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ORIGINAL ARTICLE

Experimental Study on Fire Performance of Polymer Foam Cavity Insulated Light Steel Framed Walls

Tomislav Ščapec[1] | Davor Skejić[2] | Marija Jelčić Rukavina[1]

Correspondence

Prof. Davor Skejić
Faculty of Civil Engineering, University of Zagreb
Fra Andrije Kačića Miošića 26
10 000 Zagreb, Croatia
Email: davor.skejic@grad.unizg.hr

[1] Department of Materials, Faculty of Civil Engineering, University of Zagreb, Zagreb, Croatia
[2] Chair for Metal structures, Department for Structures, Faculty off Civil Engineering, University of Zagreb, Zagreb, Croatia

Abstract

Light steel frame (LSF) building systems are a fast, reliable and economical construction system for residential and non-residential buildings. Since the thermal conductivity of steel significantly limits the effectiveness of such wall systems for use in modern energy-efficient buildings, adequate thermal insulation is essential. For this reason, numerous research studies have been conducted on LSF structures with different types and positions of thermal insulation. Due to the combustible nature of polymer foam, LSF systems insulated with this type of insulation have not been the focus of this research. On the other hand, polymer foam is ideal for automated industrial production of prefabricated load-bearing LSF walls, and research on such walls is mandatory. In this paper, the fire test results of two innovative LSF walls with polymer foam insulation and different gypsum fibreboards are presented. In the proposed configuration, spacers are also used to prevent direct contact between the wall panels and the steel studs. The study conducted shows that a suitable configuration of gypsum fibreboards can lead to satisfactory fire resistance of energy-efficient LSF wall systems with polymer foam.

Keywords

Light steel framed structures, Fire performance, Fire resistance testing, Polymer foam, Fiberboards

1 Introduction

Light steel framed (LSF) buildings have proven to be a valuable construction method for both residential and non-residential buildings [1]. Their popularity is increasing, and the market share of LSF buildings was estimated at $23890 million in 2021, while some forecasts expect it to reach $40540 million by 2028 [2]. LSF is primarily a dry construction system in which cold-formed steel (CFS) profiles are the main structural members [3].

In the construction industry, CFS is considered the most sustainable modern building product because it is easy to prefabricate, has high stiffness and strength, corrosion resistant and recyclable [4]. Moreover, these advantages also apply to the entire LSF assembly. For LSF structures, C-shaped CFS members are mostly used and such CFS members are sheathed with wallboards such as gypsum plasterboard (GPB) and usually insulated with mineral wool (MW) inside the cavity [1]. In addition, the use of thermal insulation is preferred because the high thermal conductivity of CFS members reduces thermal performance in ambient conditions due to the thermal bridge effect [5]. CFS members used for LSF constructions are also relatively thin and the thickness does not exceed 6 mm [1]. This means that the low thickness of CFS members causes them to heat up quickly and lose their stiffness and mechanical strength when exposed to fire [6]. For load-bearing LSF structures, this means that lower ultimate leads to earlier failure of the structure [7]. Such failure is delayed by the fire protective wallboards [8] but once they lose their fire protection effect, the CFS structural members are exposed to the increased heat. Therefore, to improve the potential fire performance of LSF structures, some authors have proposed different compositions.

For example, Gunalan et al [9] have proposed the use of externally insulated LSF structures where the thermal insulation is sandwiched between two layers of fire protective board. This has resulted in increased fire performance as the temperature rise on the CFS member is significantly delayed. Another example of innovative LSF design was presented in the work of Tao et al [10] in which the authors proposed the use of cold-formed square hollow sections (SHS), which were found to be more effective than conventional C-shaped CFS members. A recently proposed LSF wall configuration [4] includes spacers that spatially separate the CFS members from the outside wallboards with polymer foam insulation in the cavity. Such a structure could mitigate the thermal bridging effect at ambient temperatures and protect the members from direct fire exposure when the fire protective wallboard loses its properties. In addition, polyurethane foam insulation (PUR) increases the energy efficiency of the structure at room temperature. However, since PUR is combustible, the fire

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behaviour of such a construction assembly must be investigated. In this paper, the fire behaviour of two PUR insulated LSF wall specimens with two and three layers of gypsum fibreboard, respectively, is investigated.

