STEEL INNOVATIONS 2013 | Christchurch February 21-22

Steel Innovations Conference 2013
Christchurch, New Zealand
21-22 February 2013

FIRE PERFORMANCE OF LSF WALLS MADE OF HOLLOW FLANGE SECTION STUDS

S. Kesawan[1] and M. Mahendran[2]

ABSTRACT

Load bearing Light Gauge Steel Frame (LSF) walls made of cold-formed steel studs and tracks are commonly used in residential and commercial buildings. Fire safety of these walls is essential to minimize the damage caused by fire related accidents. Past investigations on the fire performance of load bearing LSF wall systems have been limited to LSF walls made of conventional lipped channel section studs. Although structurally efficient hollow flange steel sections are available in the building industry, they are not used as LSF wall studs due to the lack of fire performance data for such walls. The hollow flange sections have torsionally rigid hollow flanges that eliminate the occurrence of local and distortional buckling to an extent, thereby increasing their structural efficiency. The weaknesses of hollow flange sections such as lower lateral distortional buckling capacity are also eliminated when they are used as studs of LSF walls as the plasterboard restraints will prevent any lateral movement. Therefore hollow flange sections can be considered as structurally more efficient studs for use in LSF wall systems. This paper reports the full scale fire tests of LSF walls made of hollow flange section studs under standard fire conditions. The frames were made of 1.6 mm thick and 150 mm deep hollow flange section studs with two closed rectangular flanges of 45 mm width x 15 mm depth. Dual plasterboards were attached on both sides of the test wall panels. The load ratio was varied and the failure times, the lateral deflections and the axial displacements of the test walls were obtained. The failure behaviour of LSF walls made of hollow flange section studs was found to be different to that of LSF walls made of conventional lipped channel section studs. The results of these fire tests show that hollow flange section studs have a higher potential in being used in load bearing LSF Walls.

Introduction

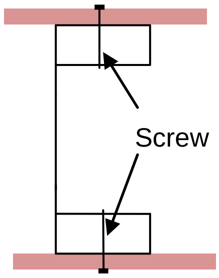
Load bearing Light Gauge Steel Frame (LSF) walls are increasingly used in the building industry and are commonly made using conventional lipped channel section studs and tracks. The LSF wall frame is normally protected by fire resistant plasterboards on both sides. Other section profiles can also be used as studs and among them the hollow flange sections are structurally more efficient for which the occurrence of local, global and distortional buckling are eliminated to an extent, when they are used as studs in LSF walls. These sections may also be structurally efficient during fire conditions. The screws which connect the plasterboards and studs could penetrate through both the inner and outer flanges of the hollow flange section stud and as a result, the connectivity between the plasterboards and the steel studs is enhanced. This can increase the fire performance of LSF walls. Previous researchers (Alfawakhiri 2001, Ariyanayagam and Mahendran 2011, Feng and Wang 2005, Gerlich et al. 1996, Gunalan et al. 2010, Kodur and Sultan 2001 and Zhao et al. 2005) have investigated the fire performance of LSF walls made of conventional lipped channel sections. However the fire performance of LSF walls made of hollow flange sections is yet to be investigated.

In this research, full scale fire tests were conducted to determine the fire resistance rating of load bearing LSF walls made of hollow flange section studs. The LiteSteel Beam sections (Fig. 1(a)) are the only commercially available type of hollow flange sections, and were used to make the test walls. The LiteSteel Beams used were of 150 mm depth and 1.6 mm thickness and have two closed rectangular flanges of 45mm width x 15 mm depth. Either single or dual plasterboards were attached on both sides of the steel frame. The wall specimen subjected to an axial compression load was exposed to standard fire conditions from one side to determine its fire resistance rating. The failure time, failure temperature, failure mode and the temperature

[1]PhD researcher, Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000
[2]Professor, Science and Engineering Faculty, Queensland University of Technology, Brisbane, QLD 4000

profiles of the plasterboards and steel studs were compared with past experimental investigations of Gunalan et al. (2010) and Ariyanayagam and Mahendran (2011) on LSF walls made of conventional lipped channel section studs. Test results will be used to develop numerical models capable of predicting the thermal and structural performance of LSF walls made of hollow flange section studs in fire conditions.

(a) LiteSteel Beam



(b) Connectivity between stud and plasterboard

Figure 1. Hollow flange section

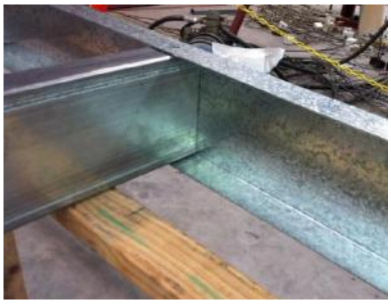
This paper describes the fire tests of LSF walls made of LiteSteel beam section studs, and presents the test results. The fire performance of LSF walls made of hollow flange section studs is explained by the clear interpretation of test results. Test results are also compared with the previous researchers' test results on LSF walls made of conventional lipped channel sections and the differences are identified. The reasons for the superior fire performance of LSF walls made of hollow flange section studs are also discussed.

