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Coimbra, Novembro de 2018

6JORNINC

JORNADAS DE SEGURANÇA AOS INCÊNDIOS URBANOS

1JORPROCIV

JORNADAS DE PROTEÇÃO CIVIL

João Paulo C. Rodrigues
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ORGANIZAÇÃO
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PARA A SEGURANÇA CONTRA INCÊNDIO
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6as Jornadas de Segurança aos Incêndios Urbanos

1as Jornadas de Proteção Civil

Departamento de Engenharia Civil
Faculdade de Ciências e Tecnologia
Universidade de Coimbra

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Atas das Comunicações das 6as Jornadas de Segurança aos Incêndios Urbanos e das 1as Jornadas de Proteção Civil

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PREFÁCIO

A Segurança Contra Incêndio de Edifícios (SCIE) tem uma importância vital na vida das sociedades, pois está em jogo não só a vida das pessoas como também interesses diversos tais como, por exemplo, os bens patrimoniais, os valores históricos e arquitéctonicos com forte simbolismo e, ainda, a continuidade de serviços estratégicos para a sociedade em geral. Contudo, apesar da sua importância, trata-se duma área que ainda não tem uma consolidação efetiva no nosso País, quer ao nível do ensino quer do projeto e da construção, apesar da profusão de regulamentação existente, dos vários projetos de investigação e dos cursos que têm sido realizados. Esta é, por outro lado, uma área em que existe ainda muito conhecimento empírico, adquirido ao longo de anos de contatos com incêndios reais, experiências e exercícios diversos, em que o progresso dos conhecimentos científicos tem sido lento, fruto da sua complexidade e interdisciplinaridade.

No entanto, Portugal tem conhecido, nos últimos anos uma evolução assinalável quer no domínio do ensino quer no domínio legislativo. A concretização de programas de mestrado e doutoramento nesta área, para além da publicação de nova legislação nacional e europeia, em paralelo com outras ações, deram à SCIE uma visibilidade que até agora não tinha. As partes dos Eurocódigos de dimensionamento ao fogo das estruturas em conjunto com a regulamentação nacional constitui hoje um diferencial positivo que permite a construção de edificações mais seguras em relação ao incêndio.

As Jornadas de Segurança aos Incêndios Urbanos (JORNINC) começaram em 2006, aquando da realização do primeiro Mestrado em Segurança Contra Incêndios Urbanos na Universidade de Coimbra e estão atualmente na sua 6ª edição. Estas Jornadas têm constituído um fórum de discussão dos problemas da área, mas também das evoluções tanto ao nível da regulamentação como também das novas tecnologias.

Este ano realizam-se também em paralelo com as 6JORNINC, as 1as Jornadas em Proteção Civil (1JORPROCIV) que pretendem também elas constituir um fórum de discussão dos problemas e dos novos desenvolvimentos da área. Estas Jornadas realizar-se-ão a cada dois anos em conjunto com as JORNINC pretendendo reunir investigadores, técnicos e demais pessoas interessadas na área.

Para finalizar queria desejar-lhe as boas vindas a estas Jornadas e à UC e espero que este evento seja do seu maior interesse para si, sedimentando o seu conhecimento técnico e científico, e que também permita estabelecer novos contatos com outras pessoas da área.

João Paulo Correia Rodrigues
(Professor de Enga. Civil e de Enga. de Segurança ao Incêndio da UC)

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LIGHT STEEL FRAMED WALLS MADE WITH COMPOSITE PANELS UNDER FIRE CONDITIONS

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ABSTRACT

Light steel frames (LSF) using prefabricated panels are widely used in partition walls and loadbearing walls, with direct application in different types of building structures. These panels can be made by a combination of materials, which is the case presented herein. Some of the materials can be combustible, being the prediction of the fire resistance by means of numerical simulation difficult. Walls that meet fire resistance standards are the result of the proper combination of certain materials and elements. These materials and elements should be experimentally tested, allowing the wall to be fire rated. Three dimensional finite element models are validated, including the simulation of all the major events (combustion and cracking of materials). The fire resistance is determined for different LSF walls and decreases with the load level. A new formula is presented for the average critical temperature of the LSF structure.

KEY-WORDS: Light steel frame; Partition walls; Loadbearing walls; Composite panels; Fire resistance.