2 Experimental study

2.1 Construction of the specimens and thermocouples placement

The experimental study was performed on two specimens of 1500 mm width and 2995 mm height, Figure 1. The steel frame consisted of studs (S1-S4), tracks (T1-T2), noggings (N1-N2) and diagonal segments (D1-D6). A steel frame formed a total of 16 nodes (1-16). C-shaped CFS members with dimensions 42x89x10x0.95 mm and steel grade S 550 GD were used, as shown in Figure 2.

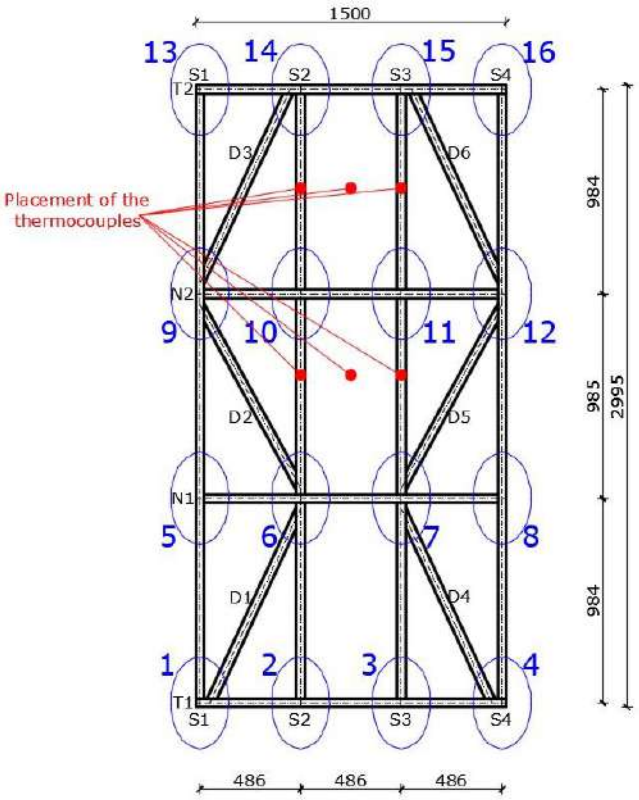


Figure 1 Steel frame of the tested LSF walls and the placement of the thermocouples (dimensions in mm)

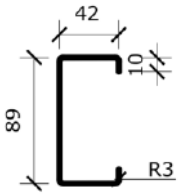
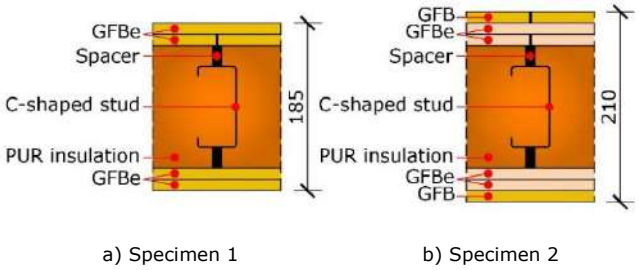


Figure 2 C-shaped CFS member (dimensions in mm)

In such a constructed frame, Z-shaped spacers were placed on the noggings and studs, as shown in Figure 3. For simplicity, the spacers were made of steel, and it is assumed that they do not significantly affect the fire behaviour of such a structure. This is because the contact area between the steel spacers and the exposed wallboards is small when compared to the total exposed area.

After the construction of the steel frame, specimen 1 was sheathed with two layers, while specimen 2 was sheathed with three layers of fire protective wallboards, Figure 3.