Experimental Investigation

Test specimens

The LSF wall test specimens were of 2.1 m in width and 2.4 m in height. The LSF walls in buildings are also commonly of 2.4 m in height and the maximum wall height that could be accommodated in the available gas furnace at the QUT laboratory is 2.4 m. The LiteSteel Beam (LSB) section shown in Fig. 1, the only commercially available hollow flange section, was used as the stud sections in building the wall frame. The chosen LSB sizes were 150 x 45 x 15 x 1.6 mm. The actual yield strengths were measured (see Table 1). The LSB studs were spaced at 600 mm and connected to channel section tracks of 2.1 m in length at both ends. The channel section tracks were of 1.9 mm thickness and made of G450 steel. The LSB studs were connected to the channel section tracks using 10g wafer head screws of 10 mm in length. The LSF wall frame made of LSB stud sections and its connections are shown in Figs. 2(a) and (b).

(a) LSB studs and Channel section tracks



(b) Stud and track connections

Figure 2. Fabrication of test specimen

Table 1. Yield strengths of LiteSteel Beam sections

LSB plate elements	Yield Strength (MPa)	Elastic Modulus (MPa)
Web	479	199,855
Inner Flange	511	194,407
Outer Flange	607	204,261

The plasterboards were then lined on both sides of the steel frame. Gypsum plasterboards manufactured by the Boral Plasterboard industries according to the requirements of AS/NZS 258 – Gypsum Plasterboard (SA,

1998) were used. These boards known as Firestop were of 2400 mm in length, 2100 mm in width and of 16 mm thickness and were manufactured at the factory located in Pinkabella, Queensland, Australia.

The plasterboards were installed in accordance with the guidance of AS/NZS 2589.1 (SA,1997). The first and second layers of plasterboards were attached vertically and horizontally, respectively on both sides. The 8g buffle head screws of 50 mm and 65 mm length were used for the connection between the steel frame and the plasterboards. The screw spacing was maintained at 300 mm, but at the joints the screws were spaced at 200 mm. The screws penetrated through the inner and outer flanges of the LiteSteel Beam studs. This kind of connection improves the connectivity of the plasterboards with the steel studs. Previous researchers (Gunalan et al. 2012 and Ariyanayagam and Mahendran 2011) who investigated the fire performance of LSF wall systems made of conventional lipped channel section studs have reported that the screws had been bent and the connection had been loosened at the end of the tests. The penetration of the screws through both the inner and outer flanges of the hollow flange section studs can enhance the connectivity. As a result, the plasterboard fall off can be prevented or delayed during fire conditions. This is likely to increase the fire performance of LSF walls. The plasterboard joints were filled with joint sealant. A reinforced paper tape of 50 mm width was kept on top of the joint sealant and then covered with the joint sealant. The procedure adapted in sealing the joint is shown in Figs. 3(a), (b) and (c).

(a) (b) (c)

Figure 3. Plasterboard lining and joint sealing

Thermocouples were attached to measure the temperature variation on the plasterboard surfaces and steel studs. K type thermo couples were used for this purpose. In each face of the plasterboard layer five thermocouples were attached. Three thermocouples were attached at mid-height (0.5h) and another two were attached at a height of 0.75h and 0.25h, respectively. The temperature inside the furnace was measured using K type thermocouples that were placed inside the furnace chamber at four locations. Thermocouples were also attached on the steel studs. They were attached on both the outer and inner flanges and on the centre of the web. Thermocouples were attached at three locations (0.25h, 0.5h and 0.5h) on the middle studs (Studs B and C), and for the remaining studs (Studs A and D), the temperature was measured at mid-height only. The locations of the attached thermocouples across the section are shown in Fig. 4. Linear variable differential transformers (LVDT) were used to measure the axial and lateral displacements during the test. Horizontal bars were fixed at 0.25h, 0.5h and 0.75h height at the wall. The LVDTs were attached to the bars and the lateral displacements were measured.

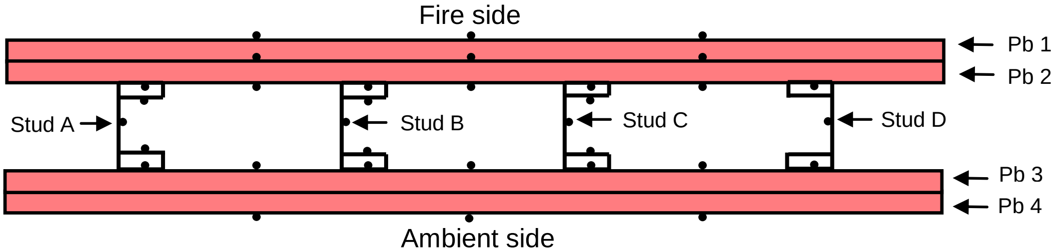
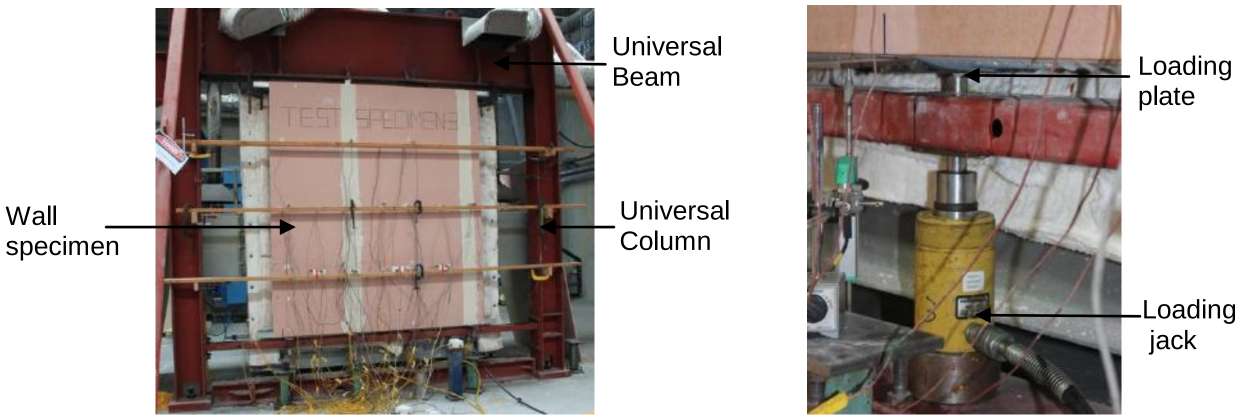


