Effects of vertical load and retrofitting
on the behaviour of newly proposed fused infill panels

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Abstract

  A new type of infilled frame has been recently proposed. It has a frictional sliding fuse, horizontally installed at the mid-height of the infill. It has already shown that such infilled frames have higher ductility, strength and damping ratio as well as more enhanced hysteresis cycles, compared with regular infilled frames. This experimental paper is focused on the influence of gravitational load on the behaviour of the fused infill panel. Furthermore, a repairing method in which damaged specimens are repaired by grout plasters is also studied. The results show that the gravitational load, applied to the surrounding frame of the infill for the dead or live loads, raises the ultimate strength of the fused infill specimens. It is also shown that repairing the failed specimen by grout was so efficient that the repaired specimen had greater strength than the original one. However, top gap, between the infill and the top beam of the enclosing frame should be absolutely avoided, because it decays the ultimate strength.

Keywords: Steel frame, Ductility, Gravitational load, Retrofitting, Damping, Imperfection.

1. Introduction

  Infill panels are used as interior and exterior walls in reinforced concrete and steel-framed structures. The rigidity and strength of frames are significantly improved when masonry panels are built in line with the frames. The improvement in strength is several times as the strength of a frame with no infill. Stiffness improvement is still more substantial, with increase up to 60 times over that of a bare frame [1, 2]. Despite, infill contribution is not considered mainly because of the lack of knowledge of the composite behaviour of the frame and the infill, the structural uncertainties and the non-linear behaviour of infilled frames [3, 4].

  Approximately 80% of the damage cost of structures from earthquakes is due to damage of the infill walls and the consequent damages of doors, windows and electrical installations [5]. Therefore, the need for strengthening infillshas been recognized for a long time by investigators. Some of the strengthening techniques are, using: shear connectors (studs) at the interface of frames and infills[6] concrete covers [7, 8], ferrocement [9], reinforcement [10], RC bond beam at mid-height of panel [11, 12] and Polymer composites [13]. Along with preventing the wall from catastrophic failure, most of these techniques raise the strength and stiffness of the buildings andare applied in old buildings to comply with the new seismic codes requirements.

  Infill panels, original or retrofitted, are usually brittle with small ductility. They typically suffer various types of damage ranging from invisible cracking to crushing. Therefore, the researchers felt a need to find engineered infill panels, with high ductility, large strength, well-defined failure modes and stable post-peak behaviour. In this regard, Aref and Jung [14] proposed a new infill panel, composed of Polymer Matrix Composite (PMC) material. El-Dakhakhniet. al. [15] applied glass fibre reinforced polymer laminates on the infill panel. Sahota and Riddington[16] used copper-tellurium lead layer in the underside of the top beam of frame prior to the construction of the infill. They showed that this method increases the cracking load of the infill, but does not change the ultimate strength so much. Crisafulliet. al. [17] proposed an approach for ductile cantilever infilled frames, in which the masonry panels are prevented from suffering severe damage. In his study, the ductile behaviour is achieved by controlled yielding of the columns subjected to tensile axial forces.

  Mohammadi and Akrami [18] have conducted a study to achieve a new engineered infill panel. They installed an

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instrument, named Frictional Sliding Fuse (FSF) in the infill. The fuse can be regulated for a definite sliding strength through some bolts, in such a way to slide before infill crushing. It was shown that applying the fuse raises the ductility and damping ratio of the infilled frame, and improvesthe hysteresis cycles. It also raised the transversal strength of the infill considerably, compared with regular infill panels. The results of two specimens with different strengths in fuses are shown in table 1 as the first group and they will be compared with the results of the specimens of the present study.

Infills are highly affected by the surrounding frame properties and loads. Vertical load of the frame, originated from gravitational loads (dead and live loads) of the building, may affectthe behavior of infill panels. This fact is stricter for infills that were constructed parallel with the structure. Therefore, influence of the applying vertical load of the frame on the fused infill panel is studied here though testing two specimens.

