

THERMAL MODELLING OF LOAD BEARING COLD-FORMED STEEL FRAME WALLS UNDER REALISTIC DESIGN FIRE CONDITIONS

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ABSTRACT: Cold-formed Light gauge Steel Frame (LSF) walls lined with plasterboards are increasingly used in the building industry as primary load bearing components. Although they have been used widely, their behaviour in real building fires is not fully understood. Many experimental and numerical studies have been undertaken to investigate the fire performance of load bearing LSF walls under standard fire conditions. However, the standard fire time-temperature curve given in ISO 834 [1] does not represent the fire load present in typical modern buildings that include considerable amount of thermoplastic materials. Some of these materials with high calorific values increase the fire severity beyond that of the standard fire curve. Fire performance studies of load bearing LSF walls exposed to realistic design fire curves have also been limited. Therefore in this research, finite element thermal models of LSF wall panels were developed to simulate their fire performance using the recently developed realistic design fire time-temperature curves [2]. Suitable thermal properties were proposed for plasterboards and insulations based on laboratory tests and available literature. The developed finite element thermal models were validated by comparing their thermal performance results with available realistic design fire test results, and were then used in a detailed parametric study. This paper presents the details of the developed finite element thermal models of load bearing LSF wall panels under realistic design fire time-temperature curves and the results. It shows that finite element thermal models of LSF walls can be used to predict the fire performance including their fire resistance rating with reasonable accuracy for varying configurations of plasterboard lined LSF walls exposed to realistic design fire time-temperature curves.

Keywords: Numerical studies, Light gauge steel frame (LSF) walls, realistic design fire time-temperature curves, load bearing walls, cold-formed steel structures, gypsum plasterboard, specific heat, thermal conductivity, mass loss (relative density)

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1. INTRODUCTION

Light gauge Steel Frame (LSF) walls are usually made of cold-formed steel studs, and are lined with gypsum plasterboard layers on both sides with and without cavity insulations (Figure 1). Cold-formed steel stud sections in LSF walls panels when exposed to fire heat up quickly resulting in fast reduction in their strength and stiffness. Hence the studs are commonly lined with plasterboard and insulation materials as fire protecting materials. These lining materials protect steel studs during building fires by delaying the temperature rise. The wall configurations include single and double layers of plasterboard lined walls with and without insulation. Insulated wall panels can be either cavity insulated or externally insulated, i.e. a thin insulation layer sandwiched between two plasterboards.

The types and thickness of plasterboard and insulation layers used will significantly influence the fire resistance ratings (FRR) of LSF wall panels. Plasterboard types include specially manufactured fire resistant gypsum plasterboards or the general purpose plasterboards in thicknesses ranging from 8 to 16 mm. Currently, gypsum plasterboard lined LSF wall systems are increasingly used in low-rise and multi-storey buildings, but without a full understanding of their fire performance.

Similarly insulation type includes rock fibre, glass fibre or cellulose fibre in different thicknesses and densities. All these materials have a significant impact on the performance of LSF wall panels when subjected to fire from one side as they delay the temperature rise of thin-walled LSF wall studs.

Many experimental and numerical studies have been undertaken to investigate the fire performance of load bearing LSF walls under standard fire conditions [1]. However, it is questionable whether it truly represents the fire scenarios in modern buildings. In reality, modern residential and commercial buildings incorporate both traditional wooden items and modern items such as cushion/fabric furniture, mattresses, fabric coated partitions, etc., which make use of thermoplastic materials including synthetic foams and fabrics. During a fire, some of these thermoplastic materials melt and flow to the floor and burn significantly faster, with higher heat release rates, than the standard fire curve used to obtain FRR, thus increasing the fire severity [2]. This means LSF walls may not provide safe evacuation, or offer the required life safety for occupants and fire rescuers. Therefore suitable realistic design fire time-temperature curves were developed and full scale fire tests of load bearing LSF walls were conducted by Ariyanayagam and Mahendran [2,4]. Type-K cable thermocouples were used to measure the temperatures across and along the LSF wall panels. Their study has shown that LSF wall studs failed when they reached their critical maximum hot flange temperatures and if similar conditions exist, LSF wall panel failure mainly depends on stud hot flange temperature. However, their experimental study was limited to six realistic design fire time-temperature curves including both rapid and prolonged fires. Hence to investigate the fire performance of LSF wall systems for a range of different fire scenarios, finite element thermal models were developed and used in a detailed study. This paper presents the details of the finite element thermal analyses of load bearing LSF walls exposed to realistic design fire time-temperature curves. It includes the details of the developed finite element thermal models of load bearing LSF wall panels and the results. Most importantly, it describes the thermal performance of LSF wall systems exposed to a range of realistic design fire time-temperature curves.

2. THERMAL BEHAVIOUR OF LOAD BEARING LSF WALLS USING EXPERIMENTAL STUDIES

Six full scale fire tests were conducted on 2400 mm x 2100 mm LSF wall panels to investigate the structural and thermal performance of load bearing LSF wall panels exposed to realistic design fire time-temperature curves [4]. LSF wall panels consisted of four cold-formed steel lipped channel sections (90 x 40 x 15 x 1.15 mm) spaced at 600 mm centres and tracks (top and bottom) made of unlipped channel sections (92 x 50 x 1.15 mm). Both studs and tracks of 2400 mm length were fabricated from 1.15 mm galvanized steel sheets having a minimum yield strength of 500 MPa (G500 Steel). Test specimens were built by lining the steel frames with one or two layers of 16 mm thick Firestop™ gypsum plasterboards manufactured by Boral Plasterboard, Australia (Figure 1). The 25 mm thick ROXUL Stonewool MPS400 Rock fibre insulation was used in externally insulated wall panels. Tests were conducted using the recently developed realistic design fire curves [2] shown in Figure 2. They were based on Eurocode Parametric [3] and Barnett's 'BFD' [5] fire curves with appropriate compartment characteristics. Details of the development of these realistic design fire curves are given in Ariyanayagam and Mahendran [2].

Fire tests were conducted in a specially designed test rig shown in Figure 3. Test specimen was placed with the stud centroids aligning with those of four loading plates and hydraulic rams. The wall studs were first loaded in axial compression using these hydraulic rams attached to a single pump via loading plates. This pre-determined axial compression load was based on the required

load ratios of 0.2 and 0.4. It was 15 kN for Tests LSF1 to LSF4 and 30 kN for Tests LSF5 and LSF6. Following the load application, one face of the test wall specimen was exposed to heat in a propane-fired vertical gas furnace while maintaining the applied load. During the tests time-temperature profiles at various locations across the specimen thickness were measured using thermocouples.

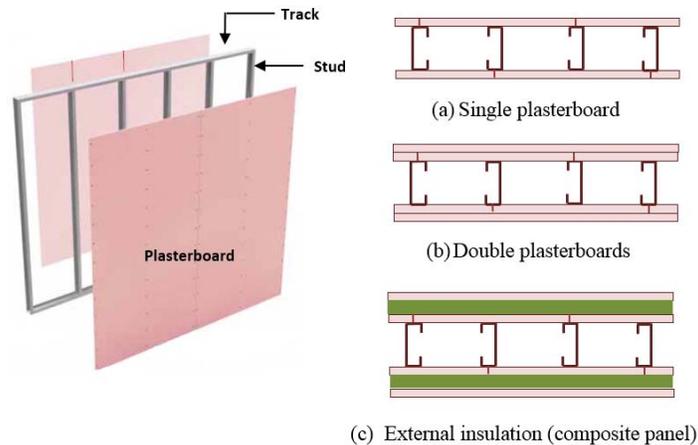


Figure 1. LSF Wall Panels

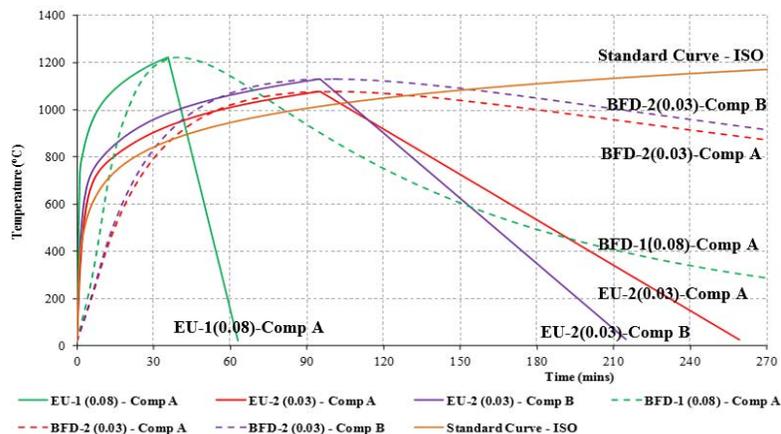


Figure 2. Realistic Design Fire Time-Temperature Curves Used in Fire Tests [2]

Table 1 shows the details of tested LSF walls and their failure times. It highlights that some realistic design fires (Tests LSF3 to LSF6) can cause severe damage to LSF wall panels than the standard fire [1] while other realistic design fire time-temperature curves (Tests LSF1 and LSF2) are not as severe as the standard fire. Ariyanayagam and Mahendran [4] provide a full description of the full scale fire tests conducted for three different LSF wall configurations and the results. Experimental studies showed that in all the fire tests structural failure of studs initiated the wall failure instead of insulation or integrity failure, except for Test Specimen LSF1 that did not fail even after 180 minutes of fire exposure. No significant differences were observed between the two different fire curves used in the tests [4]. In the initial stages of the fire, studs simply followed the shape of the fire time-temperature curve and after the calcination of gypsum plasterboard, stud temperatures increased rapidly and led to the failure of LSF wall panel. The presence of wall lining material significantly influenced the failure times of single plasterboard lined walls as the plasterboard fall-off led to higher furnace temperature exposure and loss of lateral restraint to studs. This study also showed that if similar conditions exist, i.e. restraints and applied loads are similar, LSF wall panel failure depends mainly on the maximum stud hot flange temperature [4].

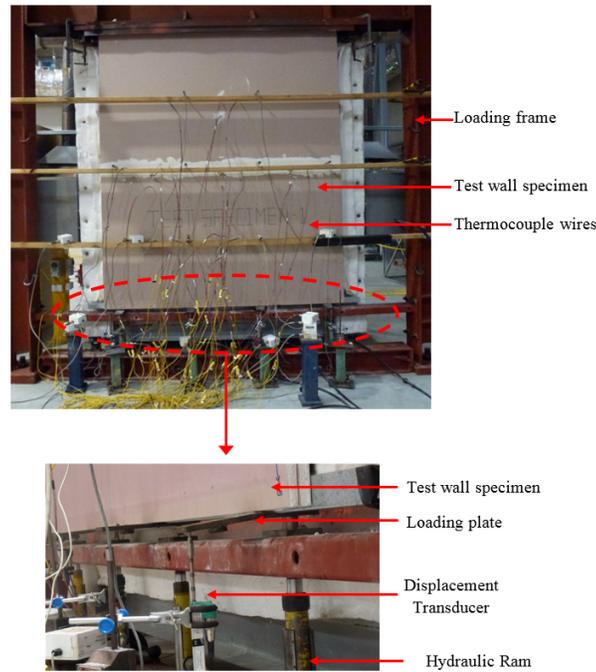
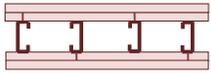
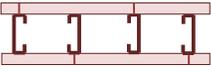
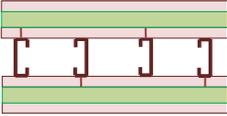


Figure 3. Fire Test Set-up [4]

Table 1. Test LSF Wall Configurations and Failure Times [4]

Test	LSF Wall Configuration	Insulation Type	Fire Curve	Failure Time (mins)
LSF1	Double layers of plasterboards (LR=0.2)	-	EU-2(0.03)-Comp A	No Failure
LSF2		-	BFD-2(0.03)-Comp A	139
Gunalan et al. [21]			ISO 834 [1]	111
LSF3	Single layer of plasterboard (LR=0.2)	-	EU-1(0.08)-Comp A	28
LSF4		-	BFD-1(0.08)-Comp A	39
Gunalan et al. [21]			ISO 834 [1]	53
LSF5	Externally insulated panel (LR=0.4)	-	BFD-2(0.03)-Comp B	118
LSF6		Rock Fibre	EU-2(0.03)-Comp B	120
Gunalan et al. [21]			ISO 834 [1]	134

Note: LR – Load ratio, the ratio between the applied axial compression load to the test ultimate capacity of the stud at ambient temperature.