Figure 4. Locations of thermocouples

The built test wall was then placed within the loading frame specially designed to accommodate the test wall specimen (Fig. 5(a)). The frame consists of two Universal Columns bolted firmly to the ground and at the top a Universal Beam is connected to these columns. At the bottom another Universal Beam is bolted to the ground. The loading system was kept underneath the test wall specimen and a very small load was applied. The verticality of the wall was tested using levels at different locations. The load was applied using hydraulic jacks of 25 ton capacity at the centroid of each of the steel studs. The loading system is shown in Fig. 5(b).



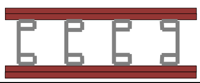
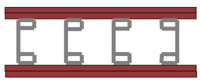
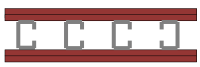
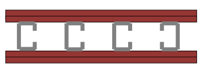
(a) Test frame (b) Loading system

Figure 5. Test Frame and the loading system

A manual hydraulic pump was used to apply the loading. The applied pressure maintained in each jack was the same. A pressure transducer was used to measure the pressure, and the jacks were calibrated using a 100 kN load cell. Therefore during the testing the load was monitored using the measured pressure. The pressure readings were then converted to Loads (kN) using the calibrated values. During testing the load increases were observed due to the thermal expansion of the steel studs. To overcome this the pressure was released using the release valve so that the load was maintained constant during the entire test.

The ratio between the applied axial compression load on the wall system during fire conditions and its ambient temperature capacity is called the load ratio. Generally the load ratio is between 0.35 – 0.45. The load ratio applied on our three test wall specimens are given in Table 2. The capacity of the LSF wall studs at ambient temperature was found by using finite element modelling. The target load for the fire tests were either 20% or 40% of its ambient temperature capacity, ie. 41.5 kN and 83 kN, respectively. At first, 50% of the target load was applied and then unloaded. This was to eliminate any residual strains and initial slackness that could be present in the wall during its fabrication and mounting of the wall specimen. The load was applied at a constant rate using the hydraulic jacks.

Table 2. Test wall specimen details

Test Specimen	Wall Configuration	Steel Stud size	Load Ratio	Fire curve
Test 1		150 x 45x 15 x 1.6	0.4	Standard
Test 2		150 x 45x 15 x 1.6	0.2	Standard
Test 3		150 x 45x 15 x 1.6	0.2	Standard
Gunalan et al. (2012) Test X		90 x 40 x 1.15	0.2	Standard
Ariyanayagam and Mahendran (2011) – 1 Test Y		90 x 40 x 1.15	0.2	Real Fire curve*
Ariyanayagam and Mahendran (2011) – 2 Test Z		90 x 40 x 1.15	0.2	Real Fire curve**

*Eurocode Parametric curve ** Modified BFD curve

The propane gas furnace available in the fire research laboratory at the Queensland University of Technology was used to simulate the required standard fire conditions on the wall. The dimensions of the furnace used were 2.4 x 2.1 m, ie. the same as the wall specimens. The furnace is able to provide heat in accordance to the given time-temperature profiles. The furnace has six burners and thus ensures the development of uniform temperature on the wall specimen. Our tests were conducted by exposing the wall specimens to the temperatures given by the standard fire curve given in AS 1530.4 (SA, 2005). The standard fire curve equation is given by Eq. 1.

$T_t - T_o = 345 \log10 (8t+1)$ (1)