1. LIGHT STEEL FRAMED WALLS

Light Steel framed walls made with prefabricated panels are widely used in partition walls and loadbearing walls, with large application in buildings structures, such as multi-storey offices, educational buildings, health buildings, residential buildings and other types of buildings. Fire protection is usually achieved by one or more layers of insulation materials. Walls that meet fire resistance standards are the result combination of materials and structural elements. Cold steel sections must be protected with layered plate to prevent their thermal and mechanical properties from being affected by the fire. The common "C" structural cold formed steel section is the predominant shape, used for steel studs in LSF walls, but other sections may also be used. The U-shaped structural section is another cold formed steel section used for tracks, usually located at the base and at the top of the light steel frame. In this investigation only these two cross sections are used. The mechanical resistance of steel decreases significantly under elevated temperature conditions, reason why this material should be protected with insulation materials. The plasterboards are normally used as a simple protection material and may also be combined with other materials, as a composite solution. The steel structure allows the formation of cavities between the plates or composite panels, which can be filled with materials that allow the increase of the thermal and acoustic performance under room temperature conditions. Special attention should be given to the assembly of the different elements of the structure, in particular the connections between the elements, installation of windows and service components.

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Light Steel Frame walls are normally built with single or double gypsum panels or with composite materials. The cavity can remain unfilled or filled with insulation material. Different studies have been developed to test the efficiency of the cavity insulation, the efficiency of the LSF, among other design parameters. One of the first experimental test on LSF walls was developed in 1973 by B. C. Son and H. Shoub [1], who explained in detail two fire-endurance tests on double-wall assemblies. The second test showed much slower heat penetration through the wall assembly, which was attributed to its thicker insulation. Authors concluded that the temperature data for the second test also indicates a much slower temperature rise in the fire-exposed gypsum board and better practice would be achieved by the use of a two-layer plates with staggered application of board joints to eliminate direct heat access to the steel studs when joints open. Kenneth J. Schwartz and T. T. Lie in 1985 [2], studied the effect of the heat transmission to prevent ignition of the materials in contact with the unexposed side of the partition wall. Authors analysed data from previous experimental tests and made more experiments to evaluate the temperature criteria of the standard ASTM E119. J T (Hans) Gerlich in 1995 [3] and later J. T. Gerlich el al in 1996 [4] investigated the parameters which affect the performance of loadbearing LSF drywall systems exposed to fire. Structural design codes for cold-formed steel members were compared. Solution methods were presented for the calculation of the reduction of steel strength and stiffness at elevated temperature, and for predicting the deformations resulting from temperature gradients and using second order effects. The heat transfer simulation was used to predict steel framing temperatures for systems exposed to the standard IS0834 [5] and real fires. Sultan, M. A. [6] in 1996 summarized the results obtained from a numerical simulation and experimental tests for predicting the fire resistance of non-insulated and unloaded steel-stud wall assemblies. The one-dimensional simple model for heat transfer was developed to determine the temperature history across the wall assembly, and the program was used to predict the temperature field for any given time. Two wall assemblies were also tested under standard fire-test conditions (Canada). The model predicted slightly different temperatures when compared to the test results, being justified by moisture migration through the gypsum board to the unexposed side. The comparisons showed that the model provides reasonable conservative fire resistance values, even though the model is not able to predict the gypsum fall-off during simulation, which can result in different fire ratings. One year later, an extensive research was conducted at room temperature by Young-ki Lee in 1999 [7] for LSF walls. This author concluded that if sheathing (gypsum) is strong enough and if there is adequate attachment provided between the sheathing and studs for lateral support of the studs, then the sheathing can increase the strength of the studs substantially. In 1999, Farid Alfawakhiri et al [8] made a literature review about LSF loadbearing walls under fire. Previous experimental and analytical studies for fire rating are presented and the temperature dependent materials properties are also discussed. Some other important considerations regarding failure of gypsum boards are presented, in particular the effect of the screw spacing, orientation of gypsum board joints, and stud spacing, which can have a very strong effect of the fire performance. One year later, the same author [9] presented a comparison study between the results coming from a numerical simulation and fire tests. The temperature histories across LSF assemblies are simulated by explicit integration of transient heat transfer equations. The model demonstrates how different heating regimes in cold formed steel studs cause different structural failure modes. The purpose of the tests was to investigate the effects of stud spacing, resilient channels and insulation material type on the fire resistance of loadbearing LSF walls. A fire resistance model for loadbearing LSF walls was presented for thermal and mechanical simulation, producing a reasonable agreement with experimental results. In 2002, Geoff Thomas [10] investigate the thermal Properties of Gypsum Plasterboard at High Temperatures. This author also developed a finite element heat transfer model for LSF walls. The heat transfer model was calibrated using standard and non-standard fire tests. The model is conservative for fast and hot fires and less accurate for specimens subjected to abrupt temperature changes. The thermal properties were modified for model calibration. The heat transfer model was not able to predict the motion of moisture and pyrolysis reaction products. An experimental investigation was also developed by Y. Sakumoto el al. in 2003 [11] to evaluate the fire resistance of walls using galvanized LSF. Authors concluded that protection layers of plywood, gypsum boards, and other materials, depend mainly on the thermal shielding performance of the attached gypsum boards. After the falling off of the gypsum boards, temperature of the LSF usually increases abruptly, resulting in failure in a short period of time. C. N. Ang and Y. C. Wang [12] in 2004 developed a numerical study of heat and mass transfer in gypsum plasterboard under natural fire conditions in building elements with the objective to evaluate the effect of moisture transfer in gypsum plasterboard. The predicted gypsum temperatures were very close to those obtained from combined heat and mass transfer analysis, which consider water motion explicitly but with more simple analysis. In 2008, Sivert Uvsløkk and