3. THERMAL BEHAVIOUR OF LOAD BEARING LSF WALLS USING NUMERICAL STUDIES

This section presents the details of numerical studies into the thermal behaviour of tested load bearing LSF wall panels exposed to realistic fire time-temperature curves and their results. Recently many numerical heat transfer models have been developed and used by researchers [6-10]. Also there are many general finite element analysis programs that can be used for thermal analyses. The finite element model employed in this study to predict the thermal behaviour of load bearing LSF wall panels was based on SAFIR Version 2004 [11] while GID Version 10.0.1 was used as pre and post-processors.

Finite element program SAFIR was used to study the two-dimensional (2D) heat transfer analysis of cold-formed light gauge steel frame walls lined with gypsum plasterboards exposed to realistic design fire curves. Most of the earlier thermal models were based on one-dimensional (1D) heat transfer analysis using mathematical models exposed to standard fire curve. SAFIR used in this study accommodates the use of various elements to accurately simulate material response and stress-strain behaviour. 2D analysis is undertaken by SAFIR with triangular (3 node) or quadrilateral (4 node) solid elements. In SAFIR, heat transfer within a body of elements is modelled through conduction, whereas heat transfer from boundary elements is modelled with both convection and radiation transfer modes.

SAFIR has some limitations in its ability to model gypsum plasterboard assemblies. Ablation has the effect of reducing the cross-sectional thickness of gypsum plasterboard and hence increasing the heat flux across the plasterboard. SAFIR does not allow the user to eliminate any elements from the section to simulate ablation. Hence ablation process must be taken into account through the use of suitable apparent thermal properties of plasterboard. Modelling moisture movement across the cavity is a complex problem and it only influences heat transfer across the cavity at low temperatures [12]. Also as it is not incorporated in SAFIR, this process is neglected in this study. To investigate the thermal performance of load bearing LSF walls under realistic design fire curves, finite element models of tested wall panels [4] were developed. Figure 4 shows the developed finite element models of LSF walls under realistic fire curves. These models were validated using the fire test results of load bearing LSF walls exposed to realistic design fire time-temperature curves [4].

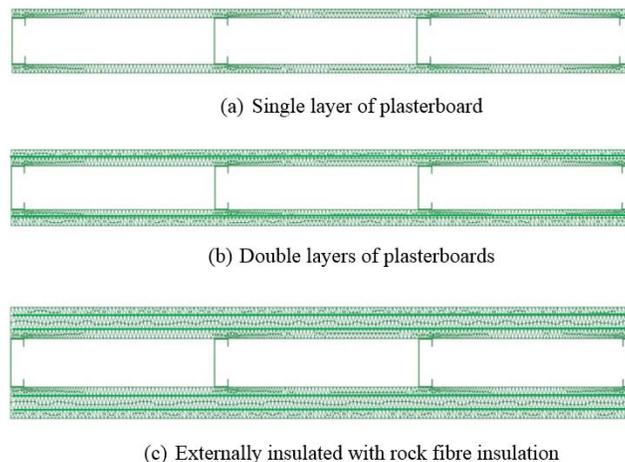


Figure 4. Finite Element Modelling of LSF Wall Panels

3.1 Thermal Boundary Conditions

The heat flux at the LSF wall boundary conditions was computed from the temperature of the fire curve T_g and the temperature on the surface T_s based on Equation (1).

$$q = h(T_g - T_s) + \sigma\varepsilon(T_g^4 - T_s^4) \quad (1)$$

where

q - Total heat flux

ε - Relative emissivity

σ - Stefan–Boltzmann constant ($5.67\text{E}-08\text{W/m}^2/\text{K}^4$)

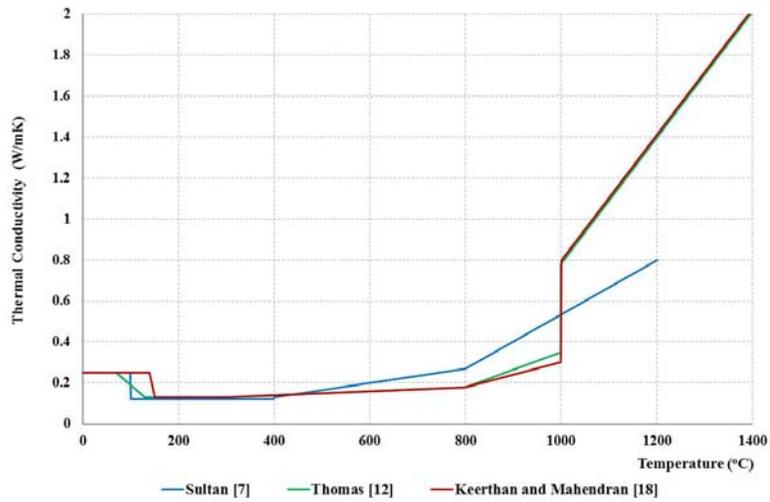
T_g and T_s - Gas and surface temperatures

In this study convective heat transfer coefficients (h) of 25 and 10 $\text{W/m}^2\text{K}$ [13-16] were used on the fire exposed and unexposed sides, respectively. Emissivity of 0.9 was used for the fire exposed surface [13,15,16]. A finite element mesh size of 2 mm was used in this study (Figure 4). This mesh size was selected based on the convergence studies undertaken by Keerthan and Mahendran [13] for similar conditions. The study showed that finite element models with a 2 mm mesh produced results that were closer to fire test results. Hence it was assigned to the plasterboard, and an automatic mesh generation was used in developing finite element models. In the numerical model three voids were created and the heat transfer in the cavities (void) was defined by radiation and convection between the boundaries of the cavity.

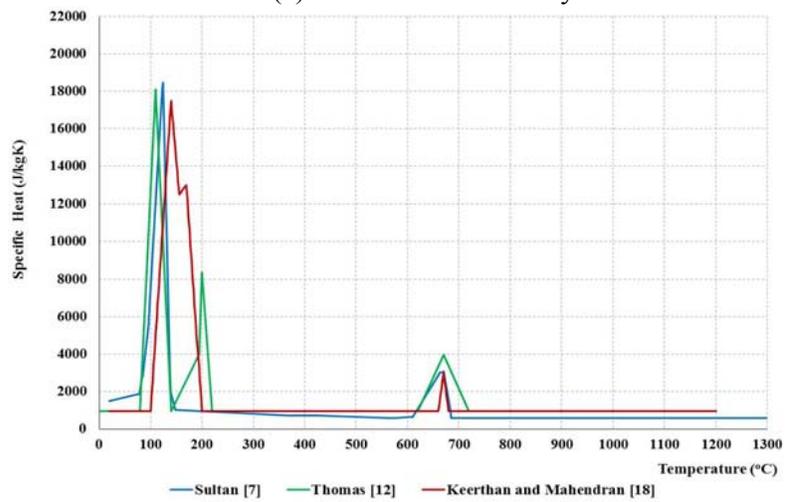
3.2 Thermal Properties of LSF Wall Components

In order to develop appropriate finite element thermal models to study the behaviour of LSF walls at elevated temperatures, accurate thermal properties of LSF wall components are needed. Thermal property values include thermal conductivity, specific heat and mass loss (relative density). The values at elevated temperatures for LSF wall components are summarized by Keerthan and Mahendran [13,15] based on a series of experimental results [15] and past research studies [6-10] for Australian gypsum plasterboards and rock fibre insulation materials. Hence these values are used in this study.

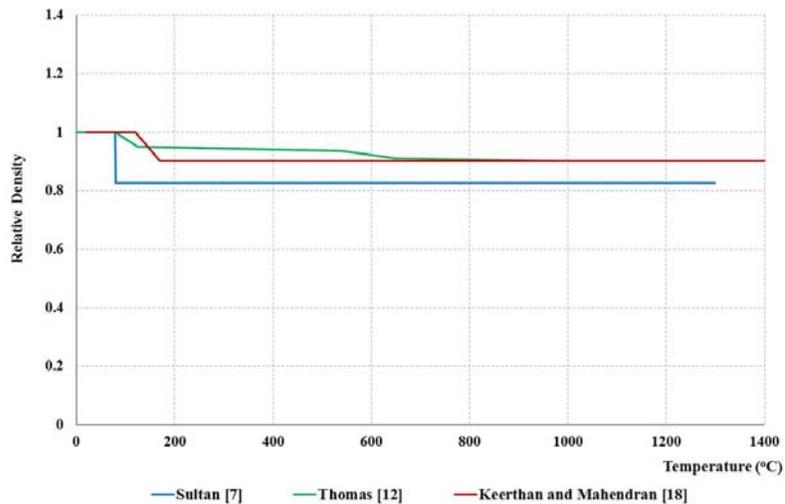
Initially, a finite element model of gypsum plasterboard was developed using finite element analysis software, SAFIR. The time-temperature curves across the plasterboard were then obtained and validated with fire test results [17] conducted for the standard fire curve [1]. This study was then extended [13] to thermal analysis of LSF wall panels lined with single and double layers of plasterboards, and cavity and externally insulated LSF wall panels, based on which suitable thermal property values for gypsum plasterboard and insulation were proposed (Figures 5 and 6). These finite element models were also validated using fire test results in [16] and are reported in [13]. A good agreement was obtained with fire test results (time-temperature curves) for LSF walls exposed to a standard fire curve, considering the complexity of gypsum plasterboard behaviour affected by processes such as ablation of plasterboards and migration of moisture into the cavity. These processes were taken into account by considering suitable values for the thermal conductivity of gypsum plasterboard [19]. Details of this process and the proposed values for specific heat, thermal conductivity and mass loss (relative density) are reported in [13,15,16]. Hence these thermal property values were used in this research for gypsum plasterboard and insulation materials to study the behaviour of LSF wall panels exposed to realistic design fire curve while cold-formed steel stud thermal properties were based on Eurocode 3 Part 1.2 [18].



(a) Thermal conductivity



(b) Specific heat



(c) Relative density

Figure 5. Thermal Properties of Gypsum Plasterboard versus Temperature

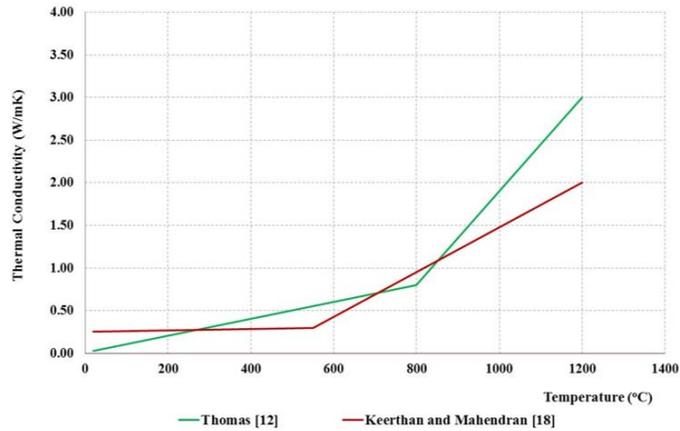


Figure 6. Thermal Conductivity of Rock Fibre Insulation versus Temperature

3.3 Comparison of Finite Element Thermal Analysis Results with Fire Test Results

Finite element thermal analysis results were compared with corresponding results from the realistic design fire tests conducted by Ariyanayagam and Mahendran [4]. Figure 7 shows the temperature distributions across the cross-section of LSF walls lined with double layers of plasterboard, whereas Figures 8 to 10 show stud time-temperature curves for the three wall configurations considered in this study. Average time-temperature curves of studs were used from the fire tests in these comparisons. The comparisons show a reasonable agreement between the fire test and finite element analysis (FEA) results for single and double layers of plasterboard lined LSF walls. The variation in stud temperatures was less than 50°C for double plasterboard lined LSF walls with a better agreement for Test LSF1 than Test LSF2 (Figure 8). The single plasterboard lined specimens also showed a temperature difference of less than 50°C between fire test and FEA results (Figure 9). The differences between the stud temperatures obtained from fire tests and FEA are relatively high for LSF wall specimens with external insulation (Figure 10). Finite element analyses overestimated the stud temperatures in this case. This could be due to the influence of rock fibre insulation as it is the new material used in the externally insulated walls other than in single and double plasterboard lined walls. As mentioned earlier, the same rock fibre insulation thermal property values used with the standard fire tests were used in the simulation of realistic design fire tests. Thermal property values of rock fibre insulation were idealized by Keerthan and Mahendran [15] based standard fire test results from [21, 22]. But these values do not appear to provide a good agreement for realistic design fire time-temperature curves. This could be due to the variation in rock fibre insulation thermal properties.

