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Development of a Simplified Design Method to Predict the Fire Rating of LSF Walls

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ABSTRACT: Recent fire research into the behaviour of light gauge steel frame (LSF) wall systems has developed fire design rules based on Australian and European cold-formed steel design standards, AS/NZS 4600 and Eurocode 3 Part 1.3. However, these design rules are complex since the LSF wall studs are subjected to non-uniform elevated temperature distributions when the walls are exposed to fire from one side. Therefore this paper proposes an alternative design method for routine predictions of fire resistance rating of LSF walls. In this method, suitable equations are recommended first to predict the idealised stud time-temperature profiles of eight different LSF wall configurations subject to standard fire conditions based on full scale fire test results. A new set of equations was then proposed to find the critical hot flange (failure) temperature for a given load ratio for the same LSF wall configurations with varying steel grades and thickness. These equations were developed based on detailed finite element analyses that predicted the axial compression capacities and failure times of LSF wall studs subject to non-uniform temperature distributions with varying steel grades and thicknesses. This paper proposes a simple design method in which the two sets of equations developed for time-temperature profiles and critical hot flange temperatures are used to find the failure times of LSF walls. The proposed method was verified by comparing its predictions with the results from full scale fire tests and finite element analyses. This paper presents the details of this study including the finite element models of LSF wall studs, the results from relevant fire tests and finite element analyses, and the proposed equations.

1 INTRODUCTION

Cold-formed steel sections are commonly used in various configurations to provide load-bearing Light gauge Steel Framed (LSF) wall systems in buildings. Under fire conditions, cold-formed steel stud sections heat up quickly as they are thin-walled, resulting in fast reduction to their strength and stiffness. Therefore these stud sections are commonly used in planar structural wall systems with plasterboard on both sides as fire protection. Plasterboards protect the steel studs by delaying the temperature rise in the studs during building fires. Since the LSF walls are often subjected to fire on one side, non-uniform temperature distributions will develop across the depth of LSF wall studs. This will induce additional bending moments on the studs due to thermal bowing, neutral axis shift and magnification effects. Hence the thin-walled steel studs will be subjected to combined actions of axial compression and bending moment during a fire event. This fire behaviour of LSF wall panels has been investigated by many researchers in the past and several fire design rules have been proposed. Klippstein (1980) and Gerlich et al. (1996) developed their fire design rules based on AISI design provisions (2007) while Alfawakiri’s (2001) study was based on Canadian cold-formed steel design rules. Ranby (1999), Kaitila (2002), Feng & Wang (2005) and Zhao et al. (2005) developed their fire design rules based on Eurocode 3 Part 1.3 (2006). These design rules are complex and time consuming and hence do not suit routine design purposes.

In order to overcome this problem related to the need for simplified design rules and to address the lack of research data on Australian LSF wall systems, a detailed investigation based on full scale fire tests and finite element analyses was conducted on both conventional Australian LSF walls with and without the use of cavity insulation and the new composite panel system developed recently at the Queensland University of Technology. Details of 10 full scale fire tests and their results including the temperature and deflection profiles measured during the tests are presented in Gunalan et al. (2013) along with the failure times and modes. A suitable finite element model of LSF wall studs subject to fire conditions was then developed using ABAQUS, and validated using the results of fire tests (Gunalan and Mahendran, 2013).
In this paper idealised time-temperature profiles were first proposed for LSF wall studs based on the results from the full scale fire tests. These idealised time-temperature profiles were then used with the validated finite element models to investigate the behaviour of LSF walls. A simple design method was then proposed based on the parametric study results to predict the fire resistance rating of LSF wall panels with varying wall configurations (single and double layers of plasterboards, cavity and externally insulated) and structural parameters (steel grade and thickness) under varying load ratios.

2 EXPERIMENTAL STUDY

This section provides brief details of the series of full scale fire tests of LSF walls conducted first to evaluate the fire resistance rating (FRR) of load bearing LSF wall assemblies. One wall specimen was tested to failure under an axial compression load at room temperature while ten wall specimens subjected to a constant axial compression load were exposed to standard fire conditions on one side to evaluate their fire performance (Table 1). Conventional Australian LSF wall panels lined with single or double layers of plasterboard with or without cavity insulation were considered. A new LSF wall system based on a composite panel was also included in which external insulation was sandwiched between the two plasterboards (Gunalan et al., 2013).