where,

t is the elapsed time in minutes

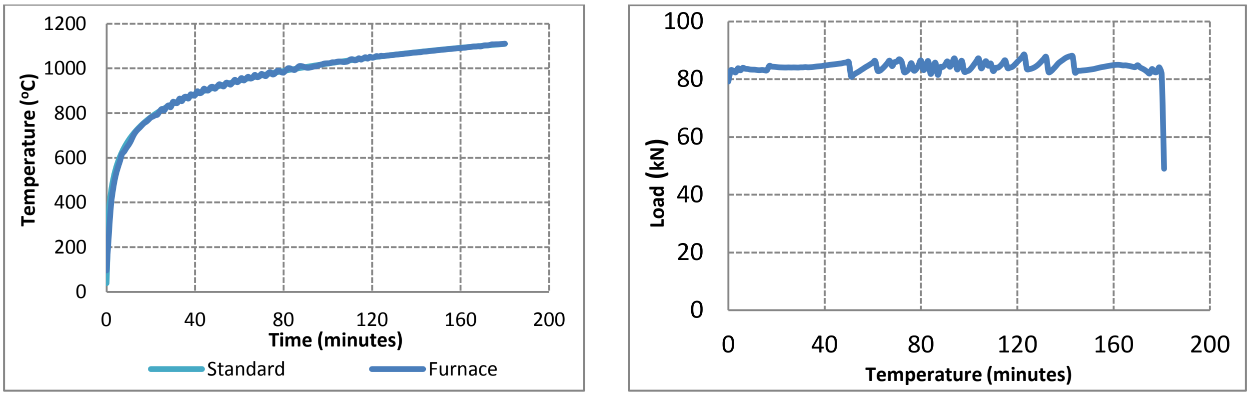
T_t is the furnace temperature (^{O}C) at time t

T_o is the ambient temperature at the beginning of the test

The temperature, displacement and pressure values were recorded with time during the experiment. LABVIEW software was used for this purpose. Details of our three LSF wall specimens made of LiteSteel beam sections are given in Table 2. It also includes the test details of Gunalan et al. (2012) and Ariyanayagam and Mahendran (2011) on the fire performance of LSF walls made of conventional lipped channel section studs. Their results will be used in this paper for comparison purposes.

Testing Procedure

The standard fire curve was selected in the furnace programme controller. The furnace was then started and the data acquisition system was also activated to record the data. The temperature development inside the furnace chamber is the same as the standard time-temperature curve given by AS 1530.4 (SA, 2005). Fig. 6(a) shows the developed time-temperature curve in the furnace and the required standard time-temperature curve in AS 1530.4, both of which agree quite well. The load was maintained constant throughout the test. During the test, the load started to increase because of the thermal expansion. This was adjusted by the use of the release valve in the hydraulic pump. At the time of failure, the applied load on the wall panel could not be maintained and dropped off rapidly as seen in Fig. 6(b). The failure was confirmed by the displacement graph and through visual observation.



(a) Standard curve versus Furnace temperature (b) Load versus time

Figure 6. Test results

Test Observations

The testing environment was very quiet for the first few minutes in all three tests. The smoke then started to develop slowly through the top of the wall specimen. This was due to the burning of the paper of the exposed side plasterboard surface. The intensity of the smoke increased with time and then decreased. This process was repeated when each plasterboard surface paper was burnt. In addition to the smoke, water drops started to appear on the top Universal Beam and then started to fall off from the top beam. The fallen water drops were visible on the bottom RHS of the frame. This was due to the evaporation of free and chemically combined water in the gypsum plasterboards.

In Test 1, the failure occurred after 180 minutes. The wall moved towards the furnace progressively due to the thermal bowing effect, and near the failure point, a very rapid lateral movement of the wall was observed. The failure occurred by flexural torsional buckling of Stud B. The failed wall specimen was carefully inspected the next day. The second (outer-pb1) layer of fireside plasterboards had partially fallen off with the loss in the middle portion. However, at the ends a very small portion of the plasterboards was retained. This was because at the ends the temperature might have been lower than at other places. The second layer of fire side plasterboards had completely calcinated, but the first (inner-pb2) layer of fire side plasterboards stayed intact with the frame. However, a big vertical crack appeared throughout the entire length of the plasterboards on top of Stud B. It had spread from the bottom track to the top track. At the ends the crack width was very small. However, towards the middle of the wall, the crack width increased. The plasterboard joint on top of Stud C was completely dislodged. Stud B had bent towards the furnace about the major axis and twisted about the minor axis. The compression side of the studs had buckled and yielded. This clearly indicated that Stud B had failed due to flexural torsional buckling. Local buckling waves were clearly present throughout the entire length of Stud B. This shows that Stud B had undergone local buckling prior to flexural torsional buckling failure. Local buckling waves and a small twist about the minor axis were observed in Stud C. The time-temperature profiles of the plasterboard surfaces and hollow flange section studs are given in Figs. 7 and 8. The interface symbols in Fig. 7 are defined in Fig. 4. The failure pictures are given in Fig. 9.