Load bearing LSF walls exposed to fires are also affected by processes such as ablation of plasterboard and insulation, migration of moisture vapours and penetration of cool ambient air or hot furnace gases into the cavity. Effects of these processes were taken into account in the models through the use of suitable thermal conductivity values for plasterboards and insulations. Although they have been considered by using apparent thermal properties values, these effects could vary with wall configurations and rate of heating. The different rate of fire temperature rise in the realistic design fire time-temperature curves influenced the stud temperatures as a result of changes to the gypsum plasterboard and rock fibre insulation thermal properties. Also gypsum plasterboard and rock fibre insulation are non-homogenous materials.

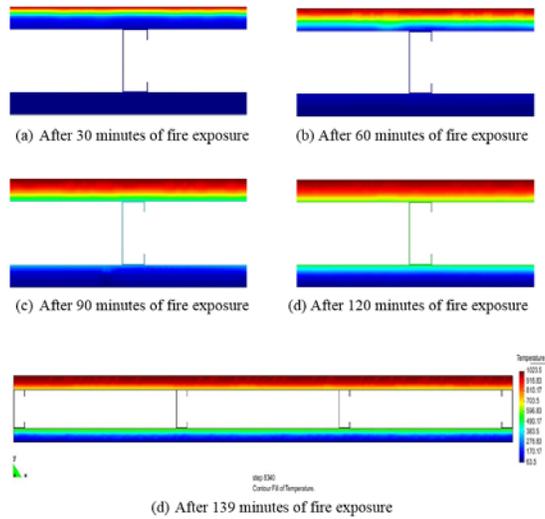
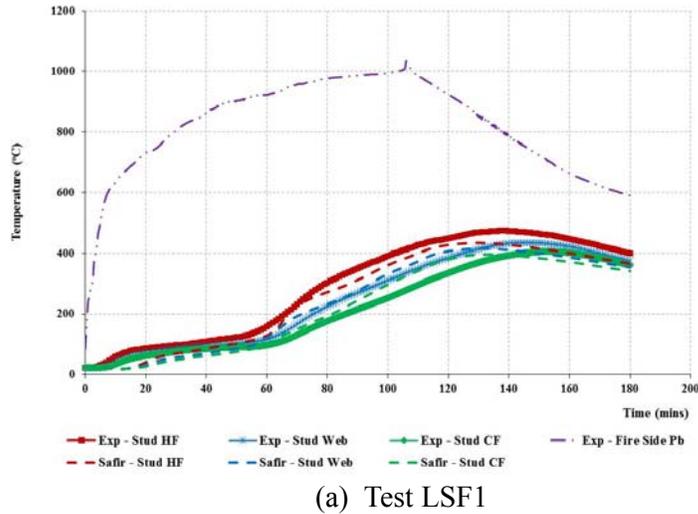
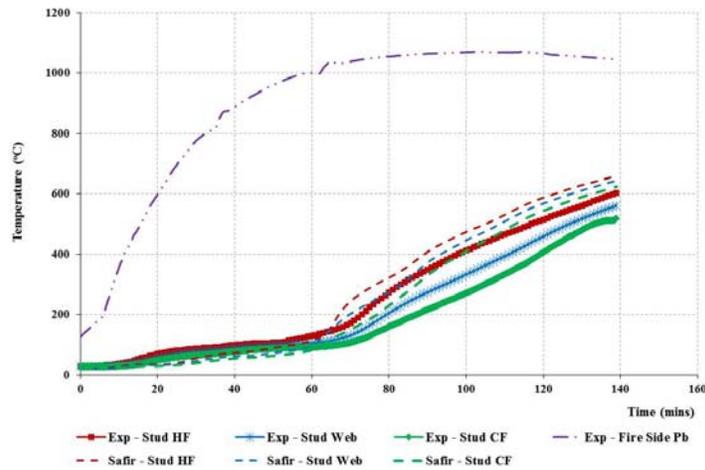


Figure 7. Temperature Distribution of Double Layers of Plasterboard Lined LSF Wall - Test Specimen LSF2



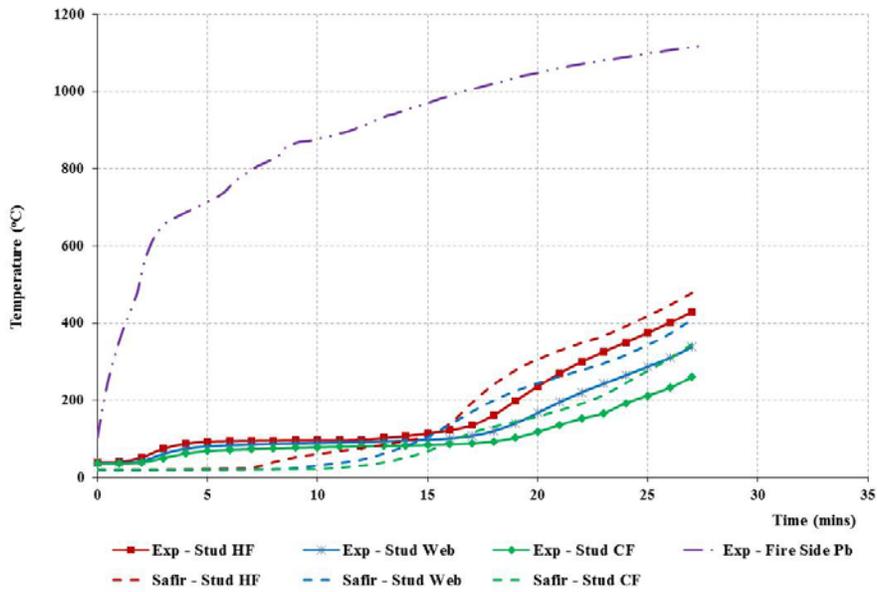
(a) Test LSF1



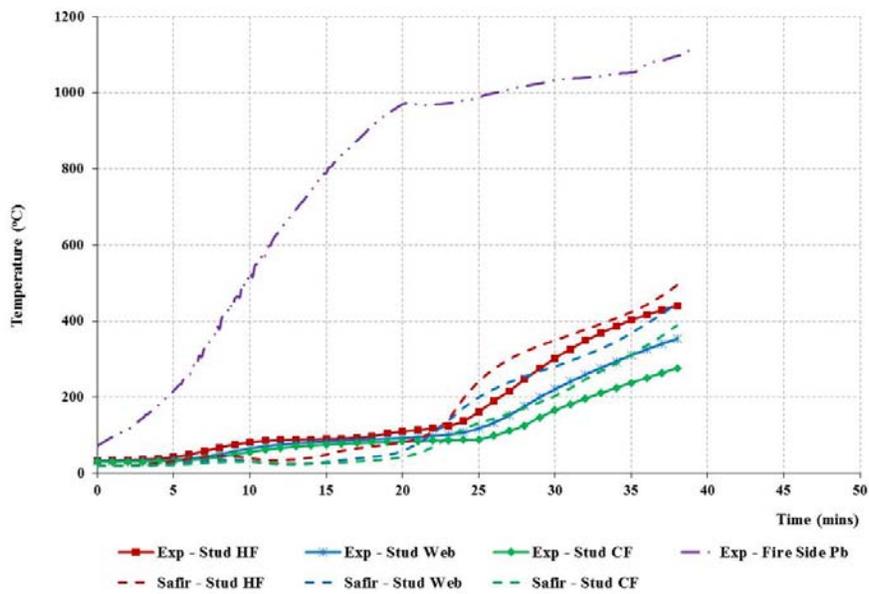
(b) Test LSF2

Note: HF: Hot flange; CF: Cold flange.

Figure 8. Stud Time-Temperature Curves from Fire Tests and Thermal Analyses for LSF Walls Lined with Double Layers of Plasterboards



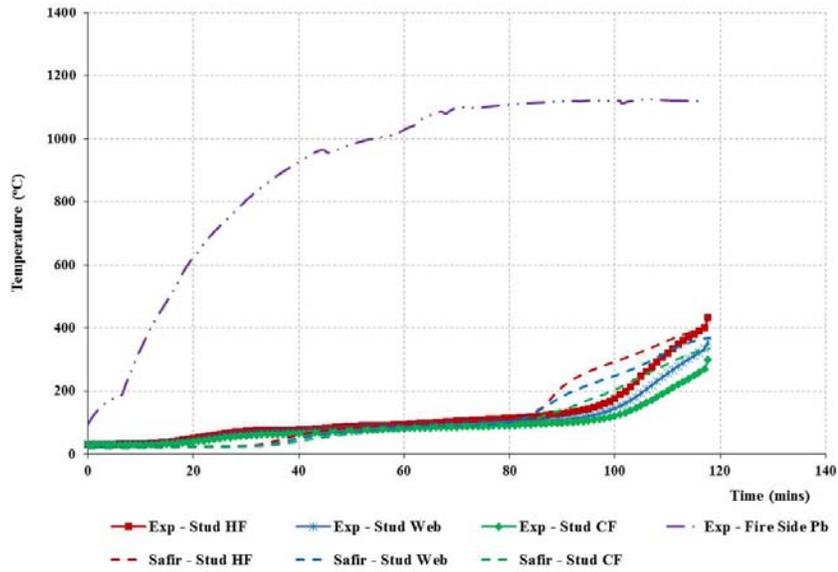
(a) Test LSF3



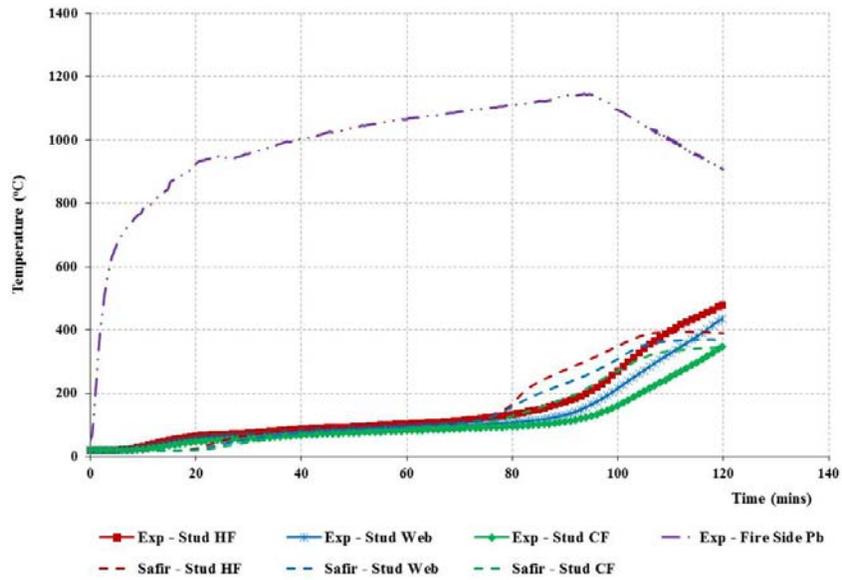
(b) Test LSF4

Note: HF: Hot flange; CF: Cold flange.

Figure 9. Stud Time-Temperature Curves from Fire Tests and Thermal Analyses for LSF Walls Lined with Single Layer of Plasterboard



(a) Test LSF5



(b) Test LSF6

Note: HF- hot flange, CF- cold flange.