Reparability of the structural elements is advantageous, specially in earthquake prone areas. Therefore, two specimens were repaired by covering their infills by grout and compared with the original specimens. In the repairing stage, a gap may be produced between the infill and the top beam, which affects the behavior of infilled frames considerablybased on previous studies [19]. Therefore, a gap was also supplied in a specimen in the underside of the top beam to study the influence of the gap on the behavior of the repaired fused infill panels.

The cryptogram for identification of each specimen is EIF-i, where EIF stands for the Engineered Infilled Frame and iis an index to identify the number of wall sequentially tested.

2. Experimental program

Four fused infilled steel frame specimens were tested here by cyclic loads, compared with two specimens of the previous study [18]. The configuration of the specimens was exactly the same as previous, shown in Fig. 1; beams and columns of the specimens were made of single standard IPE120 and IPE140, respectively. The modulus of elasticity, yielding and ultimate strengths of the section material were measured respectively as 187549, 300 and 416 MPa for IPE120 and 197927, 322 and 450 MPa for IPE140. The stiffness of the bare frame was measured as 1200 kN/m. The strength of the bare frame was calculated as 19 kN, based on the measured properties of the sections.

Each specimen has a Frictional Sliding Fuse (FSF) installed at the mid-height of the   infill with the sliding strengths mentioned in table 1. The infills were composed of 74 mm thick reinforced fibrous concrete with 1% standard steel angular fibres. The standard compressive strengths of the infill
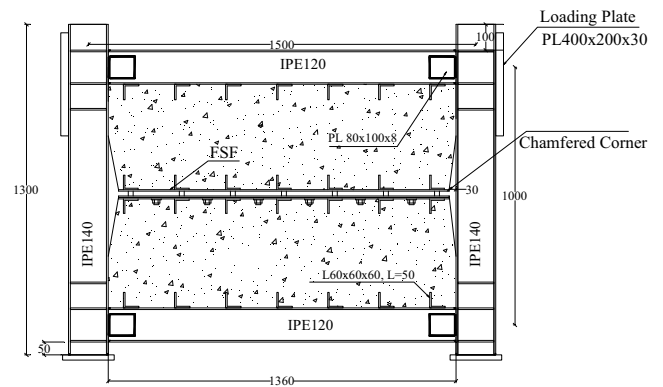

Fig. 1 Configuration of the fused infilled frame (all dimensions in mm)

material are shown in table 1. The infills had also a reinforced mesh of Φ8 mm bars with 15 cm horizontal and 10 cm vertical spacing. Modulus of elasticity, yielding and ultimate strengths of the bars were measured as 171670, 314 and 581 MPa, respectively. The infill was (30 mm) chamfered in its corners near the fuse, shown in Fig. 1, in order to prevent infill from contacting the frame and to avoid shear failure in columns.Seven shear connectors (each a 50 mm of L60 60 6 mm) with a spacing of 18cm were used on beams and each side of the FSF to transfer shear forces, shown in Fig. 1. For more information about details of the frame, fuse or infill one can refer to the reference [20].

As shown in Fig. 1, a hydraulic jackapplies the loads to the specimens through two loading plates. The compressive loadsare applied directly through the near loading plate, and the tensile loads are applied by four Φ24 bars, connected to the other loading plate. Amplitudes, number of cycles and loading rates, shown in Fig. 2, were the same for all specimens, calculated in such a way to detect FSF sliding and frame yielding, based on ATC-24 criteria [21]. The loading rate was 0.5 and 1.5 mm/sec before and after frame connection yielding, respectively.For each specimen, three lateral supports were provided on the upper beam in order to prevent out of plane movement of the specimen.