a) Specimen 1 b) Specimen 2

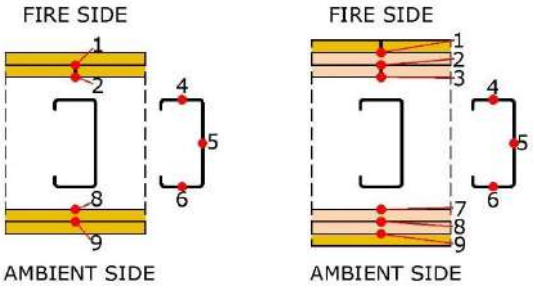
Figure 3 Cross section of the specimens

Two types of gypsum fibreboard were used: gypsum fibreboard with improved properties (GFBe), which was used for Specimen 1, and a regular gypsum fibreboard (GFB), which formed the two base layers of Specimen 2. The GFB used were 12.5 mm thick with a reported density of 1150±50 kg/m3 and were made from recycled gypsum, recycled cellulose fibres from waste paper, and recycled water [11]. The 12.5 mm thick GFBes were made of gypsum and non-flammable fibres for better fire protection with a specified density of 1200±50 kg/m^3 [12]. The specimens constructed in this way were then filled with flame retardant PUR foam. The density of the PUR foam was 45 kg/m^3 ± 5% and the added flame retardants in the mixture accounted for about 10-30% of the mass of the polyol. Table 1 provides a summary of the described LSF specimens in relation to the position of used wallboards.

Table 1 Specimens used in the experimental study

No.	Specimen	Configuration of the wall panel
1	Specimen 1	2xGFBe-PUR-2xGFBe
2	Specimen 2	GFBe-2xGFB-PUR-2xGFB-GFBe

Type K (NiCr-Ni) thermocouples were placed to monitor temperature development through the LSF wall assembly (Figure 1 and Figure 4). Figure 4 shows the placement of the thermocouples through the thickness of the specimens.



a) Specimen 1 b) Specimen 2

Figure 4 Through thickness position of the thermocouples

In addition, thermocouples were placed on the ambient side to monitor the temperature development of the specimens according to EN 1365-1 [13]. The Ø0.5 mm thermocouple wires were welded to 0.2 mm thick copper disks, which were attached to the wallboards with screws and

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welded to the steel frame. The thermocouples used to measure the temperature development through the specimens were placed at 6 positions as shown in Figure 1. The positions represent locations where the thermocouples were placed through the thickness of the specimen, Figure 4.

2.2 Fire test setup and loading/heating protocol

Each specimen was placed in the test rig and loaded with a total vertical load of 22.5 kN (15 kN/m') using hydraulic jacks as shown in Figure 5. The adopted fire load level is obtained from the analysis of the highest dead load acting on the wall of the prefabricated single-storey structure which is being developed as part of the European project "Composite lightweight panel with integrated load-bearing structure (KLIK-PANEL)" [4].

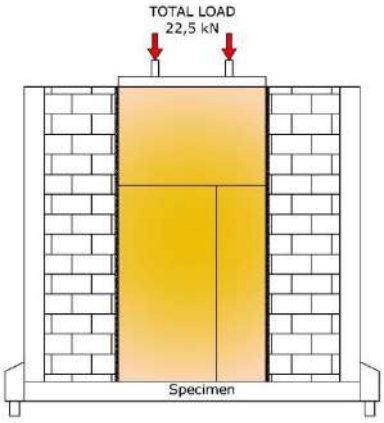


Figure 5 Specimen placement inside the testing rig and the applied total vertical load

In addition, displacement transducers were placed on top of the specimens, between the load beam and the fixed frame. They recorded the distances between the load beam and the fixed frame, which changed due to the deformations of the specimen. The fire maintained the ISO 834 fire curve ISO 834 according to EN 1363-1 [14] with 6 radiant burners, Figure 6.

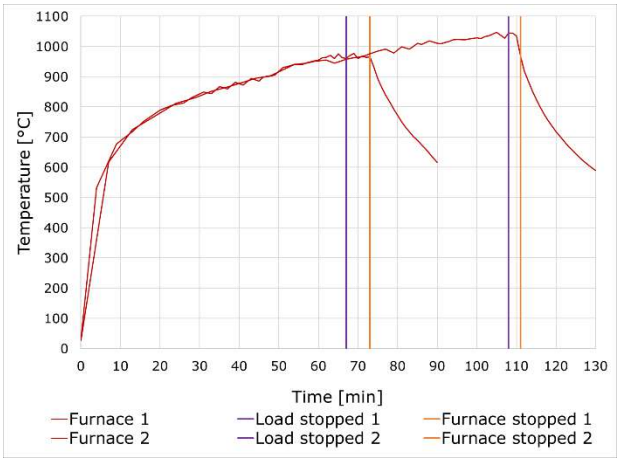


Figure 6 Representation of the testing procedure

The test procedure was terminated due to the flammability of the PUR foam when certain safety criteria were met:

- If the test specimens showed a tendency of imminent structural collapse (R criterion).
- If the isolation (I) or integrity (E) criterion was exceeded.