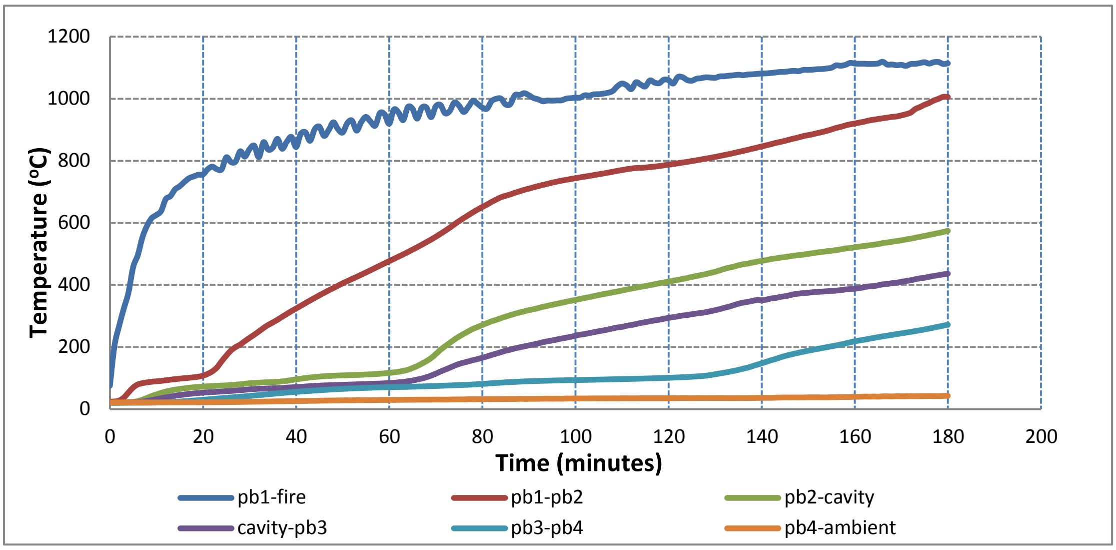


Figure 7. Time-Temperature profiles of the plasterboard surfaces in Test 1

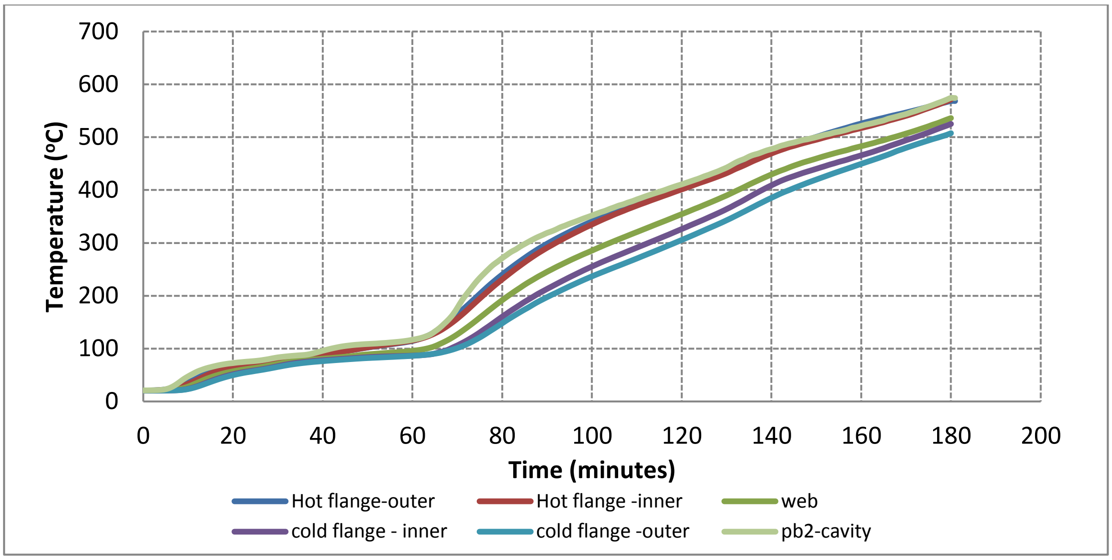


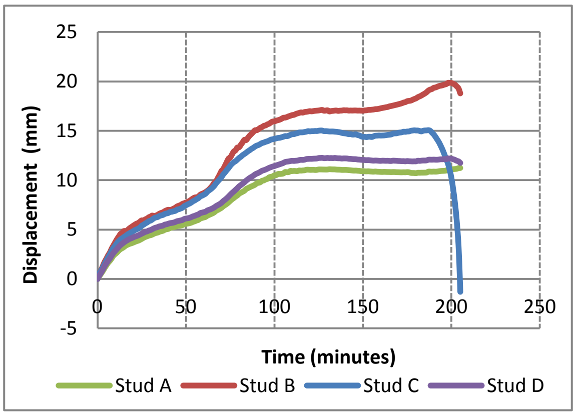
Figure 8. Time-Temperature profiles of the steel stud surfaces with time in Test 1

The temperature plateau observed in Fig. 8 at about 100^{o}C is because of the evaporation of the chemically combined and free water content of the plasterboards. After the plateau, the fire side temperature of the plasterboard increased. However after some time, the increment rate was reduced. At about 170 minutes, there was a sudden increase in temperature. This was because of the partial collapse of the second (outer) layer of the fire side plasterboards. The temperature profile of Stud B showed that there is a difference in temperatures between hot and cold flanges after 70 minutes from the beginning of the test. This difference increased in the next 25 minutes, followed by a reduction afterwards in the test.

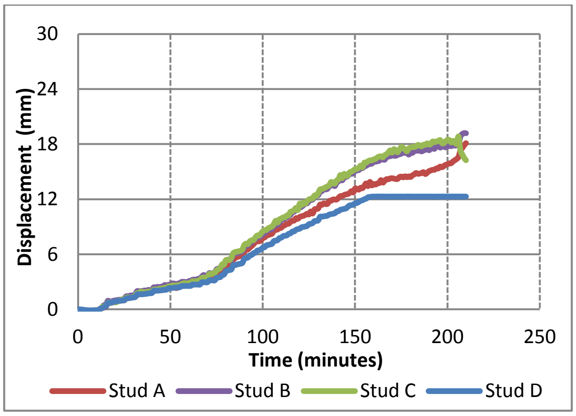
(a) Partial fall off of plasterboards

(b) Failed LSB stud

Figure 9. Failure of wall specimen in Test 1



(a) Lateral displacement



(b) Axial displacement

Figure 10. Lateral and axial displacement versus Time curves

In Test 2 also, smoke and water drops were visible. The wall moved towards the furnace from the beginning of the test, however closer to the failure sudden reversal in the direction of lateral movement was observed. The lateral and axial displacements of the studs are shown in Fig. 10. The failure time was 205 minutes. Careful inspection after the test showed that Stud C had bent away from the furnace about the major axis and twisted about the minor axis. Local buckling waves were clearly present throughout the entire stud length in Stud C. This clearly shows that Stud C had undergone local buckling prior to the flexural torsional buckling failure. The time-temperature profiles of Test 2 were similar to those of Test 1.