To study effects of gravitational loads on EIFs, two specimens were tested, listed in table 1 as the second group. For this a constant vertical loadof 90 kNwas applied by a vertical hydraulic jack to the columns of the specimens through a very stiff beam, as shown in Fig. 3 (different from
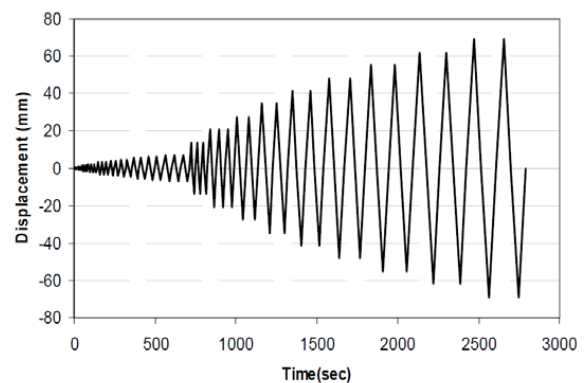
Table 1 Specimens properties

Specimens Groups	Specimens name	Fuse Sliding Strength (kN)	Infill material Strength (MPa)
1[18]	EIF-1	51	17.26
(original specimens)	EIF-2	73	15.73
2	EIF-3	51	12.75
(With vertical load)	EIF-4	73	12.75
3	EIF-5	51	17.26
(repaired specimens)	EIF-6	51	15.73

Fig. 2 Displacement history of the specimens

real cases, no vertical load was applied to the top beam of the frame, for the lack of equipment). It is worth noting that the vertical load was applied prior to lateral loading, simulating presence of the gravitational loads on structures when an earthquake strikes. Fuses of EIF-3 and EIF-4 were adjusted to have the sliding strengths of 51 kN and 73 kN, similar to EIF-1 and EIF-2, respectively. The effects of the vertical load can be studied by comparing the results of the first and second group of specimens.

To examine the reparability of the fused infilled frame, the tested specimens (EIF-1 and EIF-2), were retrofitted by grout after being failed by in-plane loading. The obtained specimens are called EIF-5 and EIF-6, respectively, categorized as the second group of specimens. To obtain EIF-5, the damaged connections of EIF-1 were improved by removing the welds and re-welding. Damaged parts of the infill, in two areas at top and bottom of the infill, were replaced with grout as well, shown in Fig. 4.

The same repairing was applied on EIF-2 to obtain EIF-6. However, to study the influence of a gap between the frame and the infill, a gap was also createdbetween the infill and the top beam. Thesliding fuse was also re-adjusted to the sliding strength of 52 kNin order to make the specimen comparable with EIF-5.

3. Test results

Failure modes of fused infill panels are generallydifferent from those of regular infills. [18]. During testing of EIF-1 and EIF-2, the infill-frame interface cracked initially. Then inclined cracking started near the shear connectors and spread throughout the top and bottom parts of the wall by a degree of 45˚. In EIF-1, the FSF sliding started in cycle 17, by the lateral load and drift of 80.28 kN and 0.39%, respectively. EIF-2 had similar behavior, in which the fuse sliding occurred in 30th cycle by the load and drift of 136.9 kN and 0.53%. For both specimens of EIF-1 and EIF-2, corner crushing of infill occurredas the loading amplitudes increased, followed by infill horizontal shear failure near the beams. Subsequently, plastic hinges at two ends of the upper beam or failure of the
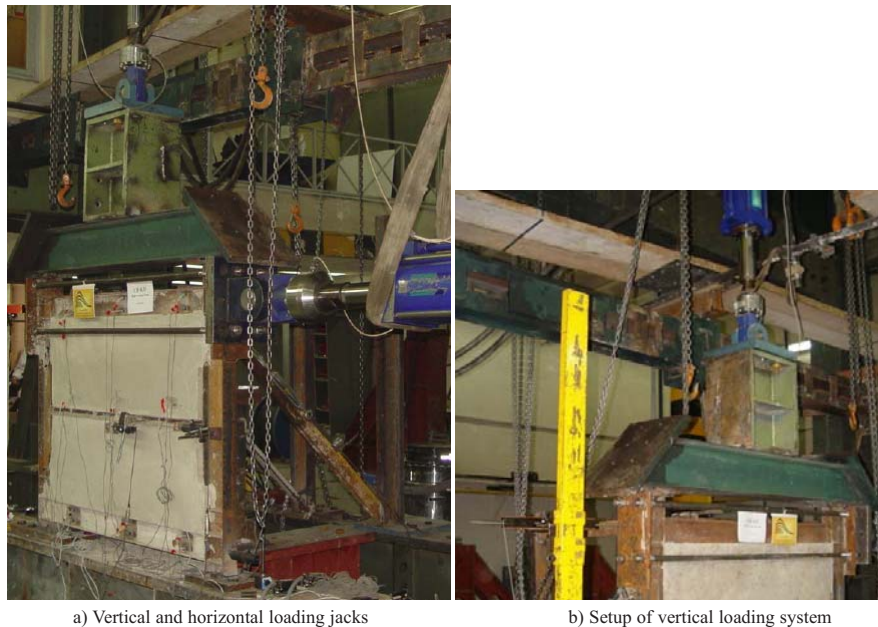

