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Fire Resistance of Cavity Insulated Light Gauge Steel Framed Walls

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Abstract

Light-gauge steel framed (LSF) wall systems are made of cold-formed steel studs and tracks and lined with gypsum plasterboards. They are mostly cavity insulated to provide acoustic and thermal performance. Cavity insulation delays the temperature rise across the wall as it restrains the heat transfer. This delays the ambient plasterboard surface temperature rise and thus improves the insulation failure time of LSF walls. However, LSF walls are also used as load bearing walls. Having cavity insulation causes the fire side temperatures to increase rapidly, resulting in a higher temperature gradient across the stud depth. This leads to higher thermal bowing deflection and crack openings on the fire side plasterboard and exposing studs to higher temperatures. These effects reduce the fire performance of load bearing walls. However, most designers consider that cavity insulation is beneficial for all LSF wall configurations. Thus experimental and numerical studies were conducted to investigate the effect of cavity insulation in both load bearing and non-load bearing walls. Experimental study was conducted on four full-scale wall panels with and without cavity insulation. Fire test results showed that cavity insulation delays heat transfer and is beneficial for non-load bearing walls. However, cavity insulation significantly reduced the fire resistance of load bearing walls. Numerical study was then conducted to obtain the structural adequacy failure times for varying levels of applied loads. This paper presents the results of these studies including the stud failure times and temperatures. The results showed that the use of cavity insulation significantly reduced the fire resistance levels of load bearing walls.

Keywords: Light gauge steel framed walls, Cavity insulation, Load bearing wall, Non-load bearing wall, Flame penetration, Cavity barriers.

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Introduction

In recent years, light gauge steel framed (LSF) walls are commonly used as load bearing and non-load bearing walls in building construction. This is due to their cost effectiveness, sustainability, consistent quality, resistance to external elements such as termites, pests and mildew, and fire and acoustic resistance. In general, LSF walls are made of conventional lipped channel section studs, unlipped channel section tracks, and lined with single or two layers of gypsum plasterboards and used with or without cavity insulation (Fig. 1). These wall lining materials delay the temperature rise of the studs by acting as a thermal barrier and prevent steel studs from being exposed to fire. The LSF walls form the compartmentation to meet the acoustic, energy and fire resistance requirements.

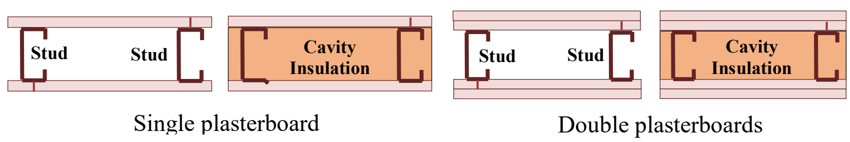


Fig. 1. LSF walls

Fire Resistance Levels (FRL) in minutes is considered as the fire performance indicator based on structural adequacy, integrity and insulation criteria and are determined by subjecting the wall panel to the standard fire time-temperature curve (SA, 2014). The fire behavioural characteristics of non-load bearing LSF walls are different from those of load bearing walls with only insulation or integrity failures governing their fire design. In non-load bearing LSF walls fire penetration to the ambient side is to be prevented for insulation and integrity failure criteria, whereas in load bearing walls, steel studs also need to be protected from heat for structural adequacy. When LSF walls are exposed to fire, heat transfer occurs across the cavity and steel studs heat up quickly and lose their strength. Passive fire protections act as a thermal barrier, preventing fire spread and structural collapse and protect lives in the event of a fire. There are several passive fire protection methods that depend on wall configurations, plasterboard thickness and number of layers, wall lining materials, insulation type and thickness, stud spacing and geometry (Alfawakhiri, 1999, Feng and Wang, 2003, Feng et al., 2005, Kodur and Sultan, 2006, Chen et al., 2012, Ariyanaygam and Mahendran, 2012, Gunalan et al., 2013 and Kesawan and Mahendran 2015). Insulating the wall cavity is one of the passive fire protection method.