Specimen 1 was exposed to furnace fire for 73 minutes, with the load removed at the 67th minute. Specimen 2 was exposed to furnace fire for 111th minutes, with the load removed at the 108th minute as shown in Figure 6. Both specimens showed signs of impending structural collapse, resulting in the termination of the test procedure.

3 Experimental results and discussion

Figure 7 shows the ambient sides of the specimens after testing. As can be seen, the ambient side of the specimens remained intact throughout the tests, and no discoloration, smoke, flames, or cracks were observed. Detailed post-test observations of the specimens also showed no cracking, discoloration and board fall offs on the ambient side.



a) Specimen 1 b) Specimen 2

Figure 7 Ambient side of the specimens after testing



a) Node 6 on specimen 1 b) Node 7 on specimen 1



c) Node 6 on specimen 2 d) Node 7 on specimen 2

Figure 8 Characteristic failures around rigid steel frame nodes

Nevertheless, post-fire examination of the specimens' side

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exposed to fire showed local buckling of the flanges and web of the steel frame members near nodes 6 and 7, as shown in Figures 8.a) - 8.d). These nodes were the stiffest part of the LSF frame and the thermal expansion of the members around these nodes was restrained. In addition, the cavity insulation has almost completely degraded and only black char layers were visible.

Figures 9 and 10 show the measured average temperatures recorded for specimen 1 and specimen 2, respectively, while Figure 11 shows the maximum recorded ambient temperatures for both specimens and Figure 12 shows the average measured ambient temperatures. A total of 8 thermocouples were used to measure the maximum ambient temperatures on each specimen and they are labelled as M1-M8. Figures 13 and 14 show the vertical displacements and displacement rates recorded during the test period.

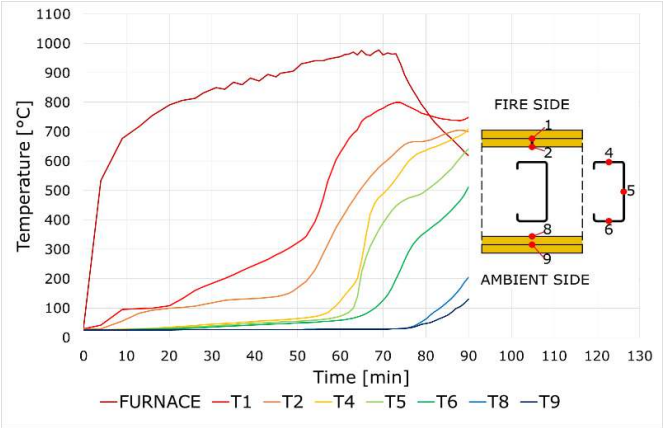


Figure 9 Average measured temperatures for specimen 1

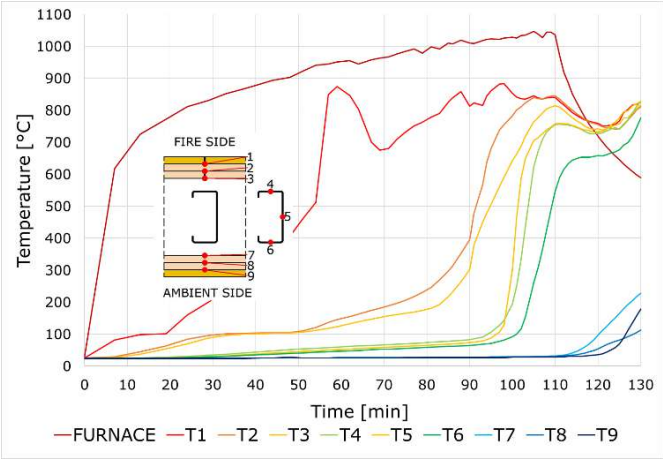


Figure 10 Average measured temperatures for specimen 2

The measured average temperatures in Figures 9 and 10, as well as the recorded ambient temperatures in Figures 11 and 12, and the deformation curves in Figures 13 and 14 show that such double sheeted LSF assemblies could have a potential fire resistance rating of 60 minutes, while triple sheeted could reach about 90 minutes. This is due to the increased vertical displacements that indicate a potential collapse of the structure. In addition, the PUR insulation layer separating CFS from the wallboards also decreases the temperature development on the CFS studs, as temperatures on T4 did not immediately increase when the wallboards lost their protective properties. The decomposition of PUR generally takes place in three steps between 200 and 300°C [16]. Since the temperature in the furnace is already above 900 °C in the 50th minute, the degradation reactions occur almost immediately.