a) Vertical and horizontal loading jacks   b) Setup of vertical loading system

Fig. 3 Applying horizontal and vertical load to specimens

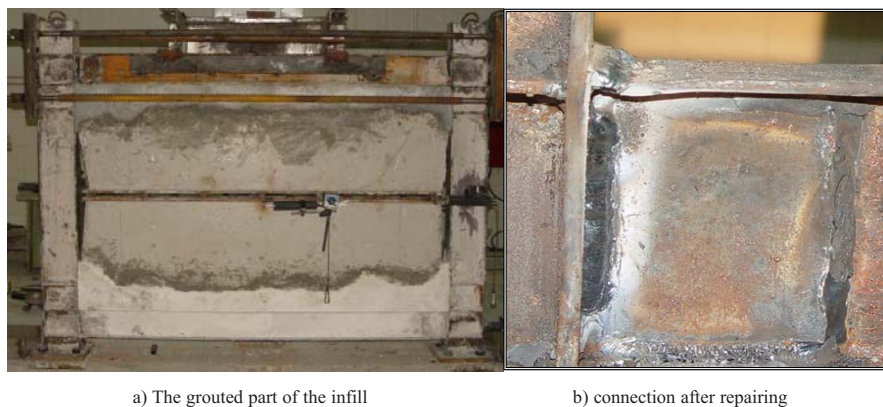a) The grouted part of the infill   b) connection after repairing

Fig. 4 The retrofitted specimen

beam to column connectionsoccurred. More information on these two specimens and their behaviors are in reference18.

For the second group of specimens (EIF-3 and EIF-4), in which the vertical load was applied, interface cracking occurred at the starting cycles of loading. Then the infill cracked as shown in Fig. 5; in EIF-4, the cracks 1 and 2 occurred inloading cycles 13 and 15 at the lateral loads of 139 kN and 181 kN, respectively. These cracks spread over the infill in the next loading cycles and produced cracks 3 and 4. The fuse started sliding in 23th cycle. Then crack 5 occurred in cycle 30 at the load of 324 kN, afterwards, the strength dropped down for the shear failure along this crack. EIF-5 had similar behaviour; cracks 1, 2 and 3 occurred in cycles 17, 19 and 23 at the lateral loads of 192, 217 and 287 kN, respectively. Fuse sliding was observed in cycle 31. As loading continued, other cracks occurred, shown in Fig. 5b, which were actually continuation of the previouscracks. The testing was finished after the specimen jumped out of the frame at the load of 346 kN. This produced many damages in the frame and infill and occurred for the insufficiency of the lateral supports.

