Fire Safety of Buildings Based on Realistic Fire Time-Temperature Curves

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Abstract

In recent times, fire has become a major disaster in buildings due to the increase in fire loads, as a result of modern furniture and light weight construction. This has caused problems for safe evacuation and rescue activities, and in some instances lead to the collapse of buildings (Lewis, 2008 and Nyman, 2002). Recent research has shown that the actual fire resistance of building elements exposed to building fires can be less than their specified fire resistance rating (Lennon and Moore, 2003, Jones, 2002, Nyman, 2002 and Abecassis-Empis et al. 2008). Conventionally the fire rating of building elements is determined using fire tests based on the standard fire time-temperature curve given in ISO 834. This ISO 834 curve was developed in the early 1900s, where wood was the basic fuel source. In reality, modern buildings make use of thermoplastic materials, synthetic foams and fabrics. These materials are high in calorific values and increase both the speed of fire growth and heat release rate, thus increasing the fire severity beyond that of the standard fire curve. Hence it suggests the need to use realistic fire time-temperature curves in tests. Real building fire temperature profiles depend on the fuel load representing the combustible building contents, ventilation openings and thermal properties of wall lining materials. Fuel load is selected based on a review and suitable realistic fire time-temperature curves were developed. Fire tests were then performed for plasterboard lined light gauge steel framed walls for the developed realistic fire curves. This paper presents the details of the development of suitable realistic building fire curves, and the fire tests using them. It describes the fire performance of tested walls in comparison to the standard fire tests and highlights the differences between them. This research has shown the need to use realistic fire exposures in assessing the fire resistance rating of building elements.

Keywords: Fire safety, Standard fire curve, Fuel load, Realistic fire time-temperature curves, Light gauge steel frame walls.

1. Introduction

Fire resistance of building elements has been traditionally determined using standard fire tests specified in ISO 834 (ISO, 1999). Fire Resistance Rating (FRR) determined from these tests should be sufficient in a fire event, for safe evacuation, fire service intervention and for

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rescue activities. Recent researches have shown that the actual FRR of building elements exposed to real building fires is significantly less than that obtained from standard fire tests (Lennon and Moore,2003, Jones, 2002, Nyman, 2002 and Abecassis-Empis *et al*. 2008). Fire testing of building elements is generally based on the standard time-temperature curve given in ISO 834. This curve was developed in early 1900s based on wood fuel burning furnaces, and was later modified slightly to give a faster temperature rise for the first few minutes of burning to represent the gas fired furnace temperatures (Babrauskas and Williamson, 1978). Many fire resistance tests have been undertaken at great expenses, and a vast database of FRR times has been collected over the years. However, this approach was not based on the knowledge of fire severities in real buildings. Since then, no significant change has been made to this standard time-temperature curve, which is being used to calculate the FRR of building elements until now. Many countries also use ISO 834 or have standards similar to ISO 834. Therefore there is a concern on the appropriateness of the standard fire in representing the real fire conditions in modern building environment.

In reality, commercial and residential buildings incorporate both traditional wooden furniture and modern items such as cushion/fabric furniture, mattresses, fabric coated partitions and many other items, which make use of thermoplastic materials, synthetic foams and fabrics. The increasing use of thermoplastic materials is clearly evident with the introduction of desktop computers, fabric coated drywall systems and upholstered furniture in modern commercial and residential buildings. Also the calorific value for cellulosic material is only 17 MJ/kg while it varies from 25 to 35 MJ/kg for plastics depending on its type (ECS, 2002). During a fire, thermoplastic materials melt and flow to the floor and starts to burn. These fires burn significantly faster, with higher heat release rates. Bwalya *et al.* (2007) conducted room-scale fire tests to evaluate the impact of new construction products and systems on the fire safety of single family residential dwellings. For this, a fuel package consisting of a sofa constructed with exposed polyurethane foam (PUF) and wood cribs were considered. The sofa was ignited first and the wood cribs provided the remaining fire load. The results showed that the rate of temperature rise during the fire growth period was more rapid than that of ISO 834 (1999) time-temperature curve.