Figure 10. Stud Time-Temperature Curves from Fire Tests and Thermal Analyses for LSF Walls with Rock Fibre External Insulation

Thermal analyses conducted by Paulik et al. [23], Hopkin et al. [24], Sergey et al. [25] and Thomas [12] for similar wall panels also found that thermal properties of gypsum plasterboard depend on the heating rate. Numerical analysis conducted by Thomas [12] on light timber framed walls on slow developing and rapid fires also showed similar results, where a good agreement was observed in slow developing fires than rapid fires. Our numerical analysis showed higher temperatures than fire test results, i.e. overestimated the stud temperatures. The likely cause for the difference in results is not including the effects of processes such as moisture flow and ablation of plasterboards that are affected by higher heating rates. The variation in stud temperatures in the early stages of the fire for single plasterboard lined walls could also be due to this higher heating rate as they were exposed to a heating rate well above 50°C/min. This higher heating rate affected the dehydration process of gypsum plasterboard. This process was studied in detail by Paulik et al. [23] and they concluded that the rate of temperature rise influenced the dehydration process, which will thus affect the specific heat values of gypsum plasterboard. In this study, the specific heat values used were measured at a heating rate of 20°C/min under a constant nitrogen gas flow. However, rapid fire curves have a heating rate of 50°C/min. Ang and Wang [26] proposed a correction factor for the specific heat to incorporate the moisture transfer inside the gypsum plasterboard. This is based on numerical analysis of heat and mass transfer in gypsum plasterboard when exposed to fire. However, under fire conditions gypsum plasterboards in LSF walls may also experience ablation, shrinkage and collapse, which were not incorporated in this correction factor. Hence in this study the correction factor for the specific heat of gypsum plasterboard was not considered, and an apparent specific heat value based on the experimental study conducted in [13,15] was used.

In our FEA, elevated temperature thermal properties used with the standard fire tests were used for both rapid and pro-longed fire curves. Hence detailed experimental studies are needed to investigate the effect of rapid fire time-temperature curves on the thermal properties of gypsum plasterboards. However, in most situations the predicted stud temperatures from FEA are higher than those from fire tests, ie. conservative predictions. Considering this outcome, it was decided to use the developed finite element model in this study to obtain the stud hot flange temperatures for a range of realistic design fire time-temperature curves for single and double plasterboard lined walls, and walls with double plasterboard lining and external rock fibre insulation. However, our test and numerical analysis results and past research studies show that specific heat of gypsum plasterboard depends on the heating rate. Detailed experimental studies should be undertaken to investigate the effect of rapid real fires (50°C/min) on the thermal properties of gypsum plasterboards and the thermal performance of LSF wall panels.

4. EFFECT OF REALISTIC DESIGN FIRE TIME-TEMPERATURE CURVES ON THE THERMAL BEHAVIOUR OF LOAD BEARING LSF WALLS

A detailed parametric study was undertaken based on the validated finite element model to investigate the thermal performance of load bearing LSF walls under realistic design fire curves. The parameter considered in this study is the type of fire time-temperature curve, hence as in the fire tests two different types of fire time-temperature curves were selected: Eurocode parametric [3] and Barnett's 'BFD' [5] curves. Eurocode parametric time-temperature curves are influenced by compartment characteristics such as ventilation openings, fuel loads and thermal inertia of the compartment lining material. To simulate both rapid and prolonged fires, two opening factors 0.06 and 0.03 m^{1/2}, were considered with fuel loads of 1268 and 780 MJ/m² of floor area. The compartment thermal lining materials are gypsum plasterboard lined walls and ceilings while concrete floor is assumed in one compartment and timber floor in the other. This will vary the thermal inertia of the compartment from 400 to 715 J/m²S^{1/2}K. Hence the use of two values for each of the three fire parameters; ventilation opening, fuel load and thermal inertia, gave eight

different fire time-temperature curves for Eurocode parametric design fires [3]. Similarly eight Barnett's 'BFD' curves [5] were also developed for the same fire parameters. Thus it resulted in a total of 16 fire time-temperature curves for a wall configuration. Also as in the fire tests, three different wall configurations were considered; single and double plasterboard lined walls and walls with external rock fibre insulation. Hence a total of 48 different fire time-temperature curves were considered in this study.

4.1 LSF Walls Lined with Double Layers of Plasterboards

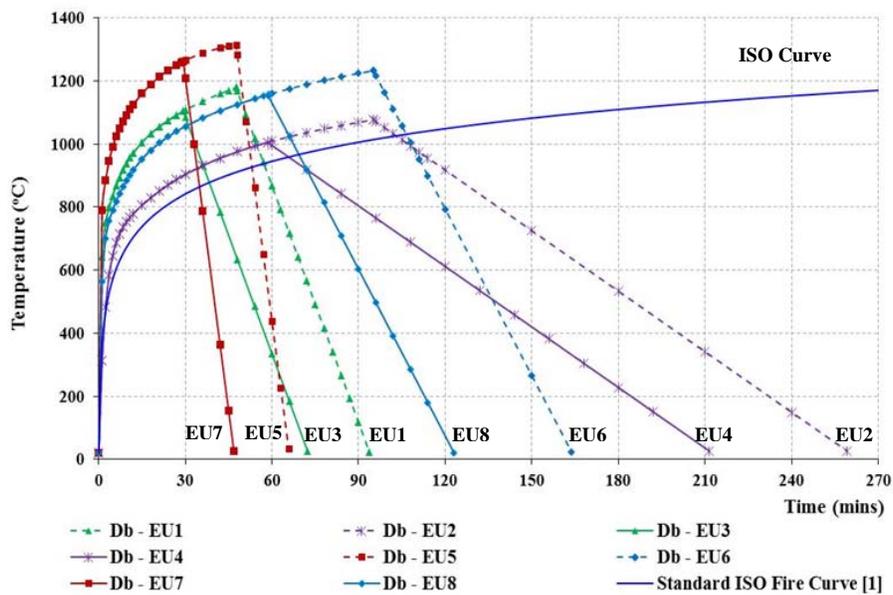
Table 2 presents the design parameters used in developing the Eurocode parametric and 'BFD' design fire time-temperature curves for LSF walls lined with double gypsum plasterboards. The developed fire curves are more severe than the standard fire curve in terms of maximum temperature and time to reach the maximum temperature (Figures 11(a) and 12(a)). Further, all these fire curves have a decay phase. Fire curves Db-EU2 and Db-EU4 are closer to the standard fire curve, but with a decay phase. Fire curves Db-EU1, Db-EU3, Db-EU5 and Db-EU7 represent rapid fires, where a rapid increase in temperature is seen and a maximum temperature higher than 1100°C is reached in less than 45 minutes. Also they have a rapid temperature decrease in the decay phase of the fire. Fire curves Db-EU2, Db-EU4, Db-EU6 and Db-EU8 represent prolonged fires for which the maximum temperature is reached after 90 minutes of fire duration and the total fire duration is more than 2 hours including a linear decay phase. The maximum temperature of the fire curves Db-BFD1, Db-BFD3, Db-BFD5 and Db-BFD7 is nearly 1200°C and it is 1057°C for other fire curves. The rate of temperature rise is gradual compared to Eurocode parametric and standard fire curves, and the decay phase is also very slow.

The stud hot and cold flange time-temperature curves for the Eurocode parametric and 'BFD' design fire curves were obtained using the finite element thermal analyses and are shown in Figures 11(b) and 12(b). The stud hot and cold flange time-temperatures for the standard fire curve are also shown in these figures for comparison purposes. For nearly 30 minutes the stud temperatures agreed well with each other despite the differences in the rate of temperature rise in the fire curve and the temperatures are also less than 100°C. This is due to the dehydration process of gypsum plasterboard. Beyond this, the stud temperatures increased and followed the fire time-temperature curve. The rapid increase in temperatures in Fire curves Db-EU1, Db-EU3, Db-EU5 and Db-EU7 in the early stage of the fire caused the stud temperatures to increase more quickly. However, the stud temperatures started to decrease after reaching the maximum when the fire time-temperature curves were in the decay phase. In the LSF walls exposed to Eurocode parametric design fire curves, the stud temperatures decrease rapidly as soon as the fire time-temperature curves are in the decay phase. This is due to the rapid decay rate in the parametric fires. But for the studs exposed to 'BFD' curves, the stud temperatures are maintained at the maximum for considerable time or are seen to increase with time.

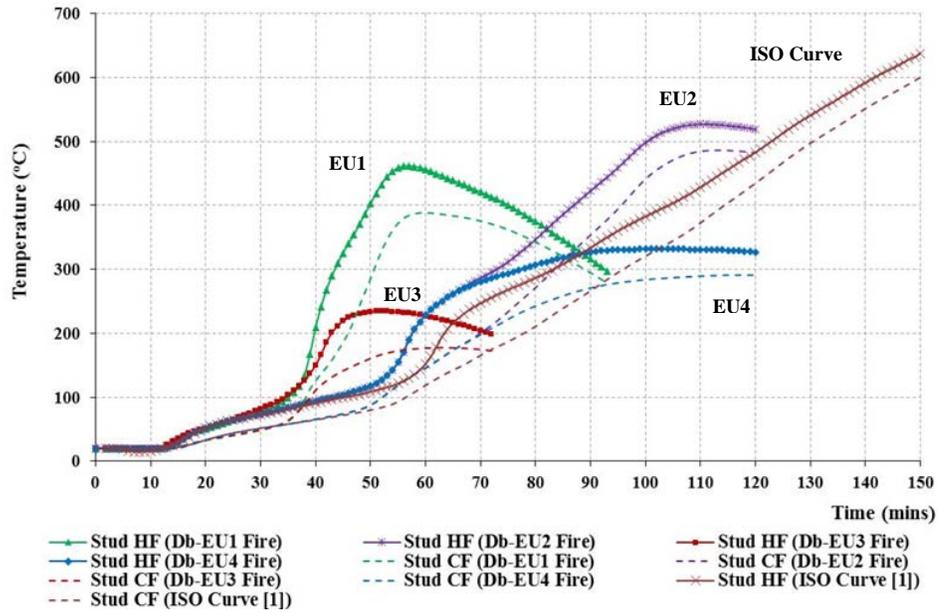
Table 2. Fire Compartment Characteristics Used in the Development of Design Fire Curves for LSF Walls Lined with Double Layers of Plasterboards

(a) Eurocode parametric fire curves					
Eurocode Parametric Fire Curves [3]	Opening Factor ($m^{1/2}$)	Compartment Thermal Inertia ($J/m^2S^{1/2}K$)	Fuel Load (MJ/m^2)		
Db - EU1	0.06	710.3	1268		
Db - EU2	0.03	702.1	1268		
Db - EU3	0.06	710.3	780		
Db - EU4	0.03	702.1	780		
Db - EU5	0.06	423.4	1268		
Db - EU6	0.03	423.2	1268		
Db - EU7	0.06	423.4	780		
Db - EU8	0.03	423.2	780		

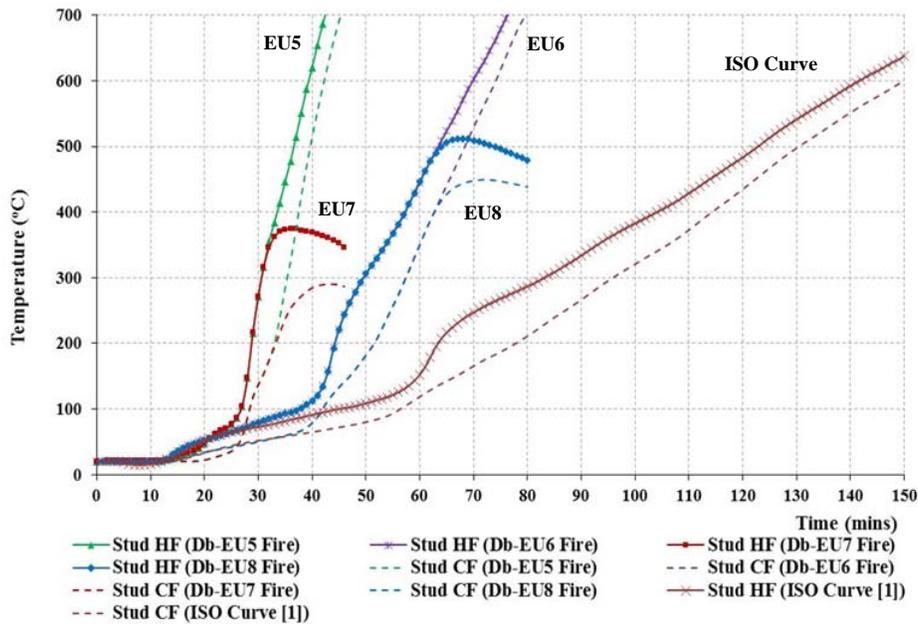
(b) 'BFD' fire curves					
'BFD' Fire Curves [5]	Opening Factor ($m^{1/2}$)	Fuel Load (MJ/m^2)	Fire Maximum Temperature - T_m ($^{\circ}C$)	Time to reach Maximum Temperature - t_m (mins)	Shape Constant - c
Db - BFD1	0.06	1268	1193	48	38
Db - BFD2	0.03	1268	1057	95	38
Db - BFD3	0.06	780	1193	29	38
Db - BFD4	0.03	780	1057	59	38
Db - BFD5	0.06	1268	1193	48	16
Db - BFD6	0.03	1268	1057	95	16
Db - BFD7	0.06	780	1193	29	16
Db - BFD8	0.03	780	1057	59	16