As explained before, EIF-5 and EIF-6 were obtained by repairing EIF-1 and EIF-2 in theier connections and the crushed parts of their infills and no repairing action was applied for the infill cracks. In summary,loadingof the retrofitted specimens was applied in the presence of original specimen's cracks. In the first retrofitted specimen, EIF-5, the fuse sliding was observed in 24th cycle, at the load and drift of 105.2 kN and 0.53%, respectively. The ultimate strength of this specimen was 320 kN (occurred at 3.65% drift), which is greater than that of the original specimen, EIF-1. For EIF-6, the retrofitted specimen with the top gap, the fuse sliding occurred in 23rdloading cycle, at the load and drift of 72 kN

and 0.53%, respectively. At the ultimate case, this specimen showed the strength of 223 kN that is much lower than EIF-5.

Table 2 shows the test results of all specimens, including initial stiffness, strengths and drifts of the interface cracking, infill cracking and ultimate case. The load-displacement diagrams of the specimens are presented in Fig. 6. As shown, strength degradations of all specimens are very slight and negligible up to the drift of 2.5%, contrary toordinary infill panelsin which the degradation is generally considerable, even in lower drifts [12].

4. Discussion

4.1.Effect of the Vertical Loading

To study the influences of vertical loads on the behavior of EIFs, each specimen of the second group is compared with the similar one of the first group (with the same fuse sliding strength). In this regard, the envelopes of EIF-1 & -3 and EIF-2 & -4 are shown in Fig. 7a and 7b, respectively. As shown, the gravitational loads raised the strengths of the specimens, without changing the initial stiffness or decreasing the deformation capacities. Thus, it can be generally concluded that the gravitational loads improves the behavior of the engineered infill panels. Raising the strength of the fused specimens by the presence of vertical loads seemsreasonable, regarding that it not only increase the confinement and shear strength of the infill material but also raises the sliding strength of their fuses by enhancing the normal load on the fuse. As shown in the first group of specimens, the infill with higher fuse sliding strength has greater strength (for more information refer to reference. 18).
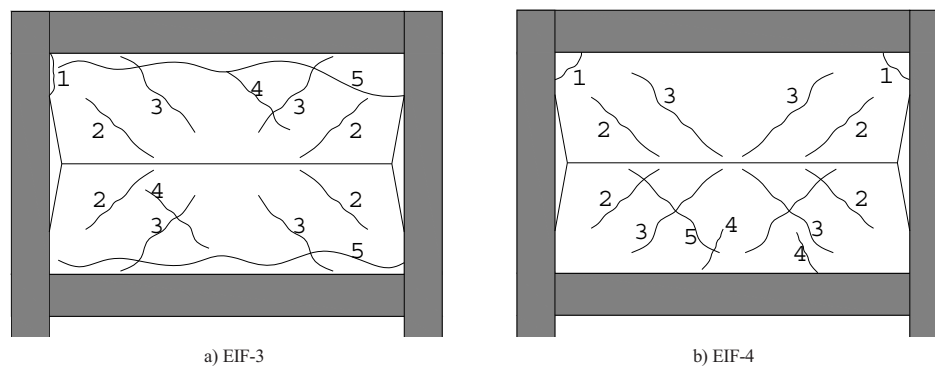

a) EIF-3

b) EIF-4

Fig. 5 Cracking occurrence sequences in the second group of specimens

Table 2 Results of the experimental testing

| Specimen | SFS Sliding | | | Interface Cracking | | Infill Cracking | | Ultimate | |
	Cycle of occurrence	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)	Strength (kN)	Drift (%)
EIF-1	17	80.3	0.39	30	0.15	50	0.21	267.6	2.51
EIF-2	30	136.9	0.53	25	0.13	60	0.2	314.7	3.50
EIF-3	23	209.1	0.56	113	0.23	164	0.41	324	2.4
EIF-4	31	263.7	1.38	107	0.3	190	0.54	346	2.88
EIF-5	24	105.2	0.53	----	----	----	----	320	3.65
EIF-6	23	72	0.53	----	----	----	----	223	3.28