Table 1: Composition of Fire Loads (Bwalya et al., 2008)

Room Usage	Fire load Percent Weight (kg)			Fuel load Percent Fire Load (MJ)		
	W	P	T	W	P	T
Kitchen	86.5	13.5	<<1%	80.2	19.8	<<1%
Living Room	65.8	32.9	1.4	57.4	41.4	1.2
Dining Room	72.6	26.6	0.8	65	34.0	0.8
Primary Bedroom	42.3	26.4	31.4	37.8	34.1	28.1
Secondary Bedroom	39.8	29.8	30.3	35.2	38.0	26.8
Basement Living Room	61.0	39.0	0.2	51.8	48.1	0.2

Note: W: Wood and Paper; P: Synthetic Plastic materials (including polyurethane foam); T: Textiles (including clothing); <<1%: much lower than 1%

Recently Bwalya et al. (2008) conducted a fire load survey for family dwellings based on information from real estate websites in Canada to quantify and to determine the composition of the combustible contents in residential dwellings. Table 1 summarizes their survey results. The composition of the combustibles in all the rooms was categorized into three main material groups: wood and paper (cellulose-based), synthetic plastics and textiles (or fabrics). It is evident from these results that wood-based materials form a significant proportion of the total combustible mass in residential dwellings. Although the cellulosic material takes up the highest contribution, plastics occupy nearly 13 to 39% by weight (kg) and contribute 20 to 48% to the fire load (MJ). The increase in percentage of fire load was due to the higher caloric values of synthetic plastics than cellulosic materials. This shows a significant contribution from synthetic plastic materials to the fire loads in residential dwellings. It must be noted that plastics were not present when the standard time-temperature curve was established. As mentioned, these modern synthetic materials increase both the speed of fire growth and peak heat release rate, thus increasing the fire severity than the standard fire curve used to obtain the FRR. Hence construction elements may not ensure safe evacuation, or offer the required life safety for occupants and fire rescuers as indicated in the technical manuals of building assemblies.

Fire testing using the standard time-temperature curve will give good comparative results for building systems tested under identical conditions, and also valuable basic data. However, these results do not provide accurate FRR for residential and commercial buildings, which have a high fire severity as shown by Lennon and Moore (2003), Jones (2002) and Abecassis-Empis *et al*. (2008). These researchers used compartment fire tests for this purpose, where the maximum temperature of a natural fire exceeded the standard ISO curve within a short period of time from ignition. In a building fire, the fire growth, fully developed and decay phases depend on aspects such as the total fuel load present in the room, fuel type and configuration, ventilation openings and thermal properties of compartment lining materials. Among them, fuel load was selected to represent the combustible contents in modern residential buildings based on the literature, and appropriate realistic building fire curves were developed. This paper presents the details of the development of such realistic fire time-temperature curves. It also describes the fire performance of steel wall panels tested under both the developed realistic fires and the standard fires (ISO 834, 1999) and highlights the differences between the effects of standard and realistic building fires.

2. Realistic fire time-temperature curves

Several equations and computer models have been developed by researchers to predict the fire behaviour. These are of two types: pre-flashover and post-flashover fire models to represent the behaviour of a fire. The post-flashover fire scenario models focuses in the analysis and design of building fire safety systems and pre-flashover fires involves fire spread around the building and toxic gas production. These time-temperature curves were derived using mass and energy balance equations, heat release rates and curve fitting to temperature profiles obtained from compartment tests. The literature on post-flashover time-temperature curves shows that it is very difficult to envisage the time-temperature profile of a fire in a compartment. Many researchers used different types of fuels and ventilation conditions to obtain and validate their fire curves. Hence most of these equations have limitations, and their range of application is limited. Similarly for computer models, reliable and detailed time-temperature data from large-scale fire tests are needed for validation.

The review of the non-standard time-temperature post-flashover fires identified that three basic parameters define the time-temperature curve in a compartment, namely, Fuel load, Ventilation and Thermal properties of lining materials. Also it is clear that a standard fire curve (ISO 834, 1999) to suit the real building fires is unrealistic and the fires have to be based on the above three parameters. Several approaches have been used to determine the equivalent severity of fire, for which, 'equal area' and 'time equivalent' concepts are commonly used. Equal area relates to the area under the time-temperature curve while time equivalent concept relates the time of exposure to the standard fire an element would need to be exposed to reach that in a real fire. It includes 'maximum temperature' 'minimum load capacity' and 'maximum deflection', and empirical formulae were developed. Empirical formulae in CIB (1986), Law (1983) and Eurocode (2002) have been derived based on these principles, and are available for computing the time equivalence for building elements. The time equivalent concept provides only an approximate value to that of real fire behaviour when comparing it with the standard fire. Also the empirical formulae are based on equivalent time of exposure to the standard fire and are derived for a particular set of design fire time-temperature curves only. Hence considering their accuracy to realistic fires and to develop realistic time-temperature profiles, Eurocode parametric curve (ECS, 2002) and Barnett's (2002) 'BFD' curve fire profile were selected.