Table 3. Fire test results

Test Specimen	Failure Mode	Failure Time (minutes)	Failure Mode	Hot Flange Temperature (^{o}C)
Test 1	Structural	180	Flexural torsional buckling	569
Test 2	Structural	205	Flexural torsional buckling	706
Test 3	Insulation/ Structural	85/136	Flexural torsional buckling	745
Gunalan et al. (2012) - Test X	Structural	111	Local Section failure	555
Ariyanayagam and Mahendran (2011) – Test Y	-	No failure	-	-
Ariyanayagam and Mahendran (2011) – Test Z	Structural	139	Local Section failure	604

In Test 3, the average ambient side temperature surpassed 140^{o}C after 85 minutes. Therefore, the failure criterion was insulation failure. However, even after the insulation failure, the test was continued until the structural failure. The structural failure occurred after 136 minutes. Similar to Test 2, the wall moved towards the furnace and then reversed its direction closer to the failure. Local buckling waves were visible throughout Stud C. Stud C had bent away from the furnace about the major axis and twisted about its minor axis. Therefore the structural failure mode was flexural torsional buckling initiated by local buckling. The results of all three tests are summarized in Table 3. Test results of Gunalan et al. (2012) and Ariyanayagam and Mahendran (2011) are also given in Table 3 for comparison purposes. These test results revealed the superior fire performance of LSF walls made of hollow flange section studs in comparison to LSF walls made of conventional lipped channel section studs.