a) EIF-1

b) EIF-2

c) EIF-3

d) EIF-4

e) EIF-5

f) EIF-6
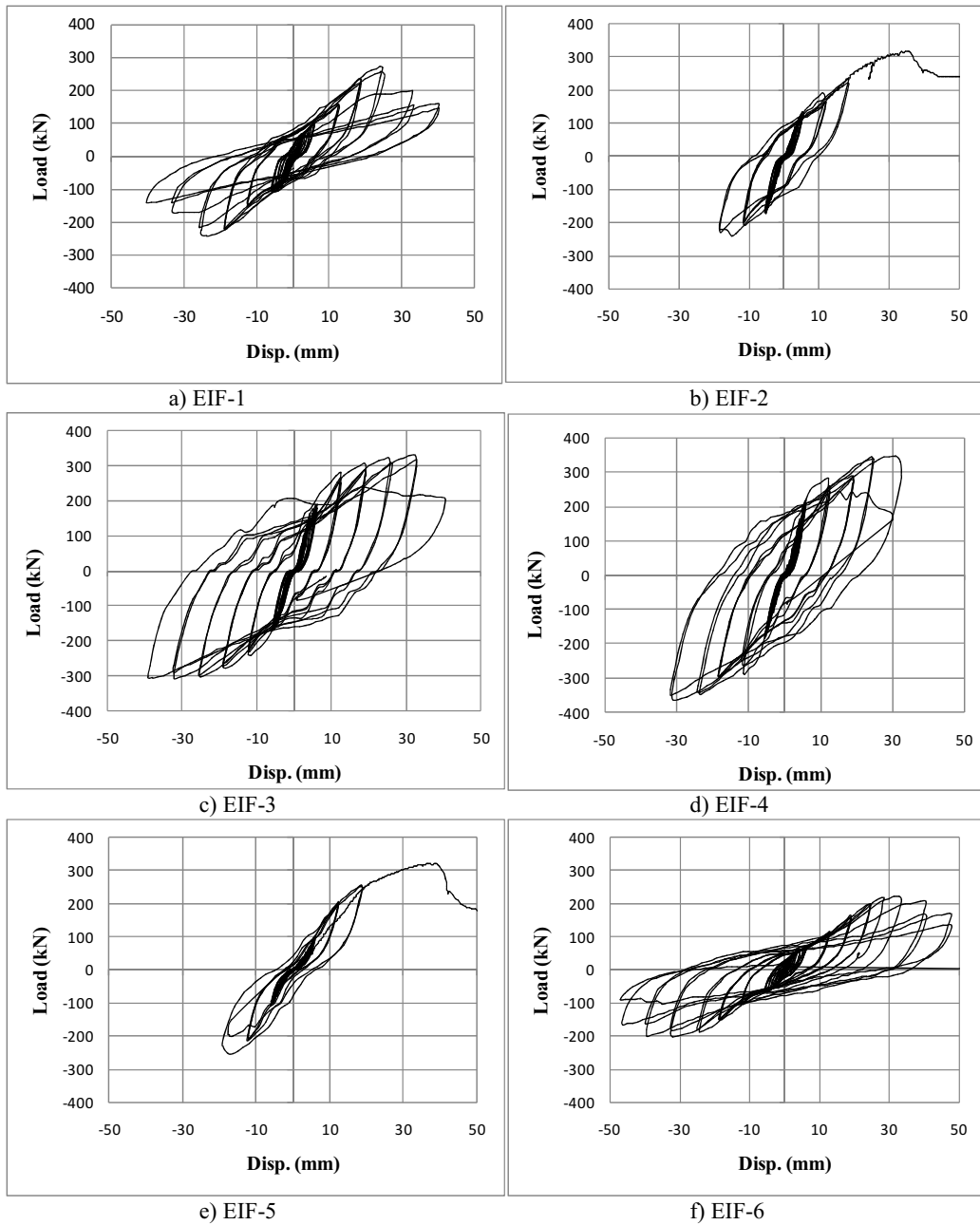
Fig. 6 Load displacement of the specimens