Eurocode 1 Part 1-2 (ECS, 2002) prescribes a simple mathematical relationship for 'Parametric' fires, allowing a time-temperature relationship for a combination of the above mentioned parameters. The curves were developed for both heating and cooling phases. The rate of temperature rise and peak temperatures in the Eurocode parametric curves are well above those in the standard fire curve and the decay rates are linear and rapid, leading to a shorter fire decay durations. The fire parameter values used in deriving the realistic fire time-temperature curves are shown in Figure 2. On the other hand Barnett's 'BFD' curve is much closer to the real fire time-temperature distribution and uses a single log-normal equation to represent both heating and cooling phases. Barnett (2002) states that 'BFD' curves has been developed using curve fitting to 142 natural fire tests with a range of fuels and different enclosure materials. The 'BFD' curve takes the shape of the natural fire curve and closely agrees with the actual fire test results than other models. Hence in order to study the behaviour under natural decay phase of a fire, Barnett's 'BFD' curve is also considered.

3. Development of realistic fire time-temperature curves

3.1 Fire loads in residential buildings

The design fire curves are determined based on three parameters, namely; fuel load, ventilation openings and thermal properties of wall lining materials. Of these fuel load is an important parameter since it represents the combustibles in a compartment. It affects the burning duration and peak temperature of the compartment. The term fuel load is defined as the energy (MJ) that could be released by the complete combustion of compartment contents. The fuel load in a compartment is expressed as Fuel Load Density (FLD). It is the heat energy released/m^2 of floor area of a compartment by the combustion of the fuel loads within the compartment. The fuel load in a room is made up of permanent and variable loads. Permanent fuel load includes materials that are rarely moved or changed during the service life of the building such as electrical, ventilation fittings, etc. Variable fuel load varies during service life, and is temporarily placed and movable such as furniture and ornaments.

Fuel loads in residential buildings depend on the geographic location, home construction and furnishing styles. Also they vary within a building depending on the room usage. The changes in the fashion trends and materials used for furnishing have resulted in significant differences in the composition of fuel load densities in modern buildings. As mentioned rapid usage of plastics in many household items over the past decade or two has greatly increased the fuel load energy in buildings. Some plastic materials burn rapidly as pool fires, therefore plastics in any item should be considered as a potential fuel load. To determine the variable FLD, surveys have been conducted in many countries and suitable values have been published in the standard codes of practice. The available mean fuel load density values for residential dwellings are summarized in Figure 1.

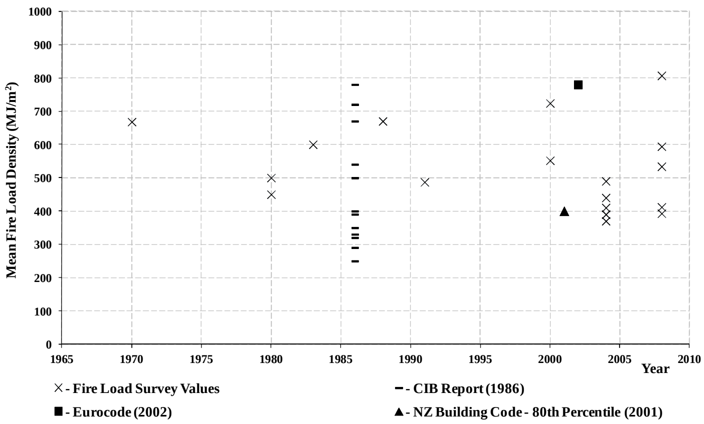


Figure 1: Summary of mean variable fuel load density values for residential dwellings

It is uncertain which mean value and percentile are to be selected in determining the time-temperature curve to represent a more realistic fire scenario for residential buildings. Hence this question was raised with many academics, researchers and experts in the field of fire engineering, whose common recommendations were to select a realistic value from the available literature that is justifiable to the present building environment than using a value obtained 20 years ago. Also there is no definitive value for a type of building, and the fuel load density value alone does not provide a realistic time-temperature curve. Instead parameters such as, fuel load composition, heat release rates, ventilation opening sizes and thermal properties of wall lining materials are also important in obtaining a more realistic time-temperature profile. However for design purposes it is obvious to select the worst case fire scenario, which reflects the actual fire profile in a modern building. Therefore an average value of 780 MJ/m^2 was selected from Eurocode 1 Part 1-2 (ECS, 2002), which is very close to Bwalya et al.'s (2008) recent fire load survey results (807 MJ/m^2) obtained for Canadian residential buildings. Also for design load, an 80th percentile value of 948 MJ/m^2 was selected and taking into account the factors such as combustion for cellulosic materials (m=0.8), fire activation risks for compartment area (δ_1=1.5), type of occupancy (δ_2=1) and active fire fighting measure (δ_n=1) as given in Eurocode 1 Part 1.2 (ECS, 2002), the design variable fuel load density for residential building was determined as 1138 MJ/m^2. For permanent fuel load density National Fire Protection Association (NFPA) proposes a value of 130 MJ/m^2.