During fire events, cavity insulation acts as a thermal barrier, resists the temperature rise and prevents flame penetration across the LSF walls. This will delay the temperature rise on the ambient side plasterboard surface. Further, as the heat energy is retained on the fire side, stud flanges on the fire side will have higher temperatures than the ambient side stud flanges, resulting in a high temperature gradient across the stud and thermal bowing deflection, and neutral axis shift due to loss of stiffness across the cross-section of the stud. However, this behaviour has not been investigated in detail and the influence of cavity insulation on FRLs is not quantified.

In this paper, the influence of cavity insulation is investigated by focusing on the fire resistance of both load bearing and non-load bearing LSF walls. An experimental study was conducted on the fire performance of LSF walls with and without cavity insulation. Full-scale fire tests of both load bearing and non-load bearing walls were conducted. This paper presents the details of the standard fire tests, and the results including the measured time-temperature curves of studs and gypsum plasterboards and the lateral deflection curves of the tested wall panels. Effects of cavity insulation on LSF walls are discussed and quantified based on fire test results. A numerical study was then conducted to further evaluate the influence of cavity insulation and the results are presented and discussed.

Experimental Studies

Fire test program consisted of four full-scale (3m x 3m) LSF wall panel tests. Test panels T1 and T2 were non-load bearing walls while T3 and t4 were load bearing walls (Table 1). All four test panels were lined with one layer of 16 mm thick gypsum plasterboard on both sides. Test panels T2 and T4 were cavity insulated with 75 mm thick glass fibre insulation (density 11 kg/m^3). Test wall panels were made of grade G300 steel 92*1.15 mm lipped channel studs spaced at 600 mm. 16 mm thick fire rated gypsum plasterboards were fastened to stud flanges at 200 and 300 mm spacing along the plasterboard edge studs and inner studs, respectively.

Table 1. LSF wall test panels and fire test results

Test wall	Cavity insulation	Remarks	Failure time (min)	Failure criterion
T1	-	Non-load bearing	94	Insulation
T2	Glass fibre (11 kg/m^3)	Non-load bearing	106	Insulation
T3	-	Load bearing (8 kN per stud)	77	Structural adequacy
T4	Glass fibre (11 kg/m^3)	Load bearing (8 kN per stud)	47	Structural adequacy

The stud and gypsum plasterboard surface temperatures were measured across the test wall panels using Type-K thermocouple wires. Thermocouple wires on the studs were connected to their hot and cold flanges (HF and CF) at the mid-height (1500 mm) of Studs 3 and 4, and at five locations on each plasterboard surface across the wall panel. The mid-height lateral (out-of-plane) deflections of Studs 3 and 4 were measured using displacement transducers placed at 1500 mm height.

Test wall panels were placed in the test rig as shown in Fig. 2. LSF wall studs were concentrically placed over six hydraulic rams positioned at a spacing of 600 mm. LSF wall fire tests were conducted using a 3 m x 3 m propane gas-fired furnace and the test wall panel was exposed to the standard fire time-temperature curve on one side (SA, 2014)]. T1 and T2 are non-load bearing wall panels, and thus an axial compression load of 0.5 kN was applied at each stud to support the self-weight of the wall panel. For load bearing test wall panels T3 and T4, an axial compression load of 8 kN per stud was applied. The applied load was calculated as 0.2 (Load ratio = 0.2) times the ambient temperature ultimate capacity (40.11 kN) of 92*1.15 mm lipped channel stud (Ariyanayagam and Mahendran, 2018).

In both non-load bearing Fire Tests T1 and T2, insulation failure occurred before the integrity or structural failure. The average ambient plasterboard surface temperature exceeded the temperature at the start of the fire test by 140^{o}C in Fire Tests LSF1 and LSF2 at 96 min (29+140^{o}C) and 106 min (28+140^{o}C), respectively. In load bearing Fire Tests LSF3 and LSF4, studs could not sustain the applied loads after 77 and 47 min, respectively, and structurally failed. Table 1 summarises the fire test results.