Heidi Arnesen [13] presented a study, developed at normal temperature conditions, about the thermal insulation performance of air cavities, bounded by the use of thin reflective material layer integrated in well insulated walls. The use of reflective materials in closed air cavities may provide a thermal insulation resistance in walls equivalent to 30 mm of Rockwool insulation. Increasing the air cavity thickness beyond this limit will not increase the thermal resistance of the cavity due to the development of natural convection heal flow. Authors also quantify the total heat transfer that flows through the wall by convection, radiation and conduction, concluding that for a wall cavity of 90 mm, 87% of the heat flows by radiation, 9% by convection and 4 % flows by conduction. An experimental investigation regarding the thermal properties was also developed by K. Ghazi Wakili and E. Hugi in 2009 [14]. Authors compared the performance of four types of gypsum samples made by different material products. Depending on the amount and types of carbonates, different endothermic reactions may occur between room temperature and 900 ºC, leading to different values of temperature dependent thermal properties for conductivity, effective specific heat and density. Authors also investigate the time-temperature evolution comparison for a box protected steel column, finding more than 100 ºC of maximum difference on the steel temperature after 90 minutes of fire exposure, when considering different types of gypsum materials. In 2010 Prakash Kolarkar [15] evaluate the structural and thermal performance of LSF wall systems under fire conditions. This work improved the knowledge about the fire behaviour of both loadbearing and non-loadbearing walls, developed a new concept for wall system and presented a reliable method to predict the fire rating. Nine experiments were developed to analyse the fire performance for different number of plates (thicknesses and materials) and the fire performance of insulation placed in different locations (cavity and between plates). The same author and his colleague Mahen Mahendran [16] published the result of this experimental study for non-loadbearing steel wall systems under standard fire conditions AS1530 [17]. Authors concluded that the use of composite panels offered greater thermal protection to the studs, when compared with the conventionally built non-loadbearing wall models. The use of insulation inside the cavity, regardless the density of the material, demonstrated to lower the fire resistance of the wall. This investigation helped to understand the effect of cavity insulation and give the opportunity to the building companies to develop LSF wall structures with higher fire rating. In 2012, Keerthan P. and Mahendran M. [16] developed a numerical study to evaluate the thermal behaviour for the gypsum panels under fire, using SAFIR. Authors also included a brief literature review about the thermal behaviour of gypsum plasterboards. Suitable thermal properties were proposed. New simple formulas were proposed to estimate the temperature in the unexposed side of the plates. In 2012, Ashkan Shahbazian and Yong Chang Wang [18] completed a numerical study which had the main focus of evaluating the analytical study of the applicability of the direct strength method to calculate the distortional buckling strength of cold-formed thin-walled steel members with uniform and non-uniform elevated temperature distributions. Additional finite element simulations were developed to compare the results. Both methods were validated with experimental tests developed in short lipped channel, using different boundary and using different sample dimensions and lengths. Authors concluded that there was a need for a small modification in the design buckling curve to improve the accuracy of the standard AISI for uniform elevated temperature conditions. Authors also concluded for a need of a big modification in the design buckling curve for non-uniform elevated temperature conditions. In 2013, the same authors [19] proposed a simple method to calculate the temperature field in the steel section when the wall panel is exposed to fire from one side. This simple calculation method is based on simple one-dimensional heat flow analysis and allows to calculate the average temperature in the flanges of the steel section, assuming that the temperature variation in the web is linear. These results agree with the results obtained from the bi-dimensional ABAQUS finite element analysis. An extensive set of parametric and sensitivity studies, covering different steel section dimensions (width, depth, thickness and lips), and different spacing between steel section, number of gypsum layers and different cavity insulation is also presented. Poologanathan Keerthan and Mahen Mahendran [20] developed a numerical study with SAFIR to determine the thermal performance of the composite panels, made by two plasterboards with an insulation layer between them. This numerical study was validated with the experimental results developed by Prakash Kolarkar [15]. Authors concluded that the use of this composite solution led to lower temperature evolution in the unexposed side, increasing the fire resistance. Rockwool provided higher fire resistance than glass fibre and cellulose fibre. Authors also concluded that the fire resistance of Rockwool and fibre glass is independent of the material density, but depends on the thickness of both types of materials. The fire resistance of composite panel made with cellulose insulation material appears to depend on its density. Authors also compared the effect of the fire curve, showing that the thermal effect of the parametric fire curve on composite panels may cause higher damage when compared to the effect of standard fire curves. Other studies have been developed at Queensland University of Technology to study the behaviour and design of cold formed steel compression members at elevated temperatures [21] and to study the behaviour and design of cold formed steel beams members at elevated temperatures [22]. More recently, the research activity developed by Leonardus Gunawan was dedicated to present numerical models to simulate the thermal performance of LSF wall panels [23]. In 2014 Poologanathan Keerthan and Mahen Mahendran [24] presented a comparison for the thermal performance of loadbearing cold-formed steel walls under fire conditions, between the result from numerical simulation, results from experimental tests developed by Kolarkar [15] and with the experimental results obtained by Gunalan et al. [25], showing good agreement between them. This ability to predict the thermal performance showed that accurate finite element models can be used to simulate full scale load bearing LSF wall panels with varying configurations of cavity insulation and external insulation. The proposed thermal properties for plasterboard, insulation materials and steel should be used accordingly. Authors emphasize the detrimental effect of the cavity insulation, leading to higher temperatures in the steel structures and increasing the thermal bowing effect. Authors also concluded that the specific heat of gypsum plasterboards depends on the heating rate of the material, which can lead to different thermal behaviour between standard fire and natural fire exposure. In 2014, Ayman Y. Nassif et al. [26] presented an investigation about an experimental test and numerical modelling of the transient thermo-mechanical behaviour of partition wall with Rockwool insulation, using ABAQUS. The temperature results of the computational model agree well with experimental results and the displacements due to thermal bowing are quite similar. Authors notice that the gypsum boards contribute little to the out of plane stiffness during fire exposure but provide restraint in the plane of the wall for the steel studs. This observation is of extreme importance to model the mechanical behaviour of the LSF. Rusthi et al in 2015 [27] performed a numerical study with 3D models using gypsum plasterboards showing good and accurate results for the temperature field. Authors also present new material properties measured in gypsum and magnesium plasterboards. Preliminary numerical analysis indicates worse fire resistance when using magnesium plasterboards. In 2016 Jonathan Vallée [28] developed numerical models with ABAQUS and FDS to validate experimental furnace tests developed for LSF partition walls, with and without cavity insulation material. The results demonstrate that insulation material in the cavity can improve the fire resistance, when considering the insulation criterion, especially when ablation of the gypsum plates occurs. Author demonstrated that the existence of holes in walls causes premature failure when considering the integrity criterion, in comparison to openings due to joints and cracks. The numerical models present different thermal properties from previous literature references. Author also concluded that using Rockwool insulation material in cavity will provide higher fire resistance (I) when comparing to the use of fibre glass in the cavity or without any other insulation material. In 2016 Sivakumar Kesawan and Mahen Mahendran [29] developed accurate finite element models with SAFIR, using apparent thermal properties for the gypsum plasterboard, involved in the fire simulation of loadbearing walls made of hollow flange channel section studs. These apparent thermal properties account for a wide number of phenomena, such as, heat and mass transfer, shrinkage, and plasterboard cracks. The results were validated with five full scale experimental tests. The models predicted very well the temperature in the gypsum and in the steel frame. A set of a parametric analysis is also presented to analyse the effect of the stud geometry (depth, width, thickness), stud spacing and wall configuration. The effect of the depth and width parameters into the thermal performance was very small (negligible), while the thickness of the stud considerable affects the thermal performance, particularly when the cavity is filled with insulation materials. In 2016, Crescenzo Petrone et