Comparison of Test Results with Previous Researchers' Test Results

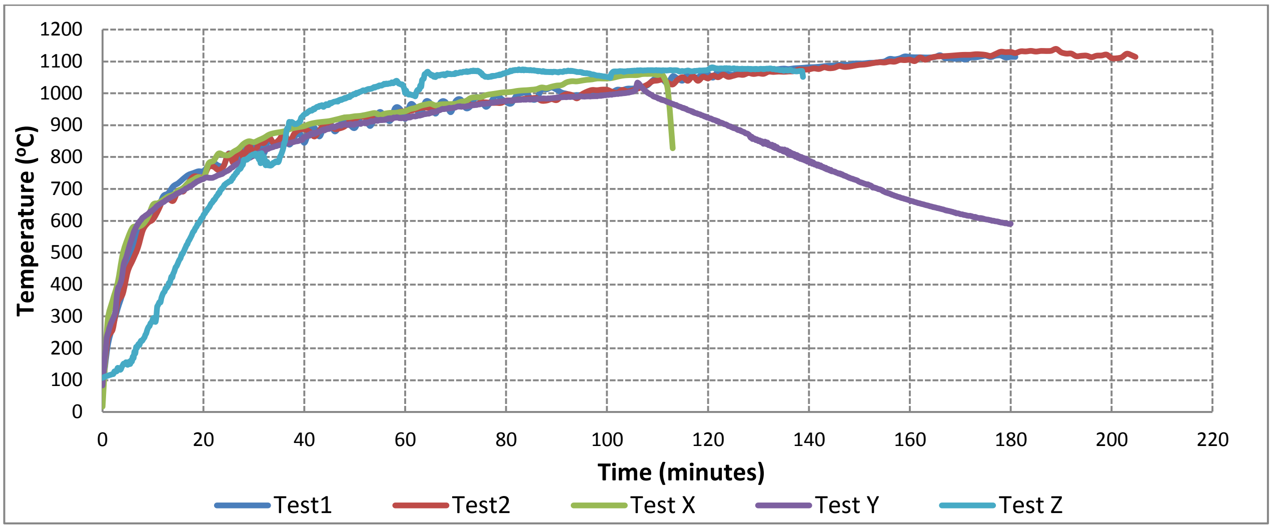


Figure 11. Temperature profiles of the furnace during the Test

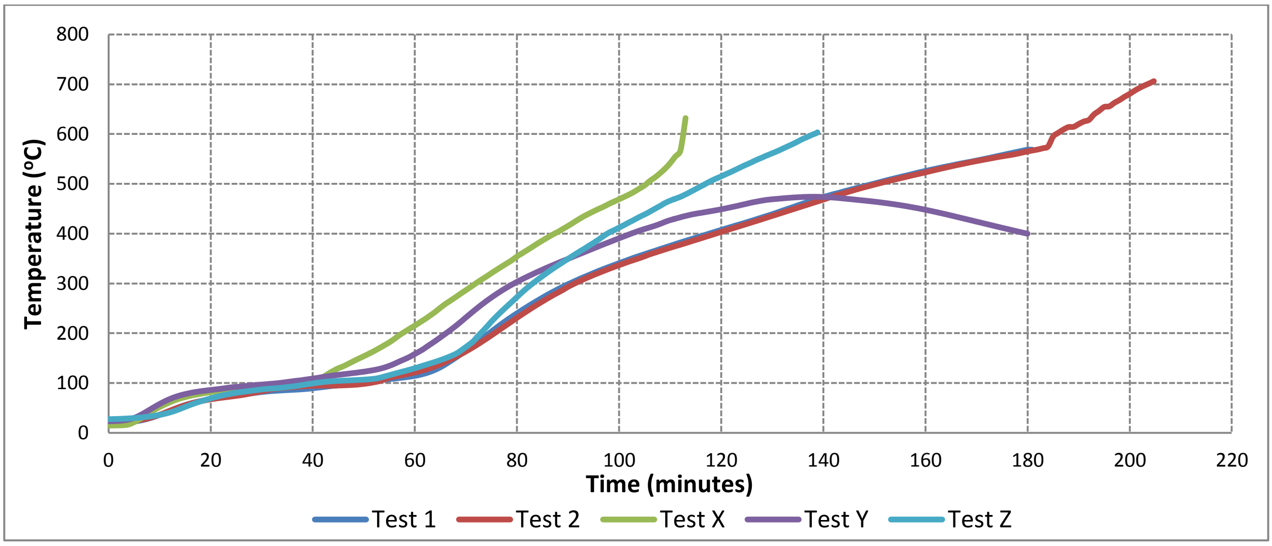


Figure 12. Hot flange temperature of failed studs

The LSF walls with hollow flange section studs showed superior fire performance in comparison to the LSF walls with conventional lipped channel section studs. The improved fire performance can be due to the following reasons.

- Stud section shape and size, and the steel type used
- Difference in the applied time-temperature curves
- Improvement in the quality of the plasterboards
- Increased cavity size
- Improved connectivity between the plasterboards and steel studs

In Tests 1 and 2, the furnace temperature was the same during testing as shown Fig.11. Further, the furnace temperature profile of Test Y also coincided with that of Test 1 until 110 minutes, and then the furnace temperature profile of Test Y started its decay phase. From about 40 to 140 minutes, the furnace temperature of Test Z was higher than Tests 1 and 2, but then the temperature profiles coincided with each other (see Fig.11). The only variable between Tests 1 and 2 was the applied load. According to Fig.12 the hot flange temperatures of the failed studs in Tests 1 and 2 almost coincided. Therefore it can be concluded that the applied load did not affect the temperature development across the LSF wall cross-section.

In Test X, the hot flange temperature profile was the same as for Tests 1 and 2 for the first 40 minutes. However, Test X hot flange temperature was higher afterwards. The temperature difference increased afterwards throughout the test, and the difference was about 150^{o}C near the failure. This could be due to the following reasons,

- Gunalan et al.'s (2012) Test X was conducted five years ago. The quality of plasterboard (thermal properties) available now might have improved.
- The amount of moisture content in the plasterboards might have been different between batches.
- In Gunalan et al.'s (2012) Test X, furnace temperature was higher than that in Tests 1 and 2

The hot flange temperature profiles of Tests1 and 2 are also compared with Test Y in Fig. 12. The hot flange temperature profile of Test Y coincided with that of Tests 1 and 2 until 70 minutes. After that, the hot flange temperature of Test Y is about 60^{o}C higher than that of Tests 1 and 2 until the decay phase. Previous researchers (Feng et al. 2003 and Keerthan and Mahendran 2012) have stated that the section profiles will not affect the temperature development across the LSF wall sections. Further, Keerthan and Mahendran (2012) have stated that the difference caused in the time-temperature profile due to the increase in cavity size is also smaller. However, these statements are based on their developed finite element models. In this research the effect on the time-temperature profiles due to the difference in steel section was observed through experimental investigation. The results are in agreement with the previous researchers' finite element analysis results. Among Tests Y, 1 and 2, the difference between the hot flange temperatures is very low. The possible reasons for the difference could be the influence of cavity size and there could be temperature loss (heat loss) on the top and bottom of steel studs because the area of the wall exposed to the environment was higher in Tests 1 and 2. Although the temperature differences due to larger cavity size was small, it had contributed to the improvement in fire resistance rating of the wall, to a greater extent.

Tests X and Z were conducted for a load ratio of 0.2. Their failure hot flange temperature is about 555 to 604^{o}C degrees. However, the failure hot flange temperature in Test 1 (load ratio = 0.4) and 2 (load ratio = 0.2) are 580^{o}C and 700^{o}C degrees, respectively. Gunalan et al. (2012) and Ariyanayagam and Mahendran (2011) conducted their test using conventional lipped channel section studs made of cold-formed steel. The tests described in this paper used hollow flange section studs (LiteSteel Beam) which are made from Duograde steel. Also the LiteSteel Beam studs have a different manufacturing process. So the elevated temperature mechanical properties of the LiteSteel Beam studs could be considerably different. Therefore, the difference in failure temperature could be associated with the difference in mechanical properties (yield strength and elastic modulus) reduction factors at elevated temperatures of the steel type. In addition to that, the difference could have been because of the section shape as well. Therefore, as future research work, the mechanical properties of the plate elements in LiteSteel Beam need to be determined experimentally. Further, the influence of section profiles on the fire performance should be investigated using computer models. For the hollow flange section studs, the ambient temperature structural capacities were determined using the numerical models. There is a possibility that if the actual ambient temperature capacity was higher, the load ratio applied in the tests could be less than 0.2. This may have increased the failure time.