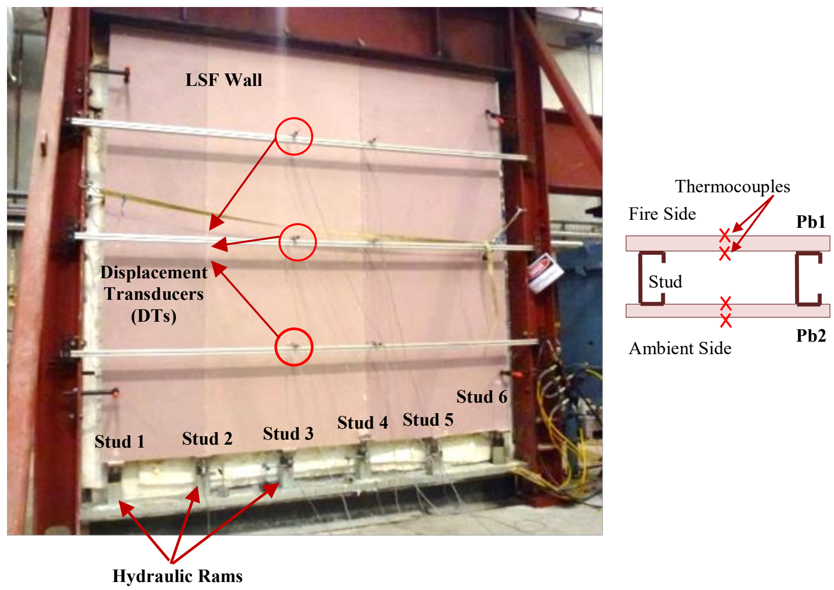
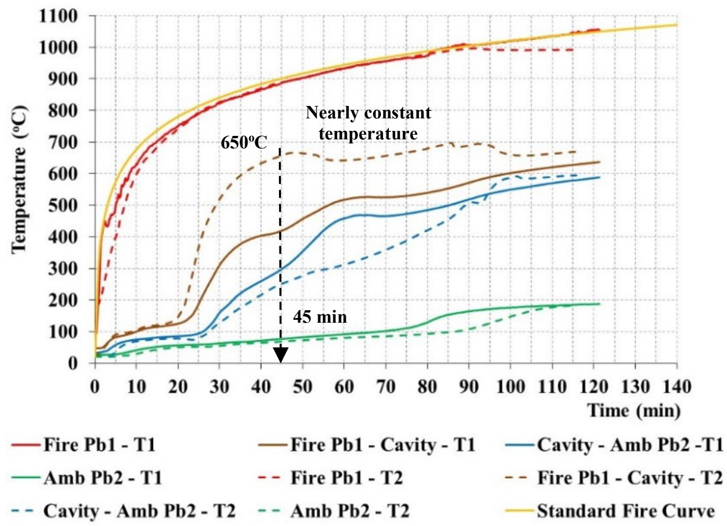