3.2 Realistic fire time-temperature curves

The compartment geometry considered was 3600 (L) x 2400 (W) x 2400 (H) mm based on ISO 9705 compartment geometry (Nyman, 2002). The boundary of enclosure materials for this research was chosen to be light steel frame partition walls lined with single and double layer gypsum plasterboards for walls and ceiling, and concrete floor slab to represent a typical single storey residential dwelling. The corresponding thermal inertia for the compartment was determined to be 715 J/$m^2S^{1/2}$K for plasterboard lined walls and ceiling, and concrete floor compartment. To account for different fire scenarios, two opening factors, 0.08 and 0.03 $m^{1/2}$ were chosen to represent a rapid fire and a long-drawn-out fire for single and double plasterboard lined wall fire tests, respectively. The opening factor is defined as $O = A_v\sqrt{h_{eq}}/A_t$ where A_v - area of vertical openings on all walls, h_{eq} - weighted average of opening heights and A_t - total area of enclosure.

Both Eurocode parametric fire (ECS, 2002) and Barnett's 'BFD' fire (Barnett, 2002) curves were drawn for the same parameters and the 'BFD' curve was modified to derive more realistic time-temperature curves for design. In comparison with the Eurocode parametric fire, the peak temperature values of 'BFD' curve are much less, but the shape of the curve fits well with the natural fire curve. The 'BFD' curve calculates the maximum temperature from the equation recommended by Law (1983) based on many experimental fires. This equation may not incorporate the temperature rise due to the modern materials as it was developed in early 1980s. Hence it was decided to use the maximum temperature of the Eurocode parametric curve (ECS, 2002) for the 'BFD' curve. Figure 2 shows the modified 'BFD' curves and Eurocode parametric curves drawn for the realistic design parameters.

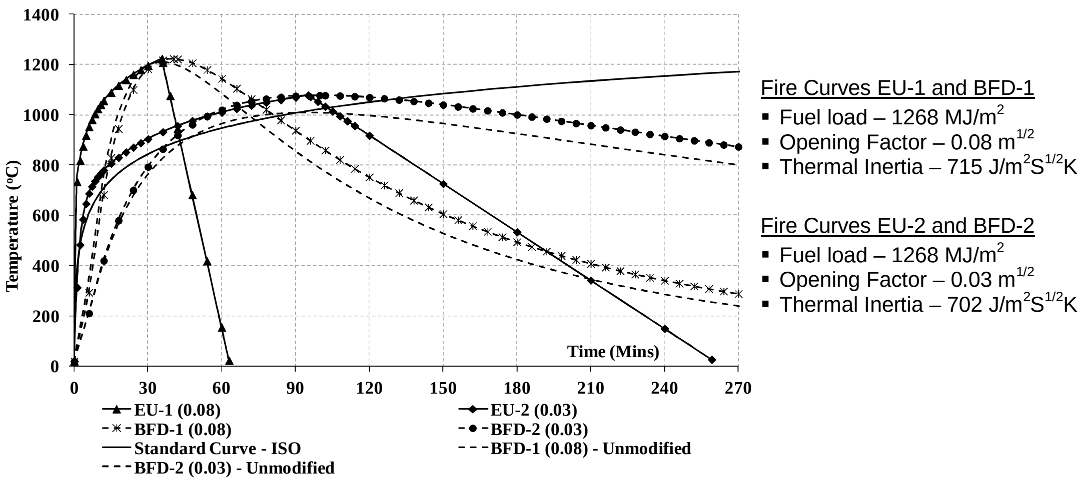


Figure 2: Realistic fire time-temperature curves

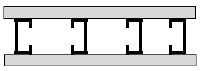
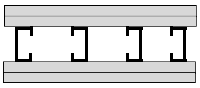
At present, experimental and analytical studies have been performed to understand the structural and thermal performances of steel frame wall panels subjected to heating based on the standard time-temperature curve. As mentioned before standard fire tests will provide good comparative results for materials tested in identical conditions, but do not reflect the true time-temperature profile during a real fire in a building. Therefore, full scale fire tests were performed to study the behaviour of light gauge steel frame wall panels lined with single and double plasterboard layers for the developed realistic time-temperature curves.