(a) Eurocode parametric design fire curves

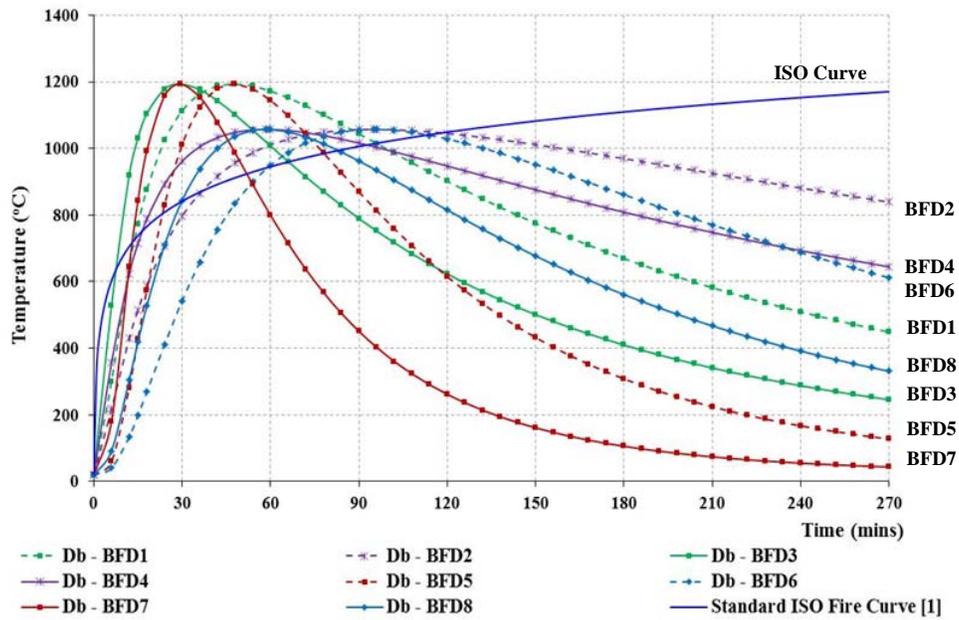


(b) Stud hot and cold flange temperatures for Fire Curves Db-EU1 to Db-EU4

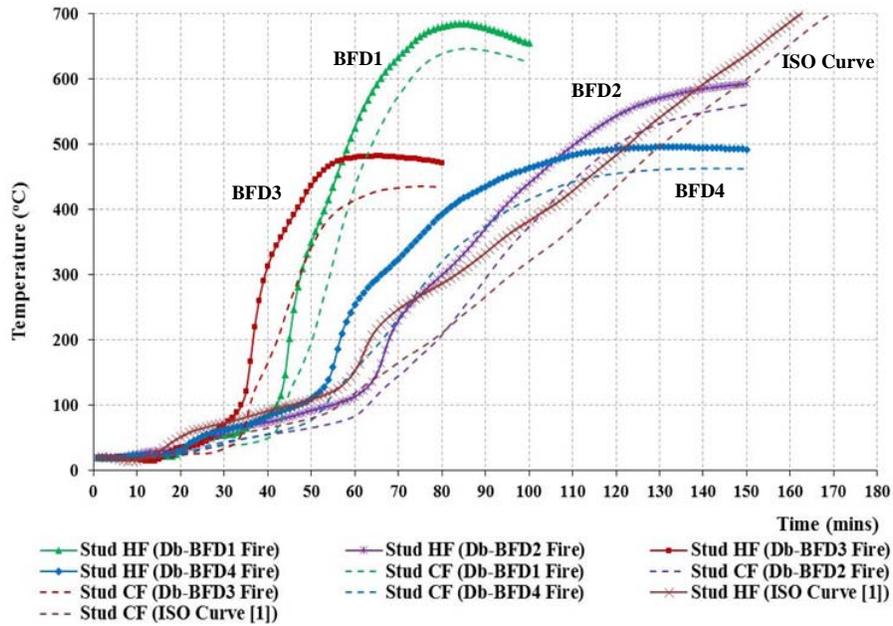


(c) Stud hot and cold flange temperatures for Fire Curves Db-EU5 to Db-EU8

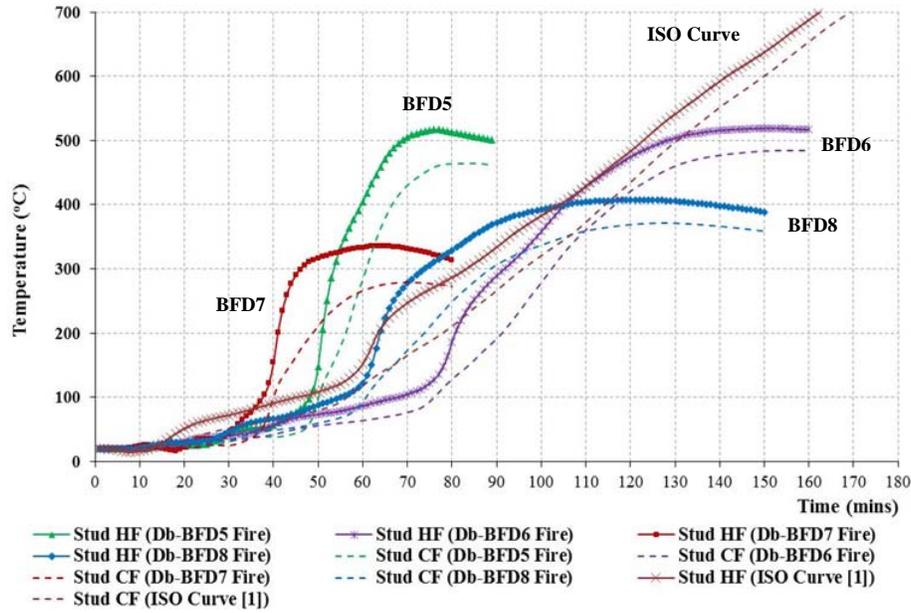
Figure 11. Stud Time–Temperature Curves Obtained from FEA for Double Layers of Plasterboard Lined LSF Walls Exposed to Eurocode Parametric Fire Curves



(a) 'BFD' design fire curves



(b) Stud hot and cold flange temperatures for Fire Curves Db-BFD1 to Db-BFD4



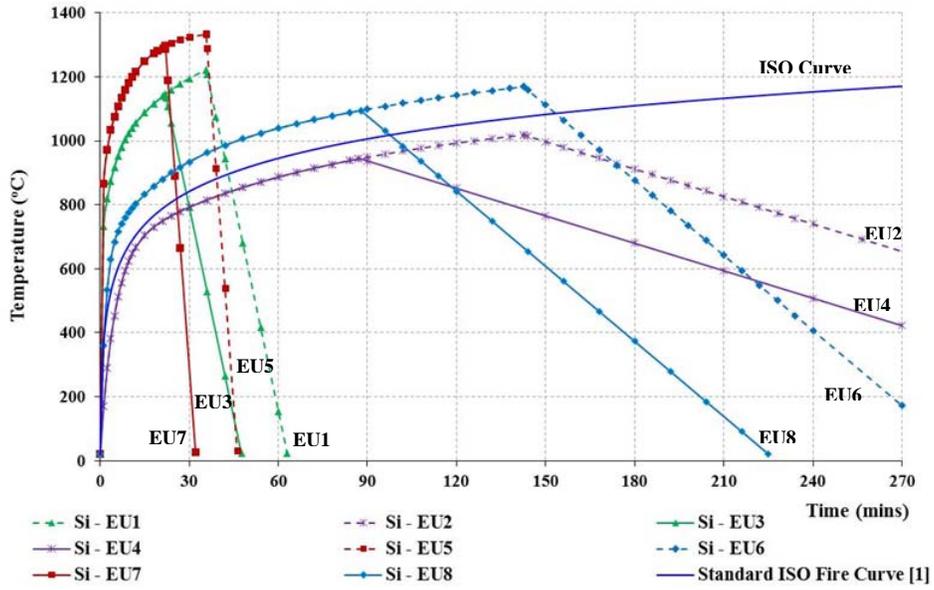
(c) Stud hot and cold flange temperatures for Fire Curves Db-BFD5 to Db-BFD8

Figure 12. Stud Time–Temperature Curves Obtained from FEA for Double Layers of Plasterboard Lined LSF Walls Exposed to ‘BFD’ Fire Curves