al. [30] investigate the mechanical behaviour of plasterboards. Authors made an extensive experimental campaign with 302 tests in compression and in tension. The tensile strength of the plasterboards was always smaller than the compressive strength, whereas both elastic moduli were very similar. A ductile behaviour was exhibited in tension and a more brittle behaviour was exhibited in compression. Larger compressive strength was obtained when increasing the thickness of the plasterboard samples. These mechanical properties may be used in case of considering the impact of the plasterboards in the loadbearing resistance of LSF walls. In 2016, Sivakumar Kesawan and Mahen Mahendran [31] analysed the effect of the hollow flanged stud cross section into the fire resistance of LSF walls. Authors developed numerical models to investigate the structural performance under fire, including the effect of non-uniform temperature field caused by the fire exposed side. The models were able to predict the thermal bowing and neutral axis shift, predicting the fire resistance and displacements with accuracy when compared with the experimental results. The experimental tests used 5 samples and specimens were tested with a load level between 20 % and 60%, using the standard curve defined by AS 1530.4 [17]. Further details about the experimental tests can be found in the conference paper of S. Kesawan and M. Mahendran [32]. In 2017 Anthony Deloge Ariyanayagam and Mahen Mahendran [33] investigated the fire resistance of non-loadbearing walls lined with calcium silicate plates, comparing the results with traditional gypsum plasterboards. Authors presented four new fire tests and compared the behaviour with previous magnesium oxide plates tests. Authors concluded that the fire resistance of the traditional gypsum plates was similar to the fire resistance when using calcium silicate plates. Both solutions have higher fire performance when compared with the magnesium oxide plates. The integrity of the calcium silicate plates was better than the traditional gypsum plates, probably due to the high level contents of glass fibres. No integrity failure was observed in the 20 mm thick calcium silicate plates. No cracking or falling down was observed for the tests using calcium silicate plates. In 2017 Sivakumar Kesawan and Mahen Mahendran [34] presented a numerical study about the structural fire performance of LSF walls under fire conditions. Authors validated the numerical models with previous 5 fire experiments [35], where they found the superior behaviour of welded hollow flange channel (HFC) cross section type in the fire resistance of LSF walls. These special cross sections present higher local buckling resistance due to the existence of two torsional rigid hollow flanges. The numerical models were able to predict the structural fire behaviour of HFC section studs using ABAQUS, based on previous temperature field, validate with SAFIR. Typical load ratio versus fire resistance rating curve is presented for each LSF wall considered. The numerical validation of 3 full scale fire tests of loadbearing LSF wall assemblies [23] has been developed in the PhD thesis of Shanmuganathan Gunalan in 2011, testing the walls under high load level. The main objective was to evaluate the new composite solution developed at the Queensland University of Technology. Later on, in 2013, Shanmuganathan Gunalan and Mahen Mahendran [36] validate the model with 10 fire tests with the purpose of simulating the behaviour of loadbearing LSF wall panels submitted to standard fire conditions, including complex structural effects such as thermal bowing, local buckling and neutral axis shift of LSF wall studs subject to non-uniform elevated temperature distributions during fires. The results from this numerical analysis proved that the high fire performance of the LSF walls with composite panels. Additionally, a very useful load ratio versus time curves for many LSF wall configurations used in the fire tests can be used to predict the fire resistance rating of these wall with similar plasterboard and insulation configurations, when submitted to other load levels without further testing or analyses. The load ratio versus hot flange temperature at failure merged reasonably well. The fire performance on LSF walls is also being investigated at the Polytechnic Institute of Bragança (Portugal), with the aim of developing accurate numerical models based on the thermal analysis with fluid structure interaction [37], validate the numerical models with experimental tests developed elsewhere [38] and herein, analysing the fire performance of LSF using the simplified one dimensional heat flow [39] and presenting a sequential numerical model to study the fire resistance of LSF walls made with composite panels [40]. This manuscript presents some experimental tests developed for partition walls, also presents the three dimensional validation model and a parametric analysis to predict the fire resistance of LSF loadbearing walls, when using the same geometry and materials of the partition walls.