a) Comparing EIF-1 with EIF-3

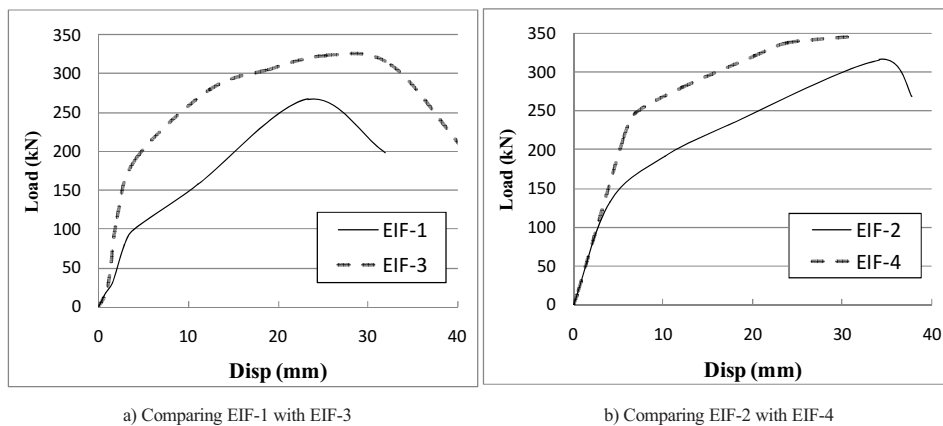b) Comparing EIF-2 with EIF-4

Fig. 7 Influence of vertical load on the load- displacement of the engineered infill

4.2. Influence of Repairing

To study reparability of the fused infilled frames, the results of the third group of specimens (EIF-5 and EIF-6) are compared with EIF-1 (all with the same fuse properties), shown in Fig. 8. As shown, all of these specimens had the same initial stiffness but different strengths; for EIF-5, strength and deformation of the ultimate case were 20% and 45% higher than those of EIF-1. This shows that applying more qualified material in the infill, e.g. grout (with higher strength than the utilized concrete), improves the behavior of the fused infill panels. However, imperfection in retrofitting of EIF-6 (presence of a gap between the top beam and the infill) decayed the strength and deformation capacity of the specimen considerably. As compared with EIF-5, the imperfect retrofit is not reliable since the strength of EIF-6 was less than the original specimen (EIF-1). Therefore, in rehabilitation of the fused infill, great efforts should be made not to produce a gap at the interface of the infill with the surrounding frame. In this regard, EIFs are similar to regular infill panels which are sensitive to the top gap[19].

4.3. Damping Ratios of the specimens

Viscous damping ratios of the specimens can be calculated for each cycle based on the hysteresis diagrams, shown in Fig. 6. Damping ratios of the first and second groups of specimens are shown in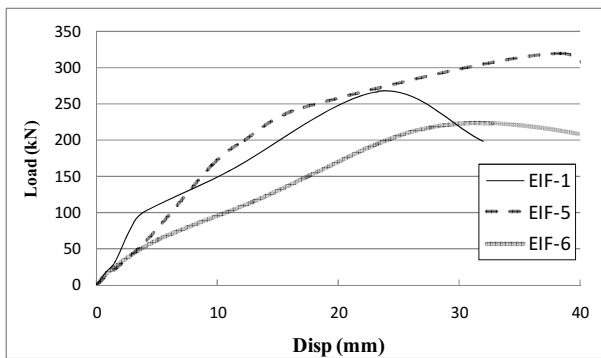 Fig. 9. Local variations of the viscous damping are for local damages of the specimens. As shown in this figure, damping of all specimens increases considerably after FSF sliding (occurred in cycles 17, 30, 23 and 31 for EIF-1 and EIF-2, EIF-3 and EIF-4). Damping ratio of EIF-2 & EIF-4 rises more abruptly, compared with EIF-1 and EIF-3, becausetheir fuses not only have greater sliding strength but also they cover greater distances just after occurrence of the first sliding; based on the measurements of an LVDT, shown in Fig. 10, the fuses of EIF-2&-4 slid greater than 5 mm in the first sliding, however in EIF-1 &-3, the sliding length was less than 0.4 mm.