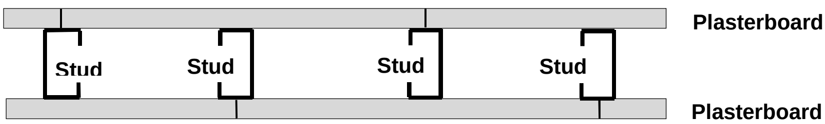
4. Fire testing of light gauge steel frame wall panels

4.1 Test wall specimens

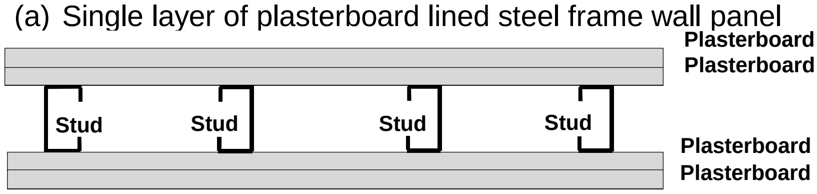
Test program consisted of four load bearing light gauge steel frame (LSF) wall panels of 2400mm width and 2400mm height, lined with 16 mm thick Firestop(R) gypsum plasterboards under the developed fire time-temperature profiles in Section 3. Tests were conducted to determine the fire resistance of these four load bearing LSF walls under realistic fire curves shown in Figure 2. Table 2 gives the details of the four load bearing test wall specimens.

Table 2: Details of test wall specimens

Test	LSF Wall Configuration	Fire Profile	Load Ratio (Load per Stud)
T1	Single layer of Pb 	EU-1 (0.08)	0.2 (15 kN / Stud)
T2		BFD-1 (0.08)	
T3	Double layer of Pb 	EU-2 (0.03)	
T4		BFD-2 (0.03)	



(a) Single layer of plasterboard lined steel frame wall panel



(b) Double layers of plasterboard lined steel frame wall panel

Figure 3: Light gauge steel frame wall panel configurations

Each test wall panel included four steel studs (90 x 40 x15 x 1.15 mm) at a spacing of 600 mm, and were attached to top and bottom unlipped channel section (92 x 50 x 1.15 mm) tracks using D-Type self drilling 16 mm long flat head screws. The studs and tracks were fabricated from 1.15 mm galvanized steel sheets having a minimum yield strength of 500 MPa. Test specimens T1 and T2 were lined with single layer of 16 mm plasterboards on both sides of the steel frame while test specimens T3 and T4 were lined with two layers of 16 mm plasterboards (Figure 3). The standard sizes of 16 mm gypsum plasterboard were 1200 mm by 2400 mm and the density is 13 kg/m^2. D-Type self drilling bugle head screws of 25 and 45 mm length were used to fix the first (base) and second (face) layers of plasterboards. The base layer plasterboard (Pb1) was screwed at 200 mm spacing along the studs where the plasterboard joints exist, and 300 mm spacing along the intermediate studs. The second layer of plasterboard (Pb2) was fixed at 300 mm screw spacing for the double layer wall panels. The base layer has vertical joints over the studs and the face layer was placed to have a horizontal joint. The plasterboard joints were sealed with two coats of plaster-based joint compound and 50 mm wide cellulose based joint tape was sandwiched between the two coats of joint compound.

4.2 Test set-up and procedure

The wall fire tests were conducted in a propane fired gas furnace lined with ceramic fibre insulation. The time-temperature curve of the furnace was monitored and controlled by four Nicrobell coated rod type thermocouples, which measure temperatures up to 1200^{o}C. These temperatures were used to control the fuel and air supply to the chamber to obtain the required time-temperature fire curve. Tests were conducted in a specially designed test rig shown in Figure 4, where a pre-determined (load ratio =0.2) axial compression load was applied to the individual studs of LSF panel from the bottom. This axial compression load was based on 0.2 times the ambient capacity of the stud (79 kN) determined by Kolarkar (2010). A lower load ratio of 0.2 was selected as it would delay the failure of the panel, enabling sufficient data to be obtained from the test. The test specimen was placed with the centroids of the studs aligning with those of the loading plates and hydraulic ramps. The axial compression load was applied by four individual ramps and transmitted through the loading plates. Each loading plate was connected to an individual hydraulic ramp while a single pump was used to apply the required axial load.