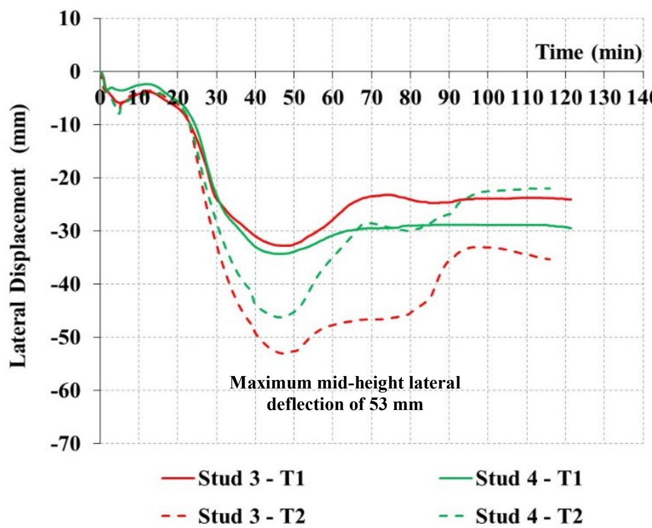
Fig. 2. LSF wall test set-up

All four LSF wall panels were lined with one layer of gypsum plasterboard, thus similar observations were made during the fire testing of walls in the first 20 to 25 min. In these fire tests, after about 5 min of starting the furnace, smoke appeared at the top of the wall panel and continued for about 2 to 3 min. This is due to the burning of the fire side paper layer of gypsum plasterboard (Pb1). Then after about 15 min, water drops were seen along the edges of the wall panel as a result of the dehydration process of gypsum plasterboard.

Fig. 3 shows the comparison of plasterboard time-temperature curves and lateral deflection curves of non-load bearing Fire Tests T1 and T2. The use of cavity insulation delayed the temperature rise on the ambient plasterboard surfaces. Ambient plasterboard temperatures (Amb Pb2) were well below those of the uninsulated wall for a longer period of time since cavity insulation retained the heat to the fire side of the plasterboard (Pb1). The use of cavity insulation increased the insulation failure time by 12 min (94 to 106 min).



(a) Average gypsum plasterboard time–temperature curves

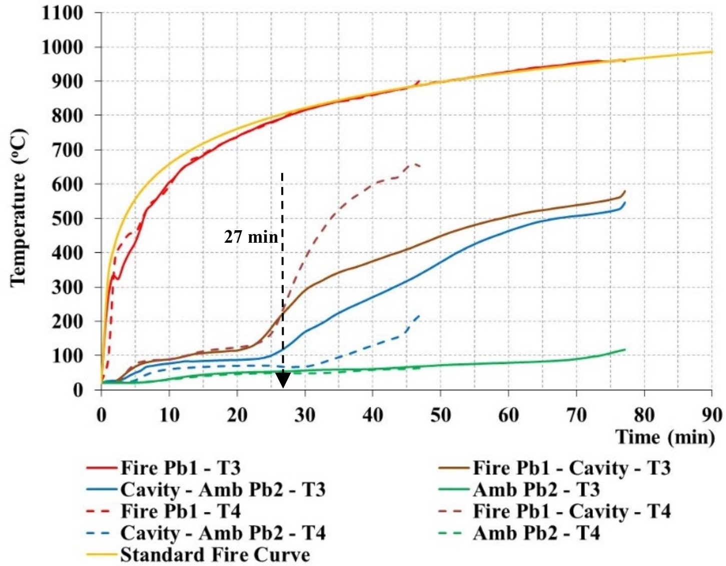


(b) Mid-height lateral deflection curves

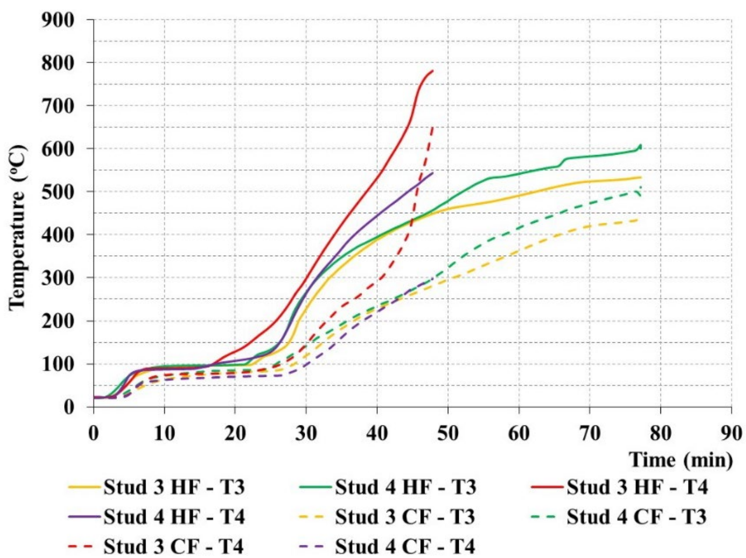
Fig. 3. Non-load bearing wall fire tests – T1 and T2

