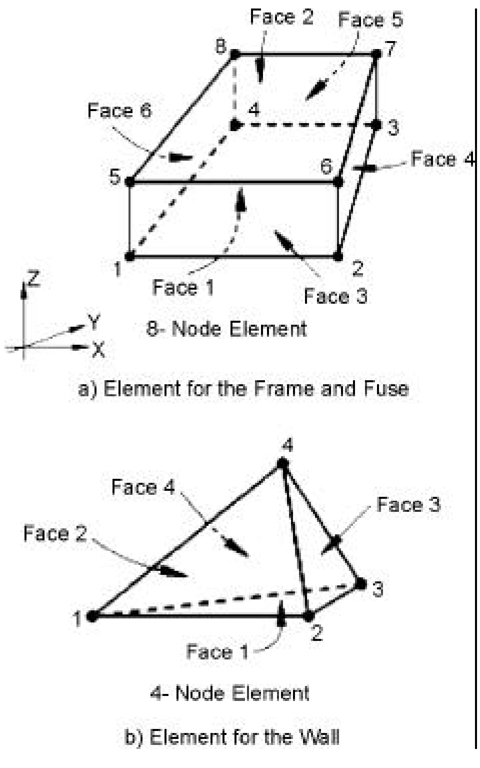


Figure 10. Element used in Finite element modelling of EIF.

plates with the friction coefficient of 0.32 as measured in the experiment. Surface to surface contact elements are used for contacting these plates. The modelled specimen is shown in Figure (11), including the fuse with the capability of sliding, infill chamfering near the fuse and even the loading plates which was welded at tops of the columns. The figure shows the deformation of the specimen and the fuse after sliding, in parts *a* and *b*, respectively.

To verify the modelling, ultimate strengths of the specimens *EIF*-0.35 and *EIF*-0.5 are calculated by the finite element analysis method, regarding their different material properties. The strengths are determined 4% and 12% lower than the experimental ones, respectively.

In order to find the relation between *Fu* (ultimate strength of the *EIF*) and *Fs* (sliding strength of the fuse), seven *EIFs* are modelled, in which all quantities are the same, except for the sliding strength of the fuse (*Fs*), the results of which are shown in Table (4).

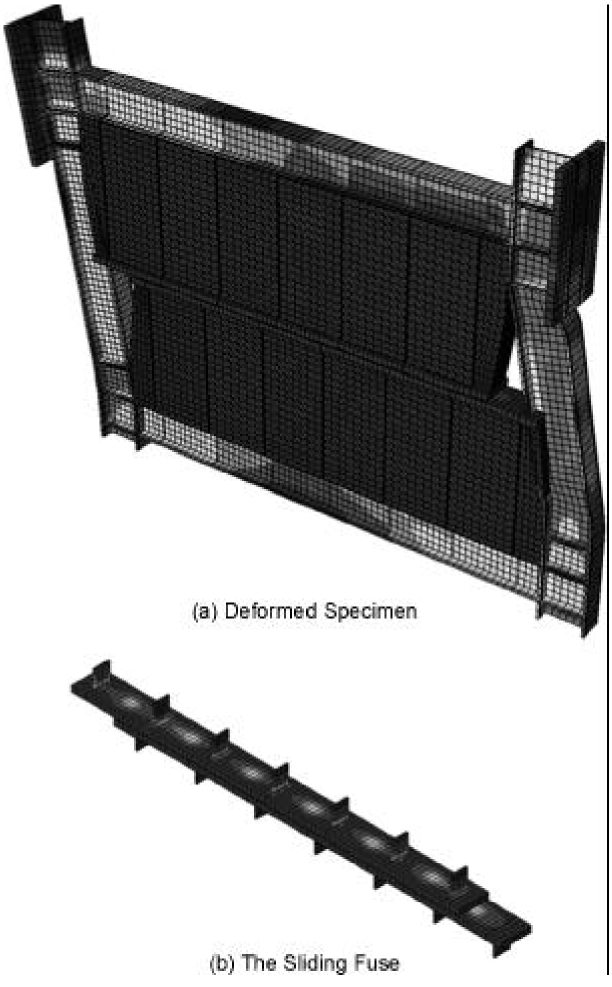


Figure 11. Deformation of the modelled specimen in ABAQUS.

Table 4. Assumed Fs and calculated Fu by the finite element method.

Fs (kN)	Calculated (kN)
0.0	206.7
45.4	219.6
90.8	232.4
158.9	254.7
227.0	277.8
272.4	293.5
363.2	324.6

As shown in Figure (12), the ultimate strength rises linearly in accordance with the *Fs*. The relation between *Fu* and *Fs* is as follows:

$$Fu = 0.326\,Fs + 204.4 \tag{1}$$

The first coefficient of relation 1 (0.326) is about the measured μ between the fuse plates (0.32) and the second one (204.4) is nearly the same as the calculated ultimate strength of an engineered infilled frame with $Fs = 0$ (206.7*kN* as shown in Table (4)), and therefore, the relation can be rewritten as:

$$Fu = \mu\,Fs + F_0 \tag{2}$$

In which, *Fu* is the ultimate strength of the engineered infilled frame, *Fs* is the sliding strength of the fuse and μ is the coefficient of friction between fuse plates. F_0 is the ultimate strength of an engineered infilled frame, in which the fuse has ignorable sliding strength. In such an infill, the fuse bolts are not prestressed but applied to supply out of plane stability of the infill.

The two relations above show that the ultimate strengths of the infilled frames, with the configuration of the present study, can be adjusted for desired values through the fuse bolts. This confirms the capability of such infills for being designed for a desired strength.

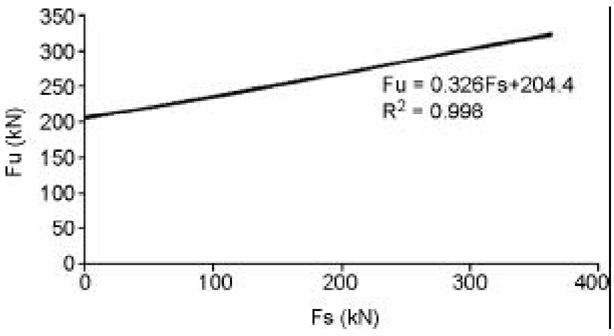


Figure 12. Relation between ultimate strength of the infilled frame (Fu) and the fuse sliding strength (Fs).

8. Conclusions

Experimental and analytical investigations are carried out here for engineered infill panels. The results of two experimental tests on fibrous concrete infilled steel frames with *FSF* are presented. The fuse applied at the mid-height of infill is capable of sliding in longitudinal direction but restrained transversally. The sliding strength of *FSF* can be regulated by some pre-stressed bolts. Comparing the behavior of the engineered infilled frame with regular fuse-less infill shows that application of *FSF* improves the ultimate strength and deformation capacity.

The out of plane strengths of the engineered infilled frame specimens are measured as more than 4.5*g* (*g* is the ground acceleration). This guarantees the transversal stability of such infilled frames, even after being collapsed by in-plane component of earthquakes.

The results of finite element analyses show that the ultimate strength of the fuse infilled frame rises linearly in accordance with *FSF* sliding strength. This confirms the capability of such infills to be regulated for a desired strength through the fuse bolts.

In summary, the proposed configuration of this study can be considered for engineered infilled frames, regarding its high ductility and out of plane stability as well as capability of being designed for desired in-plane strengths.

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