Improved connectivity between the plasterboards and steel studs may also have contributed to the enhanced fire performance of LSF walls made of hollow flange section studs. Hollow flange section studs have inner and outer flanges. The plasterboards are connected to the steel studs with screws that penetrate into the inner and outer flanges. However in Tests X, Y and Z, the screws penetrated only through one flange of the conventional lipped channel section. Also in Tests 1 and 2, 8g (4.2 mm) screws were used, but they were 6g (3.5 mm) screws in Gunalan et al. (2012) and Ariyanayagam and Mahendran (2011). However, the screw spacing was the same in all the tests. Therefore, such improved connectivity would have delayed the fall off of plasterboards, which in return would have contributed to increased fire resistance rating.

Gunalan et al. (2012) and Ariyanayagam and Mahendran (2011) used conventional lipped channel sections of 90 mm in depth. In Tests 1 and 2, hollow flange section studs used were of 150 mm depth, that is, 60 mm larger depths in Tests 1 and 2. The thermal bowing effect which contributes to the lateral deflection depends on the section depth. The larger depth of hollow flange section studs would have reduced the lateral movement caused by thermal bowing. This would lead to reduced bending moment caused by thermal bowing and its magnification effects. So the applied loading actions on the studs are reduced. This could have contributed to the increased fire resistance rating in the tests conducted using the hollow flange section studs. The reasons discussed above apply to the superior fire performance of LSF wall made of hollow flange section studs with a single layer of plasterboard as well.

Conclusions

This paper has described an experimental study into the fire performance of LSF walls made of a hollow flange stud section known as LiteSteel beam. Fire test results showed that LSF walls made of LiteSteel Beam studs displayed superior fire performance in comparison to the fire performance of LSF walls made of conventional lipped channel section studs. This is considered to be due to a number of reasons. They are: improved thermal properties of the plasterboards produced at present, the increase in cavity size delaying the temperature rise, improved connectivity between the hollow flange section studs and the plasterboard delaying the fall off of plasterboards and the resulting rapid temperature rise, and finally the section profile and the higher elevated temperature mechanical properties of the steel. It is concluded that the superior fire performance of LSF walls made of hollow flange section studs is due to the accumulation of all the above mentioned factors. However, further tests and numerical analyses are needed to investigate the effects of these factors and to fully understand the fire behaviour of LSF walls made of hollow flange section studs.

References

Alfawakhiri, F., 2001, Behaviour of Cold-formed-Steel-framed Walls and Floors in Standard Fire Resistance Tests, *PhD Thesis*, Carleton University, Ottawa, Ontario, Canada.

Ariyanayagam, A.D. and Mahendran, M., 2012, Fire Tests of Load Bearing Steel Stud Walls Exposed to Real Building Fires, *Proc. of the 7th International Conference on Structures in Fire*, Zurich, Switzerland, 105-114.

Feng, M., Wang, Y.C. and Davies, J.M., 2003, Thermal Performance of Cold-formed Thin-walled Steel Panel Systems in Fire, *Fire Safety Journal*, 38, 365-394.

Feng, M. and Wang, Y.C., 2005, An Experimental Study of Loaded Full-Scale Cold-Formed Thin-Walled Steel Structural Panels Under Fire Conditions, *Fire Safety Journal*, 40, 43-63.

Gerlich, J.T., Collier, P.C.R. and Buchanan, A.H., 1996, Design of Steel-framed Walls for Fire Resistance, *Fire and Materials*, 20 (2), 79-96.

Gunalan, S., Kolarkar, P. and Mahendran, M., 2012, Fire Tests of Cold-formed Steel Wall Systems, *Proc. of the Australasian Structural Engineering Conference*, Perth, Australia, 1-8.

Keerthan, P. and Mahendran, M., 2012, Numerical modelling of non-load bearing light gauge cold-formed steel frame walls under fire conditions. *Journal of Fire Sciences*, *30*(5), 375-403.

Kodur, V.R. and Sultan, M.A., 2001, Factors Governing Fire Resistance of Load Bearing Steel Stud Walls, *Proc. of the 5th AOSFST International Conference*, Newcastle, Australia, 1-2.

Standards Australia (SA), *AS 1530.4, 2005,* Methods for Fire Tests on Building Materials, Components and Structures. Part 4: Fire-resistance Tests of Elements of Building Construction, Sydney, Australia.

Standards Australia (SA), *AS/NZS 2588, 1998,* Gypsum Plasterboard, Sydney, Australia.

Standards Australia (SA), *AS/NZS 2589.1, 1997,* Gypsum Linings in Residential and Light Commercial Construction - Application and Finishing. Part 1: Gypsum Plasterboard, Sydney, Australia.

Zhao, W., 2005, Behaviour and Design of Cold-formed Steel Sections with Hollow Flanges, *PhD Thesis*. School of Civil Engineering, Queensland University of Technology, Brisbane, Australia.