The difference in cavity facing plasterboard temperatures was above 400ºC in the early stages of the fire and reduced with time (Fig. 3(a)). This is because the glass fibre insulation used in the wall panel started to gradually melt across the wall cavity. Fig. 3(a) shows that glass fibre insulation started to melt after 45 min at about 650ºC. Thus at the later stages of fire, the heat was transferred across the cavity through radiation and convection, and the ambient plasterboard temperatures increased and merged with the uninsulated wall plasterboard surface temperatures. As seen in Fig. 3(b) the mid-height lateral (out-of-plane) deflection of cavity insulated wall was higher than that of the uninsulated wall. This is due to the thermal bowing of the wall panel as a result of the high temperature gradient across the cavity. High lateral deflection can cause the already dehydrated, calcinated and softened gypsum plasterboard on the fire side to deform and fall-off easily. This could remove the fire side thermal barrier and allow hot gases to penetrate the cavity and cause insulation failure earlier than for uninsulated wall panels. However, in Fire Test T2, fire side plasterboard fall-off was not observed even at the maximum mid-height lateral deflection of 53 mm for the 3 m high wall with 16 mm plasterboard lining.

Both T3 and T4 were load bearing walls with glass fibre cavity insulation in wall T4. Fig. 4 compares the fire test results of T3 and T4. Similar to the observations made for non-load bearing wall fire tests, fire side plasterboard and stud hot flange temperatures were much higher than those in the uninsulated walls. As before both cavity insulated and uninsulated wall temperatures merged well in the first 27 min, and thereafter significant temperature differences were observed (Fig. 4(a)). The stud temperatures in the insulated wall were seen to be rapidly increasing until the end of the fire test, whereas in the uninsulated wall, stud temperatures increased gradually after 40 min and lagged behind (Fig. 4(b)). This is due to the heat being trapped on the fire side due to the presence of cavity insulation. Similar behaviour was also observed in the stud lateral deflection curves (Fig. 4(c)), where the lateral deflections merged well for about 30 min. Thereafter the cavity insulated wall continued to deflect laterally due to the higher temperature gradient across the stud. This shows that the cavity insulation retained the heat on the fire side causing the studs to thermally bow towards the furnace. Thus the fire side gypsum plasterboard became softer with calcination process much earlier than in the uninsulated walls. Further the studs deflecting laterally removed at least a portion of the plasterboard causing the studs to lose its thermal barrier and temperatures to rise rapidly. This led to the failure of the studs earlier than in walls without cavity insulation (47 versus 77 min).