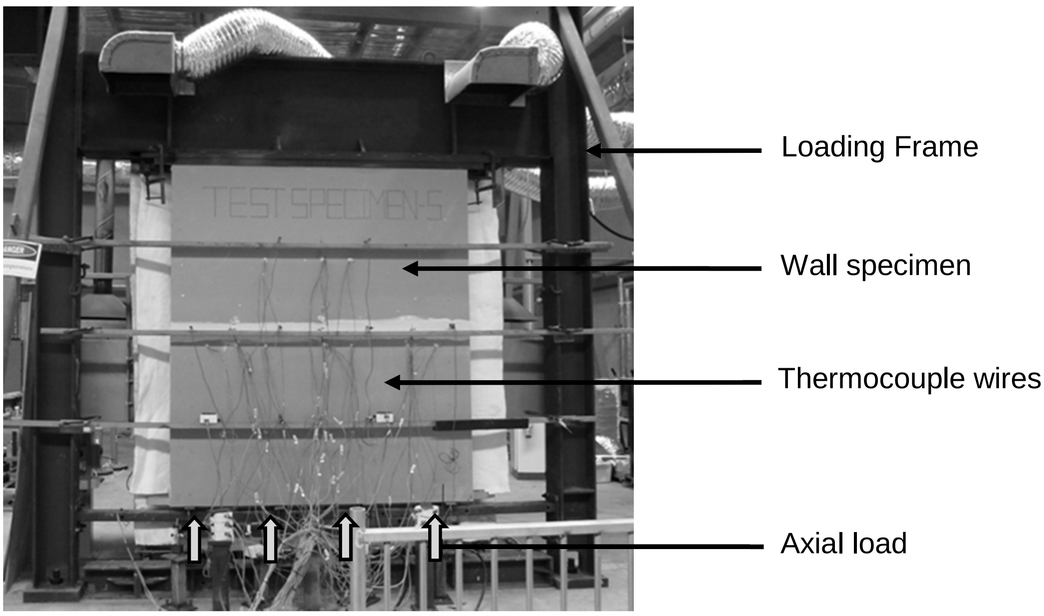


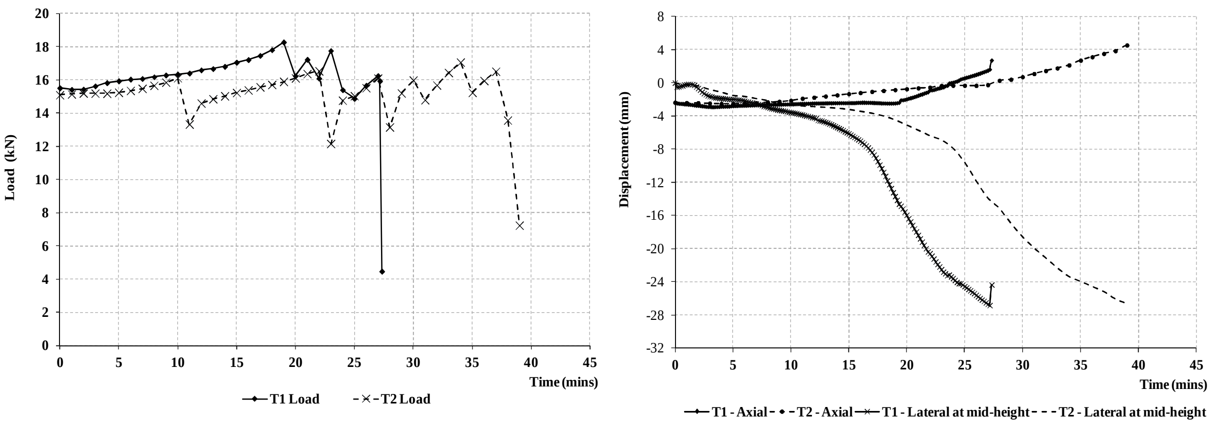
Figure 4: Fire test set-up

4.3 Observations and results

During the fire test, the furnace air and fuel (propane gas) valves were regulated such that the average furnace temperature inside the furnace followed the target fire curve. The proposed realistic design fire curves shown in Figure 2 were achieved reasonably well (within 50^oC) in all the tests, except in Test Specimen T1 where it was nearly 100^oC less for the entire duration of the test. The structural failure of the studs occurred before the insulation or integrity failure in all the tests except Test Specimen T3 that did not fail even under insulation or integrity criteria. The failure times are given in Table 3. They were based on the time when the pressure in the hydraulic ramps could not be maintained. In all the tests, after a few minutes of starting the furnace, smoke was visible at the top of the specimen while water drops were seen along the edges of the loading frame. Smoke and steam were then seen to escape from the furnace chamber during the test. This was due to the burning of plasterboard paper layer on the fire exposed side.