Table 1. LSF wall systems considered in fire tests.

<table>
<thead>
<tr>
<th>Test</th>
<th>Configuration</th>
<th>Insulation type</th>
<th>Insulation location</th>
<th>Load ratio</th>
<th>Failure time (min.)</th>
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<td>107</td>
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<td>107</td>
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</table>
(1 - 3) - Tests conducted by Gunalan (2011); (1* - 7*) - Tests conducted by Kolarkar (2010); (#) - Earlier failure time due to lack of space for thermal expansion

All the steel frames used in the load bearing LSF wall panels were built to a height of 2400 mm and a width of 2400 mm. The studs and tracks used in the test frames were fabricated from G500 galvanized steel sheets with a nominal base metal thickness of 1.15 mm, a yield strength of 569 MPa and an elastic modulus of 213,520 MPa at ambient temperature. Test frames were lined on both sides by single or double layers of 16 mm gypsum plasterboards manufactured by Boral Plasterboard. Table 1 shows the details of the 10 LSF wall specimens used in this study with two load ratios.

The furnace was designed to deliver heat based on the standard fire curve given in AS 1530.4 (2005). The loading frame was designed (Fig. 1) to load the individual studs of LSF wall specimens in compression from the bottom side using hydraulic jacks. The axial shortenings of the studs and the out-of-plane movements of the wall specimen were measured using linear variable displacement transducers. K type thermocouples were used to measure the temperature development across the wall specimens. The stud (hot flange, web and cold flange) temperatures were measured at three levels for interior studs, namely, at 0.25 H, 0.50 H and 0.75 H, and at mid-height for exterior studs.

In each fire test an axial compression load of 15 kN (for a load ratio of about 0.2) or 30 kN (for a load ratio of about 0.4) was applied to each stud (i.e. 0.2 or 0.4 times the ultimate capacity of each stud at room temperature as obtained by Kolarkar (2010)). The load was held constant at room temperature before the furnace was started and then maintained throughout the fire test. During the fire test, the furnace temperature was regulated to follow the standard time-temperature curve. The test was stopped after one or more of the wall studs failed, and the time to failure was recorded. Table 1 shows the failure times obtained from the experimental study. Further details are given in Gunalan et al. (2013).
3 IDEALISED TIME-TEMPERATURE PROFILES

Table 1 shows the LSF wall test configurations and insulations used in the experimental study. The new externally insulated wall panels with glass fibre and rockwool were tested under two load ratios of 0.2 and 0.4. Hence these 10 full scale fire tests were essentially conducted using eight different wall configurations (Table 2). Therefore idealised time-temperature profiles were developed for these eight wall configurations using the measured hot and cold flange temperature distributions along the wall stud. In the development of idealised time-temperature profiles of studs with externally insulated glass fibre and rockwool, the average temperature values of the two fire tests were used (load ratios of 0.2 and 0.4 – Tests 1 & 2; Tests 3 & 6*). The critical stud in a LSF wall panel was the stud with the vertical plasterboard joint against it. The temperature values of this stud were high compared to other studs due to the opening of this vertical joint at higher temperatures. Therefore the average temperatures along this stud were considered in the development of all the idealised time-temperature profiles for LSF wall studs under standard fire conditions.

When the LSF wall was subject to standard fire conditions, the hot and cold flange temperatures of the stud were 20°C for the initial few minutes. They then increased gradually (linearly) to reach 100°C and remained at the same temperatures during the plasterboard dehydration process. After this the steel temperatures increased rapidly with time. Table 2 shows the time-temperature values of hot and cold flanges up to 100°C. Beyond 100°C, Equations 1 to 8 represent the idealised time-temperature profiles for the LSF wall panels with eight configurations shown in Table 2, where \( T_{HF} \) and \( T_{CF} \) are the average hot and cold flange temperatures in °C and \( t \) is the time in minutes.