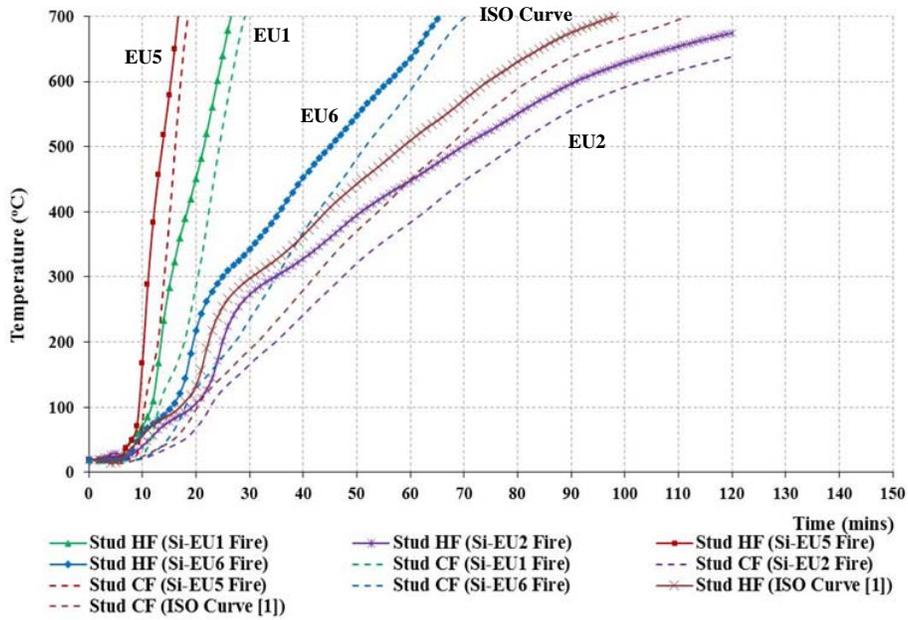
4.2

LSF Walls Lined with Single Layer of Gypsum Plasterboard

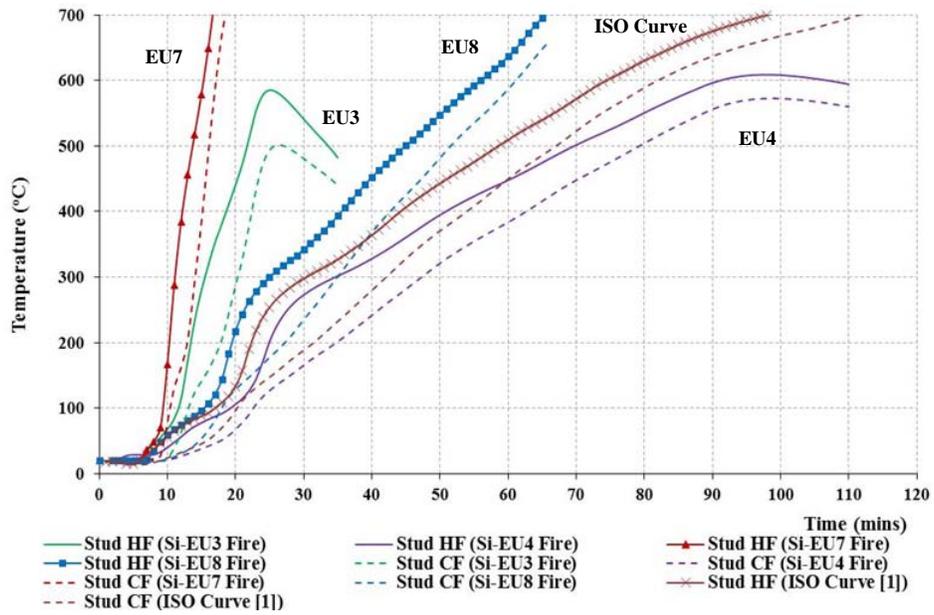
Table 3 presents the fire parameters used in developing the Eurocode parametric and ‘BFD’ fire curves, and the developed fire curves are shown in Figures 13(a) and 14(a). Fire curves Si-EU1, Si-EU3, Si-EU5 and Si-EU7 are considered rapid fires as their rates of temperature rise are higher than the standard fire [1] and reach a maximum temperature of nearly 1200°C in less than 40 minutes. Fire curves Si-EU2, Si-EU4, Si-EU6 and Si-EU8 are prolonged fires with fire durations of more than three hours. Fire curves Si-BFD1, Si-BFD3, Si-BFD5 and Si-BFD7 are considered severe fires and are rapid in temperature rise, where a maximum temperature of nearly 1200°C is reached in less than 40 minutes. Fire curves Si-BFD2, Si-BFD4, Si-BFD6 and Si-BFD8 are considered less severe fires compared to the standard fire curve [1], and are also prolonged fires. They only reach a maximum temperature of 850°C in 90 minutes or more.



(a) Eurocode parametric design fire curves

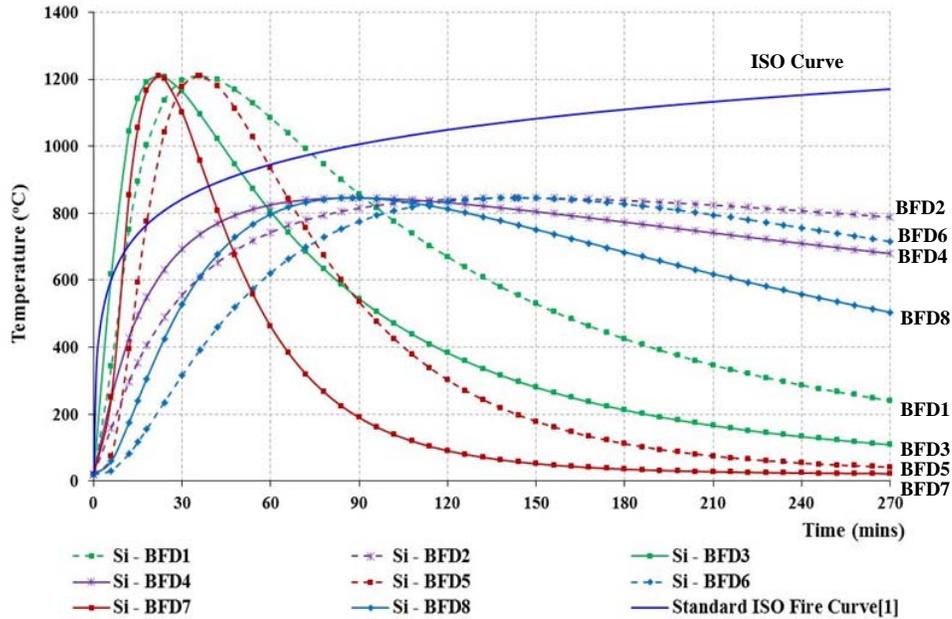


(b) Stud hot and cold flange temperatures for Fire Curves Si-EU1, Si-EU2, Si-EU5 and Si-EU6

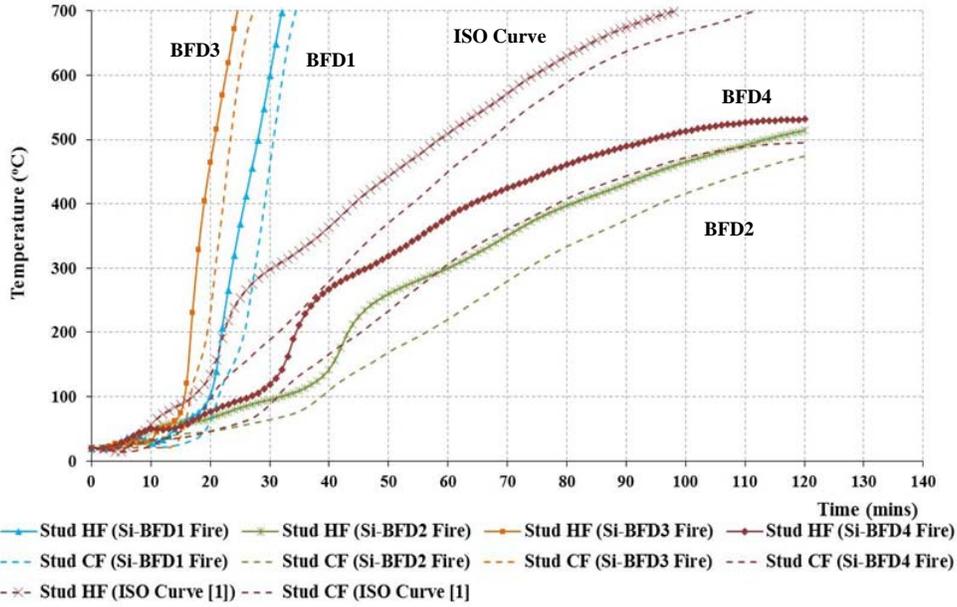


(c) Stud hot and cold flange temperatures for Fire Curves Si-EU3, Si-EU4, Si-EU7 and Si-EU7

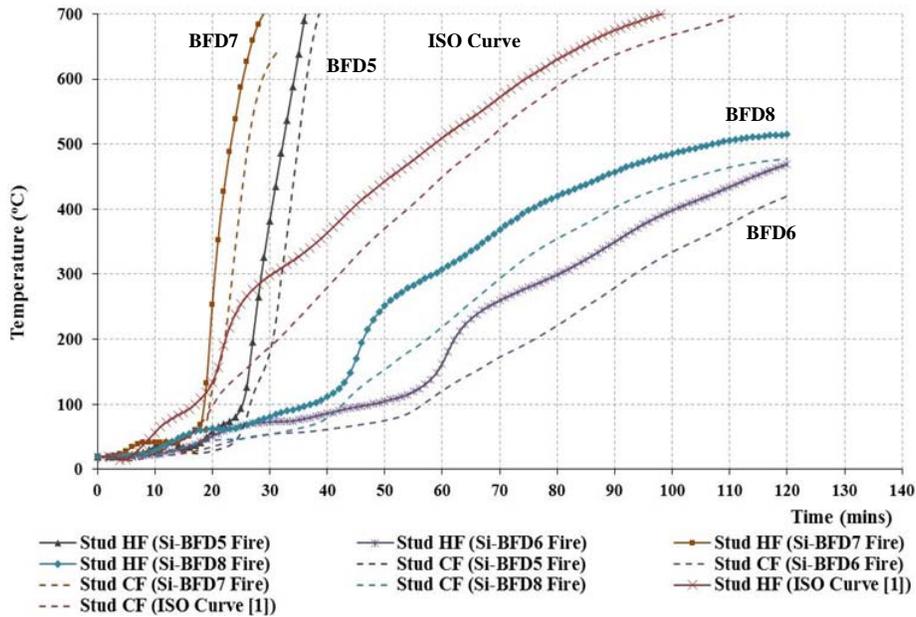
Figure 13. Stud Time-Temperature Curves Obtained from FEA for Single Layer of Plasterboard Lined LSF Wall Exposed to Eurocode Parametric Fire Curves



(a) 'BFD' fire curves



(b) Stud hot and cold flange temperatures for Fire Curves Si-BFD1 to Si-BFD4



(c) Stud hot and cold flange temperatures for Fire Curves Si-BFD5 to Si-BFD8

Figure 14. Stud Time–Temperature Curves Obtained from FEA for Single Layer of Plasterboard Lined LSF Walls Exposed to ‘BFD’ Fire Curves

Figures 13(b) and 14(b) show the stud hot and cold flange time-temperature curves obtained from finite element thermal analyses. As seen in Figure 13(a) the rates of fire temperature rise are similar in the cases of Si-EU1 and Si-EU3, Si-EU2 and Si-EU4, Si-EU5 and Si-EU7, and Si-EU6 and Si-EU8, and thus stud temperatures are also the same as seen in Figures 13 (b) and (c). Eurocode parametric design Fire curves Si-EU1 and Si-EU2 were developed for the fuel load of 1268 MJ/m², compartment thermal inertia of 715.4 and 700.1 J/m²S^{1/2}K and for opening factors 0.08 and 0.02 m^{1/2}, respectively. Opening factors 0.08 and 0.02 m^{1/2} represent rapid and prolonged fires, respectively and the fire curves reached a maximum temperature of 1222°C in 36 minutes and 1018°C in 142 minutes. Also in another instance stud hot flange temperature is 602°C at 24 minutes for Fire curve Si-EU1 and it is only 171°C for Fire curve Si-EU2. Similar behaviour is also observed for Fire curves Si-EU3, Si-EU5 and Si-EU7 when compared with Fire curves Si-EU4, Si-EU6 and Si-EU8. Hence it can be concluded that stud temperature rise is influenced by the rate of temperature rise in the fire curve, and that the rapid fires will significantly reduce the fire resistance of single plasterboard lined LSF walls. The stud hot flange temperatures for the rapid fire curves (Si-BFD1, Si-BFD3, Si-BFD5 and Si-BFD7) are greater than 700°C in less than 40 minutes of fire exposure. The corresponding stud cold flange temperatures are also very high. The stud hot flange temperatures for prolonged fires are very much less than those of rapid fire curves and are about 500°C after 90 minutes of fire exposure.

Table 3. Fire Compartment Characteristics Used in the Development of Design Fire Curves for LSF Walls Lined with Single Layer of Plasterboard

(a) Eurocode parametric fire curves					
Eurocode Parametric Fire Curves [3]	Opening Factor (m ^{1/2})	Compartment Thermal Inertia (J/m ² S ^{1/2} K)	Fuel Load (MJ/m ²)		
Si - EU1	0.08	715.4	1268		
Si - EU2	0.02	700.1	1268		
Si - EU3	0.08	715.4	780		
Si - EU4	0.02	700.1	780		
Si - EU5	0.08	423.5	1268		
Si - EU6	0.02	423.2	1268		
Si - EU7	0.08	423.5	780		
Si - EU8	0.02	423.2	780		

(b) 'BFD' fire curves					
'BFD' Fire Curves [5]	Opening Factor (m ^{1/2})	Fuel Load (MJ/m ²)	Fire Maximum Temperature -T _m (°C)	Time to reach Maximum Temperature - t _m (mins)	Shape Constant-c
Si - BFD1	0.08	1268	1211	36	38
Si - BFD2	0.02	1268	845	143	38
Si - BFD3	0.08	780	1211	22	38
Si - BFD4	0.02	780	846	88	38
Si - BFD5	0.08	1268	1211	36	16
Si - BFD6	0.02	1268	845	143	16
Si - BFD7	0.08	780	1211	22	16
Si - BFD8	0.02	780	846	88	16

4.3 LSF Walls Externally Insulated with Rock Fibre Insulation

As for single and double plasterboard lined LSF walls, LSF walls externally insulated with rock fibre insulation were also analysed for both Eurocode parametric and ‘BFD’ fire curves. The fire parameters are given in Table 4 while Figures 15 and 16 show the corresponding fire curves and stud hot and cold flange temperatures obtained from thermal analyses. The rate of temperature rise in these eight fire curves (Fire curves Cp-EU1 to Cp-EU8) is much higher than the standard fire curve, and the maximum temperatures are also well above that of standard fire curve. The maximum fire temperatures of Fire curves Cp-EU5 and Cp-EU7 are well above 1300°C achieved in less than 50 and 30 minutes, respectively, whereas in Fire curves Cp-EU2 and Cp-EU4 they are about 1100°C in 60 and 90 minutes, respectively (Figure 15).