Temperatures at the CFS members stay below 100 °C for more than 60 minutes for the double sheathed assembly (Figure 8), and for almost 100 minutes for the triple sheeted assembly (Figure 9). Nevertheless, a clear temperature rise can be seen at T4, T5 and T6 after the 60th minute for the double sheathed specimen i.e., 100th minute on triple sheathed specimen. At this point, the rapid increase can be attributed to the loss of integrity of the fire protective wallboards at the exposed side of the panel and the degradation of the cavity polymer insulation. It is believed that the rapid degradation and burning of the foam is due to the direct exposure to heat as the wallboards lost their protective properties. This increase in heat with simultaneous loading of the specimens has led to the members buckling observed after the fire test (Figures 7.a), 7.b), 7.c) and 7.d)). Furthermore, the results show that an additional layer of fire protective board (Figure 3.b)) has significant benefits for the fire performance of the LSF assembly. This one additional layer extended the temperature development to CFS for approximately 30 minutes of fire exposure.

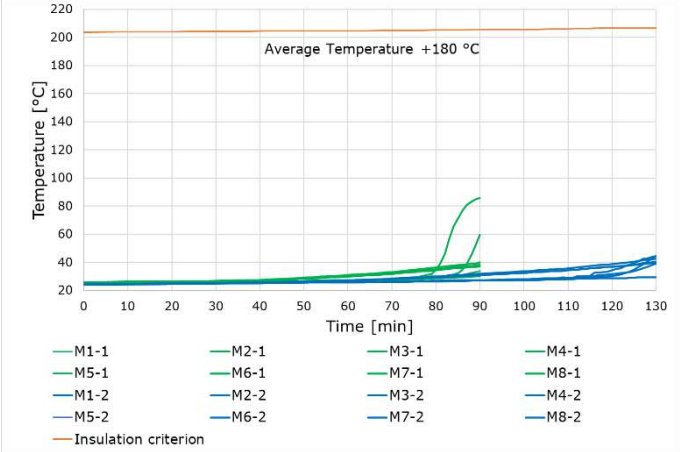


Figure 11 Ambient side maximum recorded temperatures

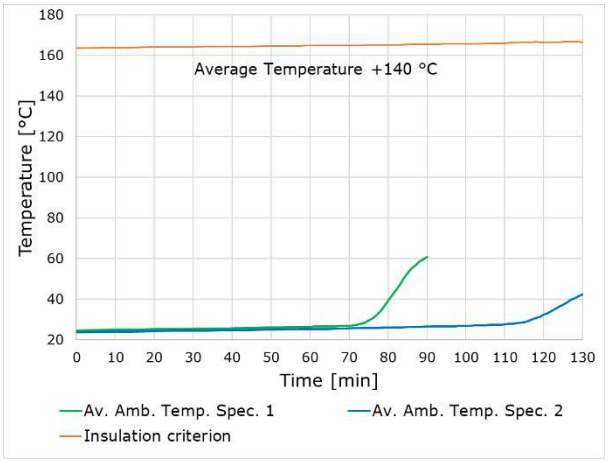


Figure 12 Average ambient side temperatures

Figures 11 and 12 show that both specimens stayed below

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the required insulation criterion during the entire test procedure. Even after the specimens had been unloaded and the furnaces stopped the maximum temperature of 88 °C was recorded for specimen 1, while the maximum ambient temperature was only 44 °C for specimen 2. The average recorded ambient temperature was only 60 °C for specimen 1, while it was only 42 °C for specimen 2. These results show that the insulation properties of the LSF specimens are significant and can be attributed to PUR.