2. FIRE RESISTANCE OF PARTITION WALLS

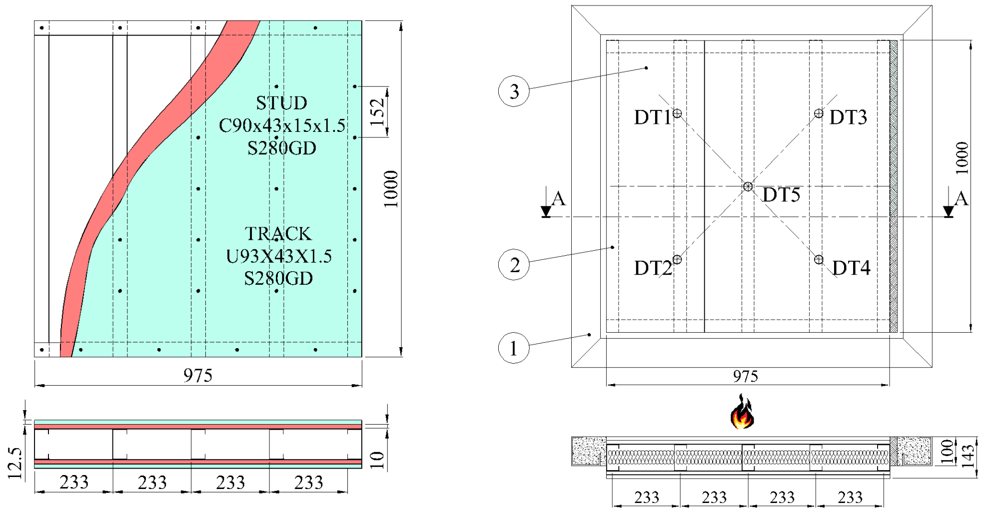
To prevent the spread of fires to adjacent compartments or to the outside of the building and to keep the loadbearing capacity of this type of elements (structural stability), these walls must meet fire resistance requirements and may be classified according to their sealing capacity to flame and hot gases (E) and to thermal insulation capacity (I). The fire rating of construction products and building elements is regulated by the European standard EN13501-2 [41], using the results of the experimental tests. The compartmentation capacity assessment may be carried out in accordance with EN1364-1 [42].

The sealing or integrity capacity (E) is the ability of the element to keep the separation function, withstanding the fire exposure, without transmitting the fire to the unexposed side, due to the passage of flames or hot gases. These heat flow would cause ignition of the unexposed surface or any material adjacent to that surface. The sealing assessment shall be carried out on the basis of the following three factors: checking cracks or excessive opening of certain dimensions; existence of ignition of a cotton pad; existence of a permanent flame on the unexposed side.

The insulation capability (I) is the ability of the element to withstand exposure to fire only on one side without significant heat transfer transmission from the exposed side to the unexposed side. The transmission should be limited so that the unexposed surface or any material close to that surface is ignited. The fire rate (I) of a wall should be attributed based on the shortest time for which the criteria of maximum or average temperature increase are satisfied in any discrete area. The fire performance level used to define the insulation shall be calculated on the basis of the increase in average temperature on the unexposed side, limited to 140°C above the initial average temperature or based on the increase of the maximum temperature in any location, limited to 180°C above the initial average temperature. Failure of the integrity (E) criterion also means the insulation criterion (I) failure, regardless of whether the specific insulation temperature limits have been exceeded or not.

The partition walls under analysis are made of 5 vertical studs and 2 tracks, being this investigation part of a larger study of materials and elements for LSF walls. The 5 specimens presented here have a structure built with profiles C90x43x15x1.5 for the studs and U93x43x1.5 for the tracks. Both profiles belong to steel grade S280GD, so the value of the 0.2% of proof strength is 280 GPa at room temperature. The geometry and dimensions are representative of a real structure, but adapted to the dimensions of the fire resistance furnace of the Polytechnic Institute of Bragança. Figure 1 shows the dimensions of the wall under investigation with a cavity thickness of 90 mm, the fixation of the wall into the testing frame and the positions of the main disc thermocouples to be applied in the unexposed side.

Self-drilling screws of diameter 4.2 and 4.8 mm and lengths of 19, 38 and 50 mm spaced 152 mm were used. The LSF was fixed to the testing frame around 3 edges (left side, bottom and top) allowing a free edge, properly filled with ceramic fibre on the right side (25 mm). All the edges were filled with gypsum. The dimensions of the sample do not comply to the dimensions normally used in practice for testing these walls, and therefore these tests cannot be used for fire rating