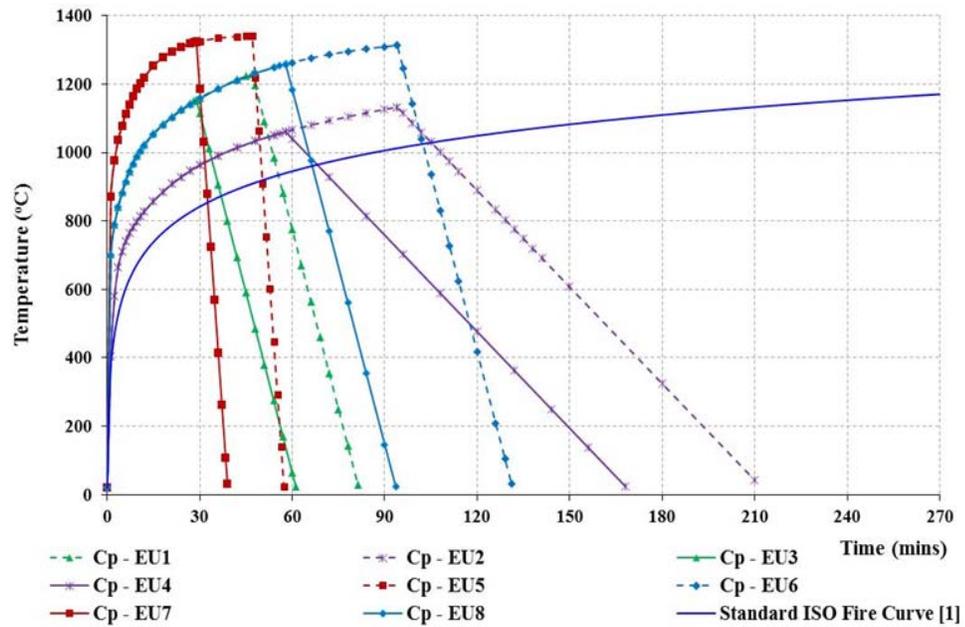
The stud hot flange temperatures for the Fire curves Cp-EU1, Cp-EU3, Cp-EU5 and Cp-EU7 started to decrease in less than 60 minutes of fire exposure. This is due to the decay phase in the fire time-temperature curve where fire temperatures started to decrease with time rapidly. Hence the stud temperatures also decreased with time. The highest stud hot flange temperature was obtained for Fire Curve Cp-EU6 and it was 740°C after 90 minutes of fire exposure. For rapid fires, stud temperatures increased much earlier than for prolonged fires. Also unlike in the Eurocode parametric fire curves, the stud hot flange temperatures are seen to increase for considerable time for ‘BFD’ fire curves even in the decay phase due to the slow rate of fire temperature decrease. For instance, Fire curve Cp-BFD1 reached the maximum temperature at 48 minutes, and the stud hot flange reached its maximum temperature at 132 minutes, which indicates that stud temperatures increased for nearly 80 minutes in the decay phase of the fire. At 48 minutes the stud hot flange temperature was 100°C while it was 534°C at 132 minutes. This was due to high fire temperatures and slow rate of fire temperature decrease. As for the previous LSF wall configurations, the stud time-temperature curves in this case also followed the fire time-temperature profiles. But the rate of temperature rise in studs is much slower than it is for single and double plasterboard lined LSF walls due to the use of rock fibre external insulation.

Table 4. Fire Compartment Characteristics Used in the Development of Design Fire Curves for LSF Walls Externally Insulated with Rock Fibre Insulation

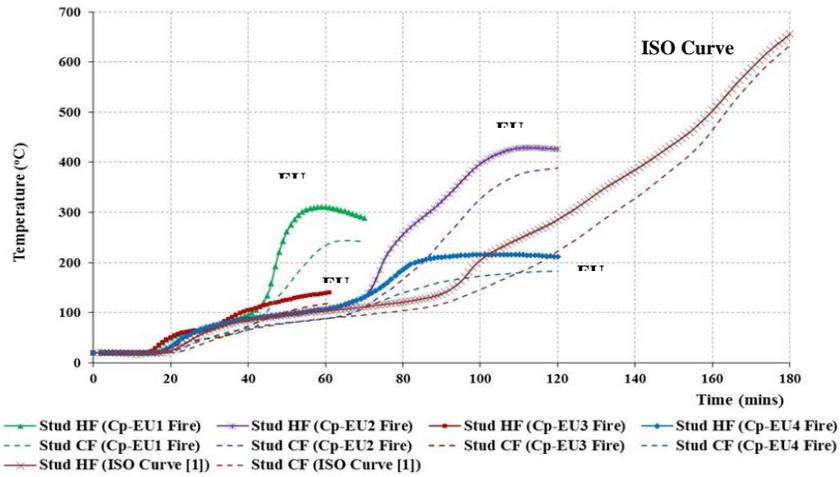
(a) Eurocode parametric fire curves			
Eurocode Parametric Fire Curves [3]	Opening Factor (m ^{1/2})	Compartment Thermal Inertia (J/m ² S ^{1/2} K)	Fuel Load (MJ/m ²)
Cp - EU1	0.06	606.3	1268
Cp - EU2	0.03	585.3	1268
Cp - EU3	0.06	606.3	780
Cp - EU4	0.03	585.3	780
Cp - EU5	0.06	316.9	1268
Cp - EU6	0.03	305.2	1268
Cp - EU7	0.06	316.9	780
Cp - EU8	0.03	305.2	780

(b) BFD' fire curves

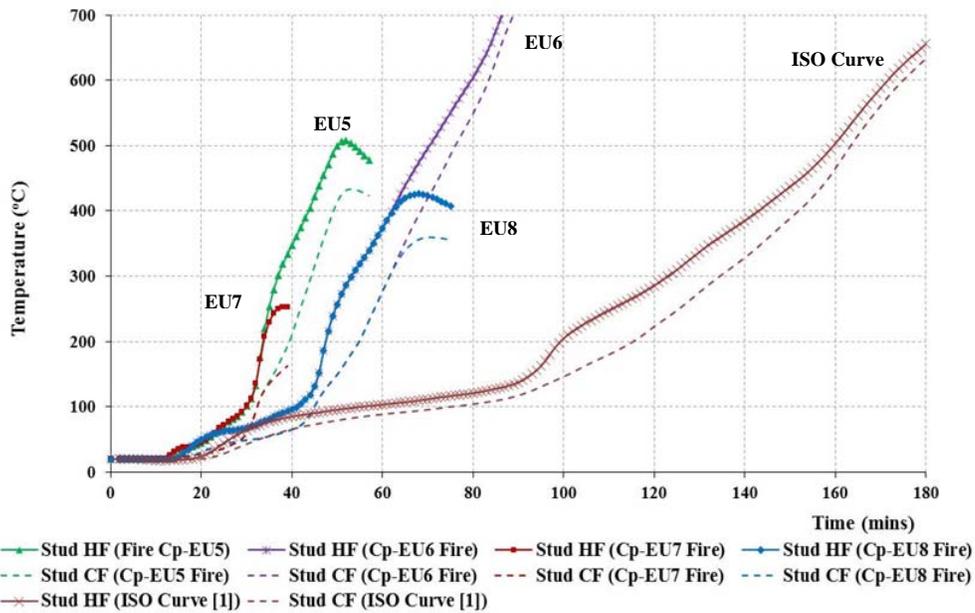
'BFD' Fire Curves [5]	Opening Factor (m ^{1/2})	Fuel Load (MJ/m ²)	Fire Maximum Temperature - T _m (°C)	Time to reach Maximum Temperature - t _m (mins)	Shape Constant-c
Cp - BFD1	0.06	1268	1193	48	38
Cp - BFD2	0.03	1268	1057	95	38
Cp - BFD3	0.06	780	1193	29	38
Cp - BFD4	0.03	780	1057	59	38
Cp - BFD5	0.06	1268	1193	48	16
Cp - BFD6	0.03	1268	1057	95	16
Cp - BFD7	0.06	780	1193	29	16
Cp - BFD8	0.03	780	1057	59	16