Figures 13 and 14 show that the first recorded deformations began at the 12th minute for specimen 1 and at the 10th minute for specimen 2. Specimen 1 deformed continuously in the direction of the applied load, while specimen 2 showed deformations in the opposite direction of the applied load from the 10th to the 20th minute. This is due to the thermal expansion of the steel frame inside the specimen, as no significant temperature was measured in the cavity at that time. The displacement rate of specimen 2 was rapid from the 100th minute, indicating that the specimen would soon fail. This fact suggests that the maximum load-bearing capacity of the specimen was reached during simultaneous fire loading.

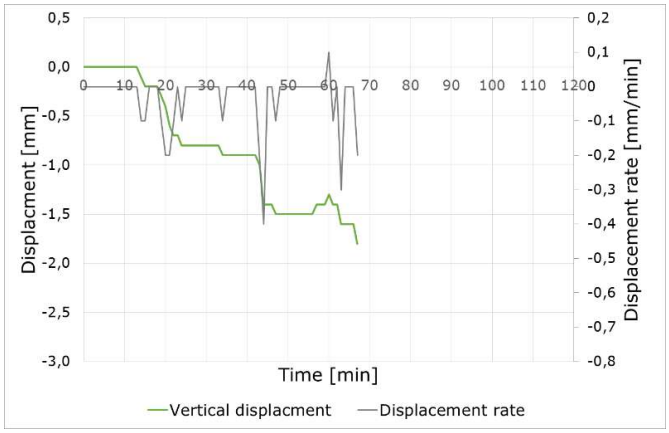


Figure 13 Vertical displacement and displacement rate of specimen 1

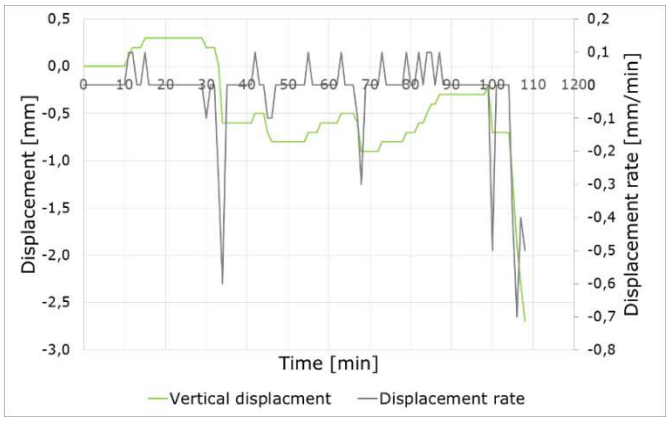


Figure 14 Vertical displacement and displacement rate of specimen 2

4 Comparison between tested specimens

The temperature-time curves between the wallboards for both specimens are shown in Figure 15. Looking at the time-temperature curves in Figure 15, there is a clear plateau at thermocouples T1 and T2 for the specimen 1 (T1-1 and T2-1) and T1, T2 and T3 for specimen 2 (T1-2, T2-2 and T3-2).

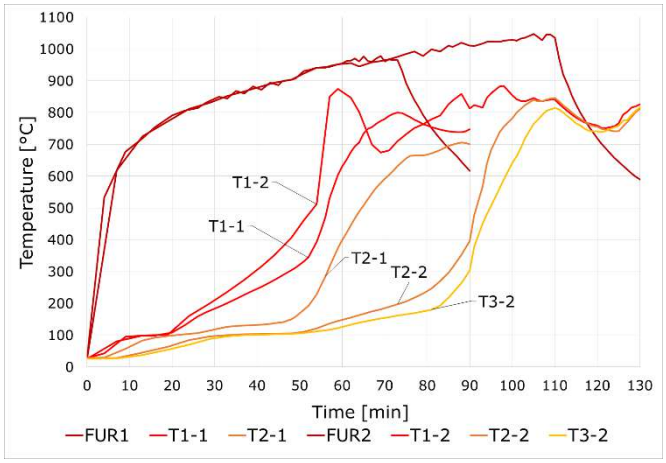


Figure 15 Comparison of the time-temperature curves between the wallboards - specimen 1 vs. specimen 2

Temperatures at thermocouple T1 rise to 100 °C in the first 10 minutes and remain so until the 20th minute. This is primarily due to the dehydration processes that occur in fire protective wallboards. Since the wallboards used were GFB and GFBe, it can be asserted that they contain about 20% bound water and 3-4% free water, similar to gypsum wallboards. This water content prevents a temperature increase on the unexposed side of the specimens [15]. Afterwards, the temperatures at T1 remain similar for both specimens because all the water has evaporated and only the gypsum core remains. This dehydration process is also evident when comparing the temperatures at T2-1, T2-2, and T3-2. For specimen 1, the temperatures remain at 100 °C (T2-1) for about 40 minutes, which is about 10 minutes less than on specimen 2 (T2-2). This again shows the advantages that an additional layer of wallboard has for the temperature development on the unexposed side.