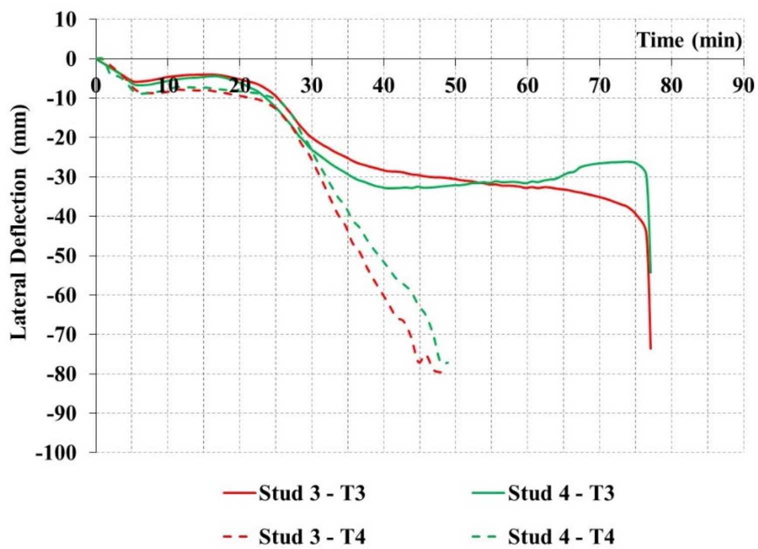


(a) Gypsum plasterboard time – temperature curves

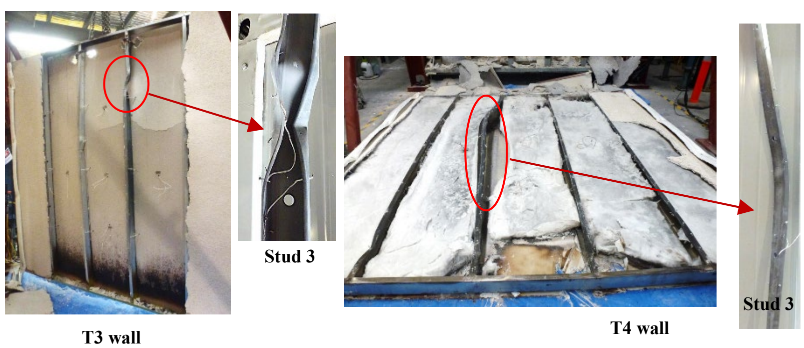


(b) Stud time – temperature curves

Fig. 4. Load bearing wall fire tests – T3 and T4



(c) Mid-height lateral deflection curves



(d) Stud failures

Fig. 4. Load bearing wall fire tests – T3 and T4

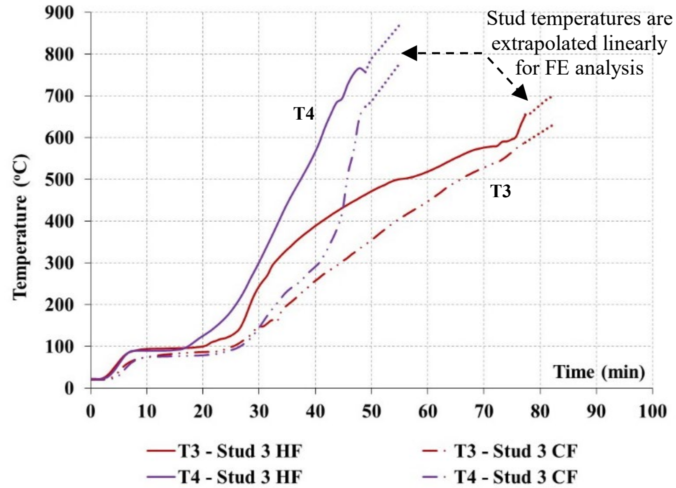
Fig. 4(d) shows the stud failure modes of load bearing walls T3 and T4. It shows that in T3, Stud 3 failed by local compressive failure and flexural-torsional buckling at the top 1/3rd height and in T4, Stud 3 failed predominantly by flexural-torsional buckling. This is due to the fire side plasterboard (Pb1) fall-off as a result of being exposed to higher temperatures than the uninsulated wall, resulting in the removal of plasterboard flexural-torsional restraints of the stud.

In summary, the use of cavity insulation will increase the insulation failure times of non-load bearing walls. However, in load bearing LSF walls the structural adequacy based FRL is more critical and the use of cavity insulation reduced the stud failure times. Fire test was only conducted on LSF walls lined with one layer of 16 mm gypsum plasterboard for a load ratio of 0.2 and the results showed that cavity insulation had a negative impact on the fire resistance of load bearing walls. Finite element analyses were performed next to quantify this effect on varying load levels.