1) LSF wall lined on both sides by a single layer of plasterboard (Test 1*).

\[
T_{HF} = -0.1066t^2 + 20.17t - 165 \quad (15 \leq t) \quad (1a)
\]

\[
T_{CF} = 10.29t - 125 \quad (22 \leq t \leq 50) \quad (1b)
\]

\[
T_{CF} = 29.35t - 1090 \quad (50 < t \leq 60) \quad (1c)
\]

\[
T_{CF} = T_{HF} \quad (60 < t) \quad (1d)
\]

2) LSF wall lined on both sides by two layers of plasterboard (Test 2*).

\[
T_{HF} = 6.35t - 160 \quad (42 \leq t \leq 110) \quad (2a)
\]

\[
T_{HF} = 12.11t - 790 \quad (110 < t) \quad (2b)
\]

\[
T_{CF} = 6.07t - 230 \quad (55 \leq t) \quad (2c)
\]

3) LSF wall lined on both sides by two layers of plasterboard with glass fibre used as cavity insulation (Test 3*).

\[
T_{HF} = 11.17t - 490 \quad (53 \leq t) \quad (3a)
\]

\[
T_{CF} = 4.92t - 225 \quad (66 \leq t \leq 96) \quad (3b)
\]

\[
T_{CF} = 12.04t - 915 \quad (96 < t) \quad (3c)
\]

4) LSF wall lined on both sides by two layers of plasterboard with rockwool used as cavity insulation (Test 4*).

\[
T_{HF} = 10.2t - 435 \quad (53 \leq t) \quad (4a)
\]

\[
T_{CF} = 4.06t - 165 \quad (66 \leq t) \quad (4b)
\]

5) LSF wall lined on both sides by two layers of plasterboard with cellulose fibre used as cavity insulation (Test 5*).

\[
T_{HF} = 8.94t - 360 \quad (53 \leq t \leq 106) \quad (5a)
\]

\[
T_{HF} = 19.83t - 1530 \quad (106 < t) \quad (5b)
\]

\[
T_{CF} = 3.83t - 150 \quad (66 \leq t \leq 106) \quad (5c)
\]

\[
T_{CF} = 17t - 1550 \quad (106 < t) \quad (5d)
\]

6) LSF wall lined on both sides by two layers of plasterboard with glass fibre used as external insulation (Tests 1 & 2).

\[
T_{HF}= 0.001007t^2 - 0.1605t^2 + 12.15t - 205 \quad (43 \leq t) \quad (6a)
\]

\[
T_{CF}= 0.09904t^2 - 9.5t + 350 \quad (61 \leq t) \quad (6b)
\]

7) LSF wall lined on both sides by two layers of plasterboard with rockwool used as external insulation (Tests 3 & 6*).

\[
T_{HF}= -0.000212t^2 + 0.0931t^2 - 5.47t + 100 \quad (71 \leq t) \quad (7a)
\]

\[
T_{CF}= 0.0580t^2 - 6.69t + 260 \quad (81 \leq t) \quad (7b)
\]

8) LSF wall lined on both sides by two layers of plasterboard with cellulose fibre used as external insulation (Test 7*).

\[
T_{HF}= -0.000286t^2 + 0.1024t^2 - 2.92t - 100 \quad (71 \leq t) \quad (8a)
\]

\[
T_{CF}= 0.0846t^2 - 9.5t + 320 \quad (81 \leq t) \quad (8b)
\]

Table 2. Idealised Time-Temperature values up to 100°C

<table>
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<th>W/C</th>
<th>Insulation</th>
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<th>HFT (°C)</th>
<th>Time (min.)</th>
<th>CFT (°C)</th>
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</tr>
</tbody>
</table>

W/C - Wall Configuration; HFT - Hot Flange Temperature; CFT - Cold Flange Temperature
4 FINITE ELEMENT MODELS

A finite element model of LSF wall studs (Fig. 2) was developed with appropriate thermal and structural boundary conditions to simulate the behaviour of LSF wall studs under standard fire conditions and to determine the FRR. Finite element analyses were conducted under steady state conditions. Here, the non-uniform temperature distributions in the steel stud cross-section were raised to the target levels at any given time during the standard fire and then maintained. A load was then applied in increments until the failure of LSF wall studs.