(a) Eurocode parametric design fire curves

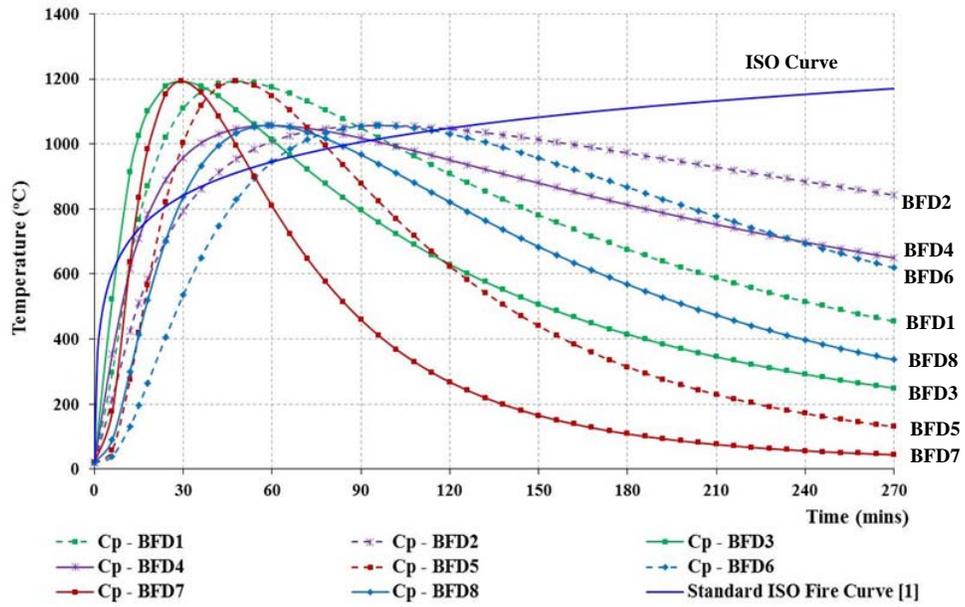


(b) Stud hot and cold flange temperatures for Fire Curves Cp-EU1 to Cp-EU4

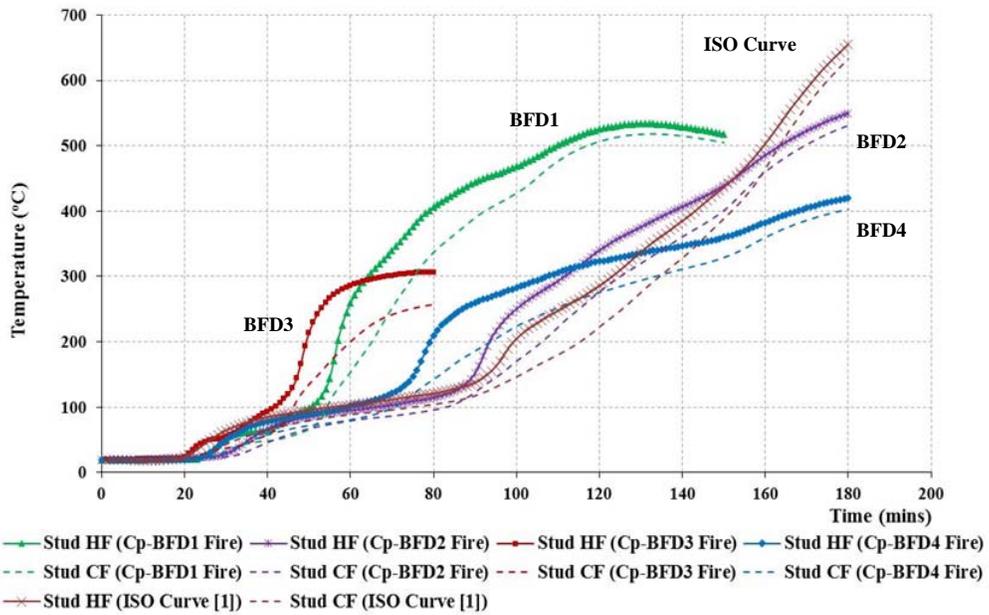


(c) Stud hot and cold flange temperatures for Fire Curves Cp-EU5 to Cp-EU8

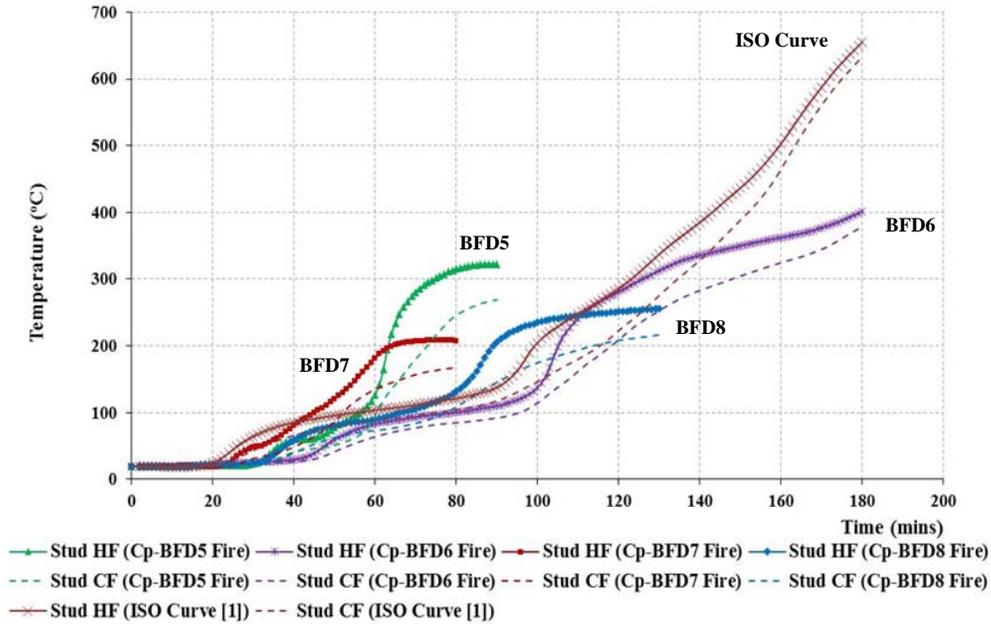
Figure 15. Stud Time–Temperature Curves Obtained from FEA for LSF Walls Externally Insulated with Rock Fibre Insulation Exposed to Eurocode Parametric Fire Curves



(a) 'BFD' fire curves



(b) Stud hot and cold flange temperatures for Fire Curves Cp-BFD1 to Cp-BFD4



(c) Stud hot and cold flange temperatures for Fire Curves Cp-BFD1 to Cp-BFD4

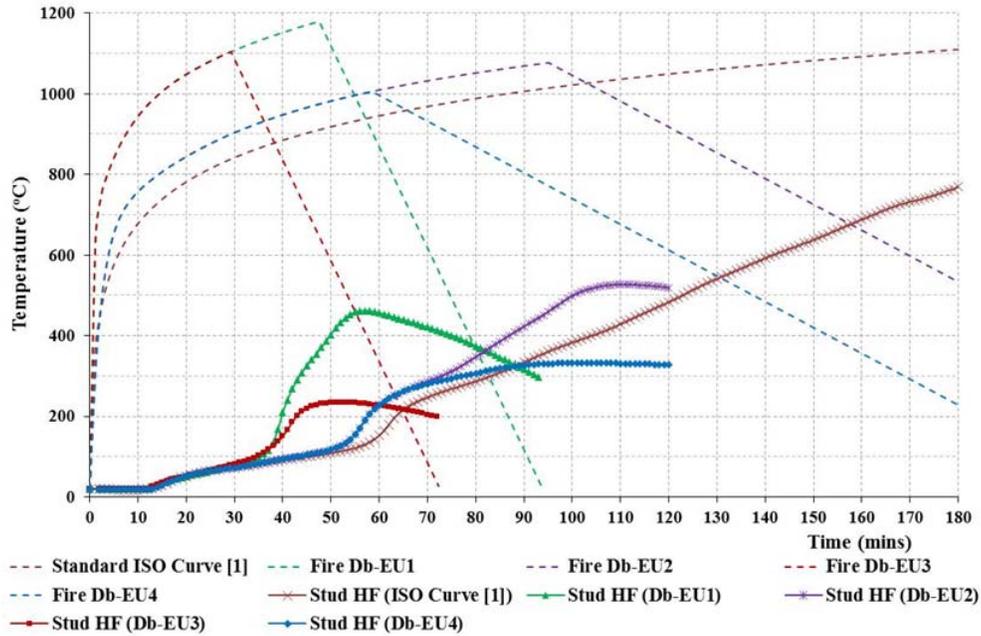
Figure 16. Stud Time–Temperature Curves Obtained from FEA for LSF Walls Externally Insulated with Rock Fibre Insulation and Exposed to ‘BFD’ Fire Curves

4.4 Final Comments and Development of a Simple Method to Estimate Fire Rating

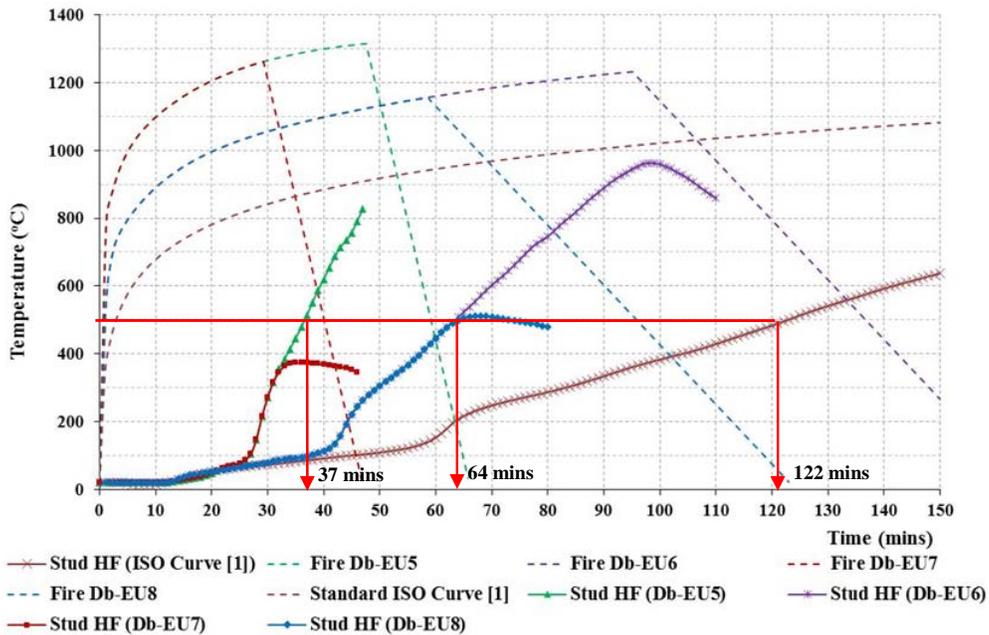
Based on the finite element analysis based parametric studies of LSF walls lined with single and double plasterboards and walls externally insulated with rock fibre insulation, the following observations can be made.

- The stud temperature rise is significantly influenced by the type of fire time-temperature curve. The maximum fire temperature and the time it occurs in the fire curve significantly influence the stud temperatures. This implies that fire resistance rating (FRR) of LSF wall will also be influenced by the type of fire time-temperature curve.
- Rapid fires cause the stud temperatures to increase rapidly than prolonged fires. Hence significant reductions of the stud capacity could be observed in the early stage of the fire.
- Temperature in the prolonged fire curves increases with time for a much longer duration than rapid fire curves. Hence stud temperatures also continue to increase with time.
- The decay rate of fire time-temperature curve has an effect on the stud time-temperature curve. A slow decay rate increases the stud temperatures for considerable time even in the decay phase of the fire whereas a rapid decay rate reduces the stud temperatures quickly.
- Stud temperatures increase even in the decay phase of the fire, and hence LSF wall studs can fail in the decay phase of the fire if the studs reach their critical failure temperature.
- Single plasterboard lined LSF walls are highly responsive to fires as the stud temperatures increase rapidly compared to other LSF wall configurations.

- LSF walls externally insulated with rock fibre insulation are able to protect the steel studs from temperature rise. The stud hot and cold flange temperatures are less than those of single and double plasterboard lined LSF wall studs.



(a) Stud hot flange temperatures for Fire Curves Db-EU1 to Db-EU4



(b) Stud hot flange temperatures for Fire Curves Db-EU5 to Db-EU8

Figure 17. Stud Time–Temperature Curves of Double Plasterboard Layers Lined LSF Walls Exposed to Realistic Design Fires

Fire tests of LSF walls under realistic fire conditions [4] have shown that LSF wall stud failure is mostly governed by its hot flange temperature for similar conditions. Hence using a limiting hot flange temperature method, LSF wall stud failure times can be computed for any realistic design fire curves provided the stud hot flange time-temperature curves are known. For instance, Figures 17 (a) and (b) show the FEA results of double plasterboard lined LSF walls exposed to different realistic design fire curves, and compare them with those under standard fire curve. If the critical limiting temperature of LSF wall studs is 500°C for a particular load ratio, then the stud failure times, i.e. fire resistance ratings of LSF walls, can be calculated from Figure 17. For the following fire Curves: Standard ISO curve, Db-EU1 to Db-EU8 the stud hot flange failure times or FRR are 122 mins, NF, 100 mins, NF, NF, 37 mins, 64 mins, NF and 64 mins, respectively, where NF – No Failure. These results show that if the critical stud hot flange temperature is 500°C, the realistic design fires such as Db-EU2, Db-EU5, Db-EU6 and Db-EU8 can cause more severe damage to LSF walls than the standard ISO fire curve [1]. On the other hand LSF wall panels will not fail under realistic design fires such as Db-EU1, Db-EU3, Db-EU4 and Db-EU7. The limiting stud hot flange temperature varies as a function of load ratio for load bearing LSF wall panels [4]. Using the same method, FRR of LSF walls under realistic design fire curves can be determined for load bearing walls with varying load ratios by using the corresponding limiting stud hot flange temperatures. The same can be achieved for Barnett's BFD fire curves or any other type of fire curve provided the stud time-temperature curves and limiting (critical) stud hot flange temperatures are available. Finite element thermal models such as those developed in this research can be used to determine the stud time-temperature curves.

5. CONCLUSIONS

This paper has presented the details of a numerical study on the thermal performance of load bearing LSF wall panels under realistic design fire time-temperature curves. It includes the details of the developed finite element models of load bearing LSF wall panels, the thermal analysis results from SAFIR under realistic design fire curves and their comparisons with fire test results obtained by Ariyanayagam and Mahendran [4]. A reasonable agreement with fire test results showed that accurate finite element models can be developed and used to simulate the thermal behaviour of full scale load bearing LSF wall panels under realistic fire conditions. Finite element models were then used in detailed parametric studies to investigate the effects of different LSF wall configurations such as single and double layers of plasterboard lining and external rock fibre insulation and realistic design fire scenarios. The study shows that the type of fire time-temperature curve significantly influenced the stud time-temperature curves. The characteristics of real fire curves such as the maximum fire temperature, the time this occurs and the rate of decay significantly influenced the stud temperatures. The analysis results also show that finite element thermal models of LSF walls can be used to predict the fire performance including their fire resistance rating with reasonable accuracy for varying configurations of plasterboard lined LSF walls exposed to realistic design fire curves. Further, a simple method is also proposed in this paper to estimate the fire resistance rating of LSF walls under varying fire scenarios based on finite element thermal analysis predicted stud time-temperature curves and appropriate critical stud hot flange temperatures.

ACKNOWLEDGEMENTS

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