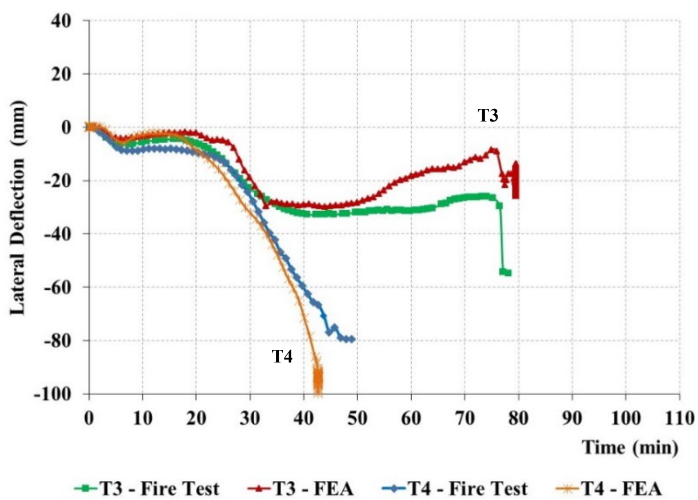
Numerical Studies

In this section numerical studies were performed to investigate the effects of varying axial compression load levels on the fire performance of cavity insulated load bearing LSF walls. For this purpose, structural finite element models of fire tested load bearing wall panels (T3 and T4) were developed and then validated using the fire test results reported in the previous sections. This was followed by a parametric study on varying axial compression loads on steel stud walls.

Transient state non-linear FE analyses were performed to predict the structural failure times of the fire tested load bearing walls. FE model and analysis method used in this study were similar to that described for single LSF wall studs under axial compression and exposed to non-uniform temperature distributions in Feng and Wang, 2003 and Ariyanayagam and Mahendran, 2014. Single LSF wall stud with appropriate boundary conditions was considered in the FE analysis. The shell element type S4R with 4 mm mesh size was used. The Multiple Point Constraints (MPC) was used to simulate the end constraints. The ends of the studs were restrained about the two major axes (y and z) while twisting was restrained about the x-axis. Also, the axial displacement was restrained along x-axis at one end. The measured ambient temperature mechanical properties, i.e. yield strength = 339 MPa and elastic modulus = 197,909 MPa, were used. The elevated temperature properties were calculated based on the reduction factors given in Kankanamge and Mahendran, 2010, and the thermal expansion coefficient was obtained from Eurocode 3 Part 1.2 (ECS, 2002). For FE model validation, the failed stud temperatures, i.e. Stud 3 temperatures in both tests T3 and T4, were selected (Fig. 5). Structural FE analyses of studs exposed to fire were performed under transient state conditions, where the axial compression load was applied to the stud first and the stud temperatures were increased at every minute until failure. For this purpose, a coupled temperature-displacement analysis was selected in Abaqus CAE with transient state analysis conditions.



(a) Average stud temperatures used in FE analyses



(b) Mid-height lateral deflection curves

Fig. 5. Finite element analysis of LSF wall studs – T3 and T4

Structural FE analyses conducted on Test walls T3 and T4 predicted the stud failure times as 80 and 42 min, respectively and the stud failure times in the fire tests are 77 and 47 min. The predicted failure times are within 5 min to that of fire tests. The differences in failure times between the fire tests and FE analyses were due to the approximations of stud temperatures used in FE analyses. Fig. 5(b) shows that the FE analysis predicted mid-height lateral deflections agreed reasonably well with the fire test results. These comparisons show that the developed FE model is capable of predicting the LSF wall stud failures with reasonable accuracy. The aim of this numerical study is to investigate the effect of varying axial compression loads on the FRL of load bearing walls with and without cavity insulation, thus using the above validated FE model, a parametric study was conducted.

The failure stud temperatures (Stud 3) obtained from Fire Tests T3 and T4 were used in this study (Fig. 5(a)). As before transient state analyses were conducted where the stud was subjected to a predetermined axial compression load and then the stud temperatures were increased until failure. The applied axial compression load was based on the load ratios at 0.1 intervals from 0.2 to 0.8.

Fig. 6 shows the load ratio versus stud failure times of single gypsum plasterboard lined LSF wall with and without cavity insulation. The stud failure times, i.e. structural adequacy based FRLs of cavity insulated walls are less than those of uninsulated walls. At lower load ratios (LR = 0.4) the reductions in failure times are significantly high compared to those at higher load ratios (LR = 0.7). For instance, at LR of 0.7 the stud failure time reduced from 29 to 25 min while at LR of 0.4 it reduced from 46 to 35 min. At load ratio 0.2 the difference in stud failure time further reduced from 80 to 42 min in cavity insulated LSF wall. That is 38 min, i.e. 47% reduction in stud failure time for load ratio of 0.2. This is a significant reduction due to the use of insulation in the wall cavity.