Table 3: Failure times of test specimens

Test	LSF Wall Configuration	Fire Profile	Failure Time
T1	Single layer of Pb	EU-1 (0.08)	28 mins
T2		BFD-1 (0.08)	39 mins
T3	Double layers of Pb	EU-2 (0.03)	No Failure
T4		BFD-2 (0.03)	139 mins

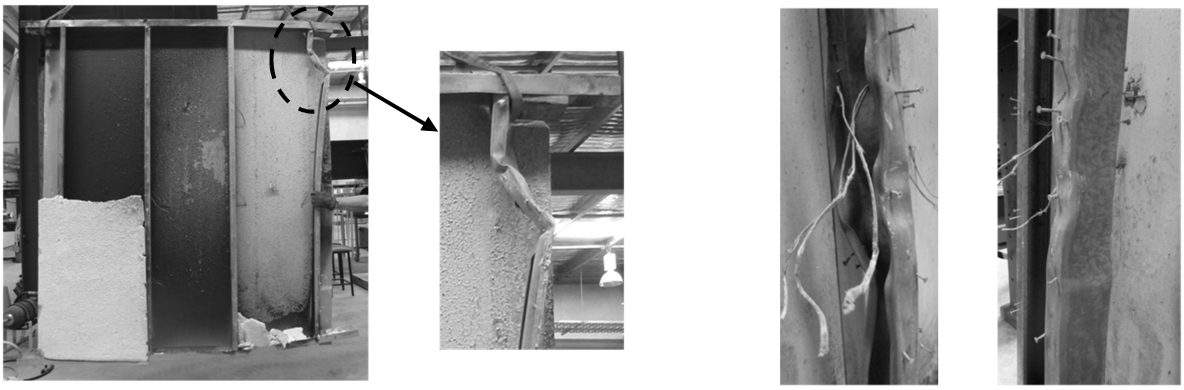


a. Applied load vs. time profiles

b. Stud displacement vs. time profiles

Figure 5: Applied load and stud displacement profiles for Test Specimens T1 and T2

Figure 5a shows the average measured applied load to the studs and the decrease in the load confirms failure times to be 28 and 39 minutes for specimens T1 and T2, respectively. From the ignition of the furnace, the wall was observed to thermally expand until the failure in test specimen T1, T2 and T4. Near the failure this deformation decreased and the test panel deformed in the opposite direction. In specimen T3 the wall was observed to expand thermally until 140 minutes and then it started to contract due to the rapid decrease of the furnace temperature in the decay phase of the fire (EU-2 (0.03)). This showed that studs were regaining their strength and the chance of failing structurally was impossible. Also the wall specimen was observed to bend towards the furnace from the beginning of the fire test. Figure 5b shows the axial deformation and lateral deflection of the failed studs in specimens T1 and T2. Figure 6 shows the failure modes of test specimens T1 and T4. Single plasterboard lined test specimen T1 failed structurally after 28 minutes of fire exposure.