![Figure 2. Loading and boundary conditions used in FEA](image)

Based on other numerical studies and the experimental behaviour of LSF wall studs, one of the two central studs that had the vertical plasterboard joint against it was considered in the analyses. Pinned support conditions were simulated for studs using rigid plates while an axial compressive load was applied at the section centroid at one end as shown in Figure 2. It was assumed that the plasterboards screw-fixed to both flanges provided sufficient lateral restraint until the failure of studs (Kaitila 2002, Feng et al. 2003 and Zhao et al. 2005).

S4R shell element type with a 4 mm x 4 mm mesh size was selected based on detailed convergence studies. Nominal mechanical properties and idealised time-temperature profiles using the predictive equations were used (Equations 1-8). The yield strength and elastic modulus reduction factors at elevated temperatures and the stress-strain curves were based on the predictive equations developed in Dolamune Kankanamge & Mahendran (2011). The strain hardening material model was used for steels with gradual yielding type stress-strain curve except for G250 steels at 20°C, 100°C and 200°C for which an elastic-perfect plastic material model was used (Dolamune Kankanamge & Mahendran 2011) as they had a well defined yield point. The coefficient of thermal expansion given in Eurocode 3 Part 1.2 (2005) was used.

The first eigen mode of the elastic buckling analyses was used to introduce the initial geometric imperfection with an amplitude of 0.006b. The residual stresses were not considered in the modelling of studs under fire conditions since they are insignificant at elevated temperatures.

Under fire conditions, many steady state analyses conducted in close time intervals led to a load ratio (ultimate load of stud in fire conditions / ambient temperature capacity) versus failure time (FRR) curve for the LSF wall systems. Figure 3 shows this curve for the case of LSF wall with glass fibre external insulation. As shown in the figure, the failure time for Test 1 with a load ratio of 0.2 was obtained as 115 minutes. The main advantage of FEA with steady state conditions is that figures such as Figure 3 can now be used to obtain the fire resistance rating (failure time) for any given load ratio. Table 3 gives the failure times predicted by FEA under steady state conditions for all the tests. These comparisons show that the developed finite element model accurately predicts the ultimate capacities and failure times of LSF wall studs subjected to axial compression under standard fire conditions. Further details on the development and validation of the finite element model can be found in Gunalan and Mahendran (2013).

The results from finite strip analyses (CUFSM) and tests (Gunalan et al., 2013) were used to validate the results of finite element analyses (FEA). The validated finite element model was used in a detailed parametric study into the fire performance of LSF wall panels using a 90 x 40 x 15 stud section.

![Figure 3. Variation of load ratio with time](image)

5 SIMPLIFIED DESIGN METHOD BASED ON THE CRITICAL HOT FLANGE TEMPERATURE

Lawson (1993) adopted the so-called limiting temperature method used for hot-rolled steel structures to cold-formed thin-walled steel structures. In this method the limiting temperature is defined as a function of the load ratio of the structural member. The load ratio is the ratio between the load on the member at the fire limit state and the load carrying capac-
ity of that member under ambient conditions. Kolarkar (2010) proposed simple design rules to determine the failure times of LSF walls by combining the yield stress reduction factors and idealised time-temperature profiles. The critical temperature (i.e. the maximum hot flange temperature at failure) corresponding to a load ratio (strength reduction factor) was used with idealised time-temperature profiles to obtain the approximate failure times of each type of wall specimen.

In this study FEA results of eight wall configurations (Table 2) were used to determine the critical temperature of LSF wall studs. Figure 4 shows the variation of load ratio with hot flange temperature at failure for LSF walls with glass fibre, rockwool and cellulose fibre used as cavity insulations for 1.15 mm G500 steel studs. It is interesting to note the plots for different insulations merged together. This clearly indicates that the failure temperature of LSF wall studs does not depend on the type of insulation. In other words the effect of using different types of insulation is simply to delay the time to reach the same hot flange temperatures in the LSF wall studs. Similar behavior was observed in externally insulated wall panels as well (Fig. 5). The results of cavity and externally insulated wall panels did not merge when they were plotted together. This indicates that the arrangement of insulations and plasterboards influences the failure temperature although the type of insulation does not. Similar behavior was also observed for LSF wall studs made of G250 1.15 mm and 1.95 mm steels.