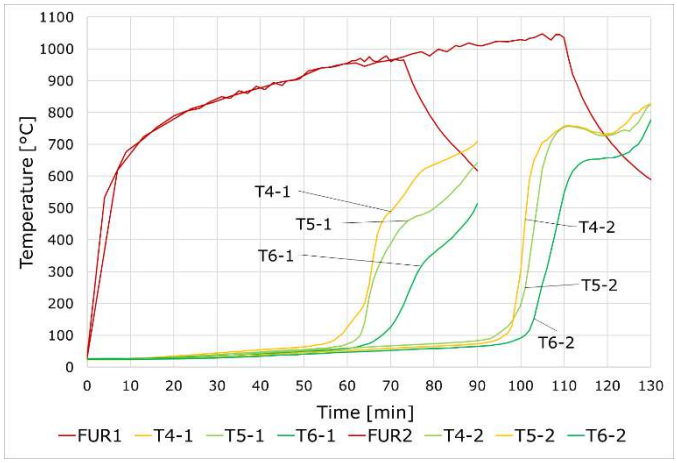


Figure 16 Comparison of the time-temperature curves on the steel studs - specimen 1 vs. specimen 2

The time-temperature curves on the steel studs for both specimens are shown in Figure 15. In the figure, T4 is the hot flange, T5 is the web and T6 the cold flange of the CFS members. As it is expected, the temperatures on the specimen 1 started to increase earlier than on specimen 2. Initially the wallboards prevented the temperature rise on the CFS steel frame, for around 50 minutes on specimen 1 and 90 minutes on specimen 2 while the PUR layer only prevented the temperature rise for around 5-10 minutes.

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However, as soon as the fire protective wallboards lost their function (around the 50th, i.e., 90th minute, as seen in Figures 8 and 9), the foam began to rapidly decompose, resulting in a rapid increase in the recorded temperatures on the steel frame members. This can also be clearly seen in Figure 15, where the temperatures at T4 began to rise at the 50th and 90th minutes, respectively. The same can be seen when comparing the temperatures at the steel frame for specimen 2 in Figure 15. Since steel loses strength in elevated temperatures, by 550 ºC only about 60% of its room temperature yield strength is maintained [17]. In the tests conducted, this temperature was reached at about the 70th minute for specimen 1 and the 100th minute for specimen 2, Figure 15. As the temperature on the steel studs increased further, the structural stability of the studs rapidly decreases. This loss of strength can also be seen in Figures 12 and 13 when the vertical displacement curves began to increase. It also explains the local buckling of members observed in Figures 7.a), 7.b), 7.c) and 7.d). This implies that the PUR insulation can be used as cavity insulation for LSF structures but once the fire enters the cavity, the foam cannot provide any significant benefit to the continued fire resistance of the structure. Consequently, most of the PUR insulation benefit is reflected in its thermal behaviour at ambient temperatures.

5 Conclusion

This paper presents the results of two fire tests conducted on double- and triple-lined PUR cavity insulated LSF wall specimens that used spacers to physically separate wallboards form the CFS frame. The results show that this LSF composition can be used where fire resistance higher than 60 (double sheathed specimen) or 90 minutes (triple sheathed specimen) is not required. The gypsum fibreboards used have the most important protective function. The evaporation of bound and free water in their microstructure prolongs the temperature development in the whole assembly. Once the gypsum fibreboards lose their protective properties on the exposed side of the specimen, temperatures rise rapidly in the rest of the specimen. The temperature rise is amplified by the low fire behaviour of the PUR foam, which ignites in the cavity and further heats up the CFS frame.

Although tests have shown that an additional layer of fibreboard increases fire resistance (about 30 minutes), additional studies should be carried out to fully investigate other properties and economic aspects depending on the purpose of the LSF assembly itself.