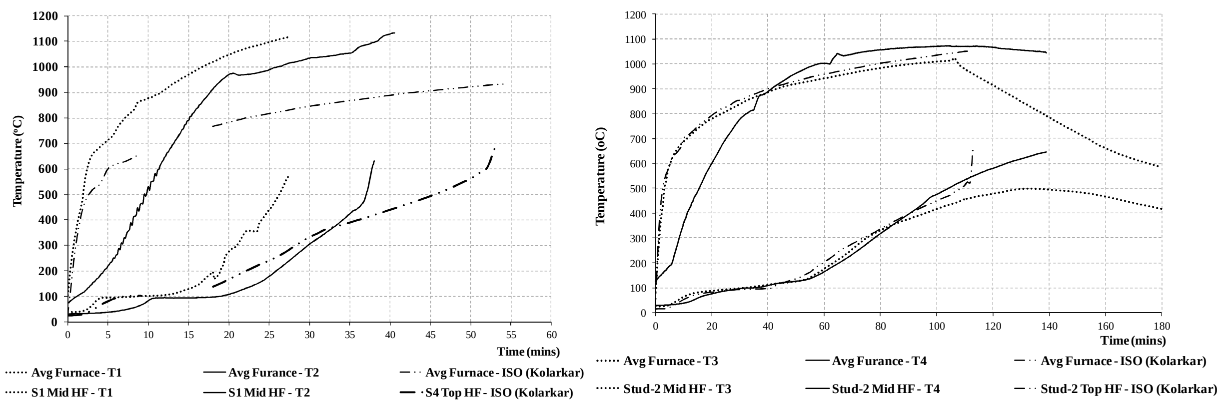
a. T1 – Stud 1 b. T4 – Stud 2

Visual inspection after the test revealed that the exposed plasterboard strip over stud 1 had fallen off, which led to Stud 1 losing its lateral support and failing by flexural torsional buckling. Similar observation was also noted in specimen T2. The middle stud (Stud 2) in specimen T4 experienced local buckling of the entire cross section near the mid-height.

Figure 6: Test specimens T1 and T4 after fire tests

4.4 Discussions

Test specimens T1 and T2 were identical in wall configuration (lined with single plasterboard layer), but were exposed to realistic fire curves of EU-1(0.08) and BFD-1(0.08), respectively. In both tests, the failure occurred in the stud that had the 150 mm strip plasterboard joint (over Stud 1), and partial collapse of this plasterboard initiated the failure. Kolarkar's (2010) standard fire test also showed the same behaviour. T1 and T2 specimens failed after 28 and 39 minutes, respectively, and the corresponding failure time in the standard fire test was 53 minutes (Kolarkar, 2010).



a. Specimens - T1, T2 and ISO834 b. Specimens - T3, T4 and ISO834

Figure 7: Average furnace and stud hot flange temperatures at failure

Figure 7a shows the stud hot flange temperatures at failure together with the average furnace temperature profiles for specimens T1, T2 and Kolarkar's (2010) standard fire test. In T1 and T2 realistic fire tests, the furnace temperatures were much higher than the standard fire test (ISO 834, 1999), and were also maintained at higher temperatures. A rapid temperature rise with a short plasterboard dehydration period can be seen in the stud hot flange for specimen T1. In T2 and standard fire tests, the stud temperature rise was gradual compared to T1 fire test. The higher heat flow must have caused the plasterboard to partially collapse at a lower temperature. Plasterboard calcinated and shrunk rapidly at higher temperatures, and the rapid temperature rise caused the studs to fail earlier than in the standard fire test. The stud hot flange temperature of specimen T2 (630^{o}C) at failure under the 'BFD' curve differs from those for the Eurocode parametric (561^{o}C) and standard fire curves (550^{o}C). This is possibly due to the plasterboard fall-off at different temperatures resulting in a rapid temperature rise in the studs and causing them to fail earlier than in the standard fire test.

Test specimens T3 and T4 were double gypsum plasterboard lined walls and exposed to Eurocode parametric and 'BFD' curves, respectively. Specimen T3 did not fail even after 180 minutes of fire exposure. Specimen T4 failed when the stud hot flange temperatures reached 645^{o}C, which is similar to Kolarkar's standard fire test (663^{o}C). Kolarkar's (2010) standard fire test failed at 111 minutes. Specimen T3 stud hot flange temperature reached only 497^{o}C at 140th minute during the decay phase of the fire. Stud temperatures were seen to increase for nearly 35 minutes even in the decay phase of the fire. This implies that LSF wall studs could also fail during the decay phase of the fire. The wall panels were seen to fail in the fire tests when the studs reached the critical temperatures depending on the lateral stability provided by the plasterboard restraints. Hence it is clear that the failure time of LSF wall panels depends on the real design fire curves. Severe fires in terms of fire temperature and duration will significantly influence the failure time of wall panels.

5. Conclusions

This paper has described the differences between the standard and realistic building fires and the need to assess actual fire resistance ratings of building assemblies under realistic fires. It presents a review of the fuel loads for residential buildings, based on which appropriate realistic building design fire time-temperature curves have been developed. The paper also describes a series of tests of LSF walls conducted under the developed realistic design fires, and compares the fire test results with Kolarkar's (2010) standard fire test results for similar wall panels. This study confirmed that the failure time of steel wall panel depends on the characteristics of the realistic fire profile. Further research is in progress to better understand the behaviour of steel wall panels when exposed to realistic design fires.

6. Acknowledgements

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