Eurocode 3 Part 1.2 (2005) recommends a limiting temperature value of 350°C irrespective of the load ratio as shown by a horizontal line in Figures 4 and 5. This did not agree with the FEA results. Kolarkar’s (2010) and Lawson’s (1993) design methods were also found to be unsuitable. Therefore it was decided to propose a new set of equations (Equations 9 to 20) to determine the critical hot flange temperatures at failure. These equations represent the temperature values ranging from 100°C to 800°C where T is the critical hot flange temperature in °C and LR is the load ratio. The load ratio was more than 0.90 when the hot flange temperature was below 100°C. Similarly the load ratio was less than 0.10 when the hot flange temperature was above 800°C. They were not included in the proposed equations.

1.15 mm G500 steel studs lined on both sides by
A single layer of plasterboard
\[ T = 1298LR^3 - 1894LR^2 - 14LR + 708 \]  
(9)

Two layers of plasterboard
\[ T = -527LR^3 + 895LR^2 - 1166LR + 825 \]  
(10)

Two layers of plasterboard with cavity insulation
\[ T = 196LR^3 + 428LR^2 - 1379LR + 854 \]  
(11)

Two layers of plasterboard with external insulation
\[ T = 870LR^3 - 1291LR^2 - 260LR + 768 \]  
(12)

1.15 mm G250 steel studs lined on both sides by
A single layer of plasterboard
\[ T = -1300LR^3 + 2312LR^2 - 1927LR + 934 \]  
(13)

Two layers of plasterboard
\[ T = -1113LR^3 + 2583LR^2 - 2367LR + 968 \]  
(14)

Two layers of plasterboard with cavity insulation
\[ T = 863LR^3 - 990LR^2 - 581LR + 804 \]  
(15)

Two layers of plasterboard with external insulation
\[ T = 314LR^3 - 1136LR + 891 \]  
(16)

1.95 mm G250 steel studs lined on both sides by
A single layer of plasterboard
\[ T = 866LR^2 - 1712LR + 938 \]  
(17)

Two layers of plasterboard
\[ T = 5455LR^3 - 10681LR^2 + 6727LR^2 - 2244LR + 868 \]  
(18)

Two layers of plasterboard with cavity insulation
\[ T = -1162LR^3 + 2085LR^2 - 1811LR + 920 \]  
(19)

Two layers of plasterboard with external insulation
\[ T = -708LR^3 + 1846LR^2 - 1995LR + 921 \]  
(20)

In the simplified method proposed here to predict the fire resistance rating of LSF wall systems, Equations 9 to 20 predicting the limiting hot flange temperature of LSF wall studs are used with Equations 1 to 8 giving the idealised hot flange time-temperature profiles. For one of the 24 LSF wall systems considered here (3 LSF wall stud cases with different steel grades and thicknesses X 8 wall configurations as
shown in Table 2) with a given load ratio (LR), the limiting hot flange temperature can be found first by using Equations 9 to 20, which can then be used in Equations 1 to 8 to find the time required to reach the calculated limiting hot flange temperature. This is the fire resistance rating in minutes (stud failure time) for the selected wall system. Table 3 shows the fire resistance rating (failure times) of LSF walls predicted by the simplified method proposed in this section and the corresponding FEA and test results. This table shows that the results agree well.

<table>
<thead>
<tr>
<th>Index</th>
<th>Test</th>
<th>FEAn</th>
<th>Eqn.</th>
<th>Test</th>
<th>FEAn</th>
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<td>117</td>
<td>86</td>
<td>88</td>
<td></td>
</tr>
</tbody>
</table>

(*) - Tests conducted by Kolarkar (2010); (#) - Earlier failure time due to lack of space for thermal expansion; LR - Load ratio; Eqn. - Proposed equations.

6 CONCLUSIONS

This paper has presented the details of an investigation into the fire performance of LSF wall panels based on an extensive finite element analysis based parametric study and the results. The LSF wall panels with eight different plasterboard-insulation configurations were considered under standard fire conditions. This paper has developed two sets of equations to predict (1) the hot flange temperature as a function of time during a standard fire and (2) the critical (failure) hot flange temperature as a function of load ratio for LSF wall systems with varying plasterboard-insulation configurations. It then proposes a simplified design method to predict their fire resistance rating based on these two sets of equations.

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8 REFERENCES


Klippstein, K.H. 1980. Strength of cold-formed steel sections exposed to fire, American Iron and Steel Institute. Washington DC, USA.