References

[1] N. Soares, P. Santos, H. Gervasio, J. J. Costa, and L. Simoes da Silva, "Energy efficiency and thermal performance of lightweight steel-framed (LSF) construction: A review." Renewable and Sustainable Energy Reviews, pp. 194–209, 2017, doi: 10.1016/j.rser.2017.04.066.

[2] Business Research Insights, "Light Steel Framing (LSF) Market Size, Share, Growth, and Industry Growth by Type (H-Shapped, C-Shapped, Hollow Pipe, and Others), By Application (residential and Comercial) Regional Forecast to 2028," 2021. https://www.businessresearchinsights.com/market-reports/light-steel-framing-lsf-market-100135.

[3] P. Santos, "Energy Efficiency of Lightweight Steel-Framed Buildings," in *Energy Efficient Buildings*, 2017.

[4] M. J. Rukavina, D. Skejić, A. Kralj, T. Ščapec, and B. Milovanović, "Development of Lightweight Steel Framed Construction Systems for Nearly-Zero Energy Buildings," *Buildings*, vol. 12, no. 7, 2022, doi: 10.3390/buildings12070929.

[5] E. Roque and P. Santos, "The effectiveness of thermal insulation in lightweight steel-framedwalls with respect to its position," *Buildings*, vol. 7, no. 1. 2017, doi: 10.3390/buildings7010013.

[6] J. C. Batista Abreu, L. M. C. Vieira, M. H. Abu-Hamd, and B. W. Schafer, "Review: development of performance-based fire design for cold-formed steel," *Fire Sci. Rev.*, vol. 3, no. 1, pp. 1–15, 2014, doi: 10.1186/s40038-014-0001-3.

[7] P. S. Dilini Perera, K. Poologanathan, M. Gillie, P. Gatheeshgar and K. M. C. K. S.M.A. Nanayakkara, "Fire performance of cold, warm and hybrid LSF wall panels using numerical studies," *Thin-Walled Struct.*, vol. 157, no. 107109, 2020.

[8] S. Gnanachelvam, A. Ariyanayagam, and M. Mahendran, "Fire resistance of LSF wall systems lined with different wallboards including bio-PCM mat," *J. Build. Eng.*, vol. 32, 2020, doi: 10.1016/j.jobe.2020.101628.

[9] S. Gunalan, P. Kolarkar, and M. Mahendran, "Experimental study of load bearing cold-formed steel wall systems under fire conditions," *Thin-Walled Struct.*, vol. 65, pp. 72–92, 2013, doi: 10.1016/j.tws.2013.01.005.

[10] Y. Tao, M. Mahendran, and A. Ariyanayagam, "Load-bearing walls made of cold-formed steel hollow section studs exposed to fire," *9th Int. Conf. Steel Alum. Struct. ICSAS19*, pp. 1533–1544, 2019.

[11] Fermacell ®, "Fermacell ® Gypsum Fibreboards Product Data sheet," no. October. pp. 5–6, 2019.

[12] Fermacell ®, "Fermmacell Firepanel A1 Product Data Sheet." 2019.

[13] CEN EN 1365-1:2012; Fire resistance tests for loadbearing elements - Part 1: Walls. European Comitee for Standardization: Brussels; Belgium, 2012.

[14] CEN EN 1363-1:2020; Fire resistance tests - Part 1: General requirements. European Comitee for Standardization: Brussels; Belgium, 2020.

[15] E. Steau and M. Mahendran, "Elevated temperature thermal properties of fire protective boards and insulation materials for light steel frame systems," *J. Build. Eng.*, vol. 43, no. April, p. 102571, 2021, doi: 10.1016/j.jobe.2021.102571.

[16] J. C. Q. Amado, "Thermal Resistance Properties of Polyurethanes and its Composites: A Short Review," *J. Res. Updat. Polym. Sci.*, pp. 66–84, 2019, doi: 10.6000/1929-5995.2019.08.10.

[17] Australian steel institute, "Fire Damage Assessment and Reinstatement of Steel Structures." https://www.steel.org.au/what-we-do/focus-areas/steel-and-fire/fire-damage-assessment-and-reinstatement-of-steel/#:~:text=Like all materials%2C steel weakens,and increases rapidly after 400ºC.

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