In the initial stages of the fire the wall lining on the fire side delays the cavity temperatures and both walls with and without cavity insulation had similar temperatures during this time period. Therefore at higher LR (0.7), the stud failure times were about the same. However, with increasing fire duration, cavity insulation restricted the heat transfer across the cavity, thus stud hot flange temperatures rise rapidly in cavity insulated walls than in uninsulated walls. This generates higher thermal gradient across the stud, resulting in neutral axis shift, eccentric loading and higher second order deflection due to bending. Thus cavity insulated wall studs structurally failed much earlier than the uninsulated wall studs. Previous studies on the LSF wall studs exposed to non-uniform temperature distribution highlighted that stud hot flange temperature was the governing parameter for load bearing walls (Gunalan et al., 2013 and Ariyanayagam and Mahendran, 2014). This study has highlighted the detrimental effect of having cavity insulation in load bearing LSF walls. Thus if any passive fire protection is to be provided for load bearing walls, it should resist the stud hot flange temperature rise in order to have an increased structural adequacy based FRL.

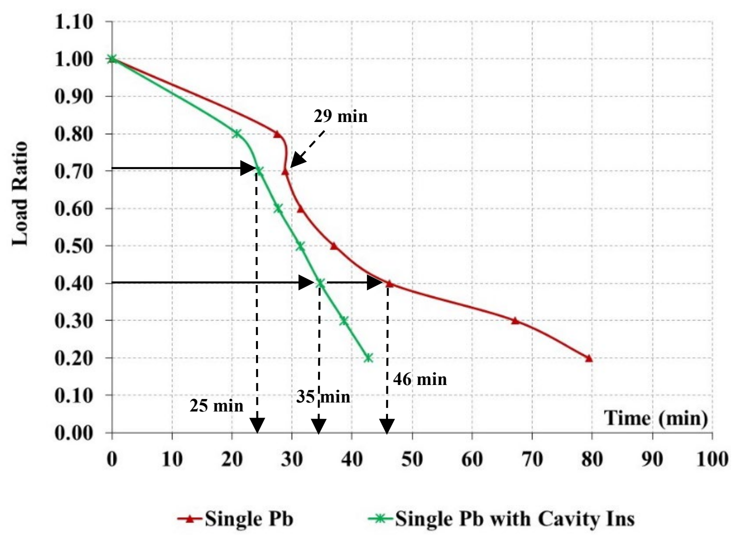


Fig. 6. Load ratio versus failure time curves of LSF walls

Conclusions

This paper has presented the details of full-scale standard fire tests conducted on both non-load bearing and load bearing LSF walls with and without cavity insulation. Fire test results showed that cavity insulation restricts the heat transfer across the wall, thus it delays the temperature rise on the ambient plasterboard surface. This behaviour increases the insulation failure time, i.e. fire resistance level (FRL) of non-load bearing walls. However, stud hot flange temperatures increase rapidly and causes the studs to fail much earlier than the uninsulated wall studs in load bearing LSF walls. The use of glass fibre cavity insulation increased the insulation FRL of non-load bearing walls by 12 min while it reduced the FRL of load bearing walls by 30 min for the 16 mm gypsum plasterboard lined walls tested in this study.

Structural finite element analysis based parametric study was conducted on load bearing walls with and without cavity insulation for varying applied load levels. The results showed that the use of cavity insulation reduced the FRL of load bearing walls significantly for load ratios below 0.4. For a load ratio of 0.2, the stud failure time was reduced by 47% (38 min). This study has highlighted the benefits of using cavity insulation in non-load bearing LSF walls and its detrimental effects in load bearing LSF walls.

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