Large damping ratios of EIFs, especially those occur in high lateral loads after fuse sliding, is beneficial for the seismic behavior of structures, since it reduces the structural displacement response.

5. Conclusions

It has been previously shown that the infills with frictional sliding fuses (FSF) at the mid-heightare much more ductile than similar non-fused infills. Strength of such infill panels can also been improved by increasing the sliding strengths of their fuses.

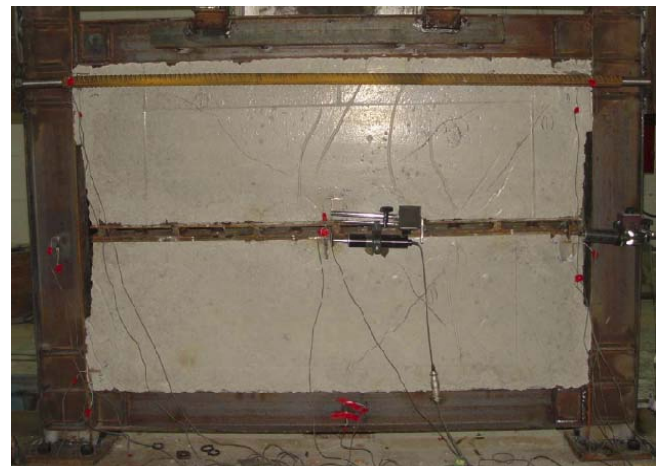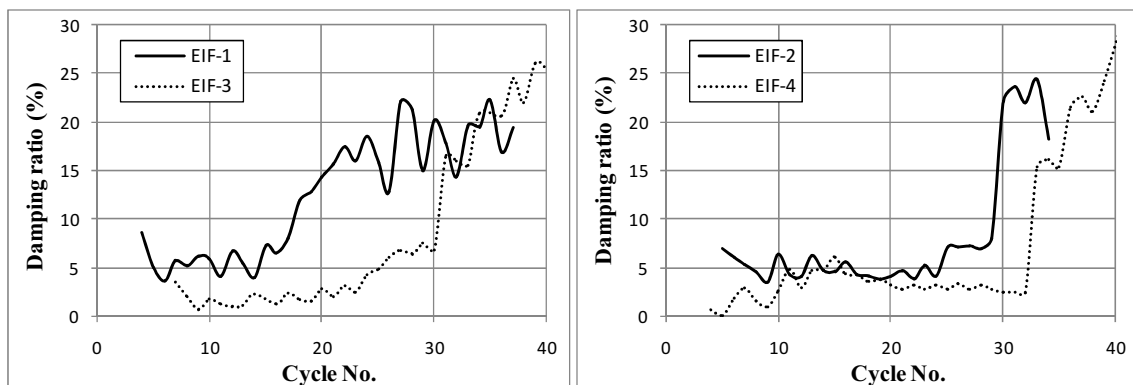In this paper, a complimentary experimental investigation is

Fig. 8 Effect of top gap and repairing

Fig. 10 LVDT that records relative displacement of fuse layers

a) EIF-1 & EIF-3

b) EIF-2 & EIF-4

Fig. 9 Damping ratio of the first and second group of specimens

carried out through six specimens to study effects of the gravitational loads (dead and live loads) on the surrounding frameas well asreparability of such infilled frames. Influences of a gap, between the infill and the top beam is also studied in a repaired specimen.

The obtained results show that applying gravitational loads on the frame increase the ultimate strength of the fused infills. It is also shown thatrepairing damaged specimens by grout plasters leads to a specimen with greater strength than the original one. However, enough care should be taken in retrofittingnot to have any gap between the infill and the top beam of the frame.

In summary, infills with the proposed configuration of this study can be regarded engineered. Because they have high ductility, large damping ratio, stable post-peak behaviour,capability of being designed for a certain strength and high transversal strength that make them stable even in intensive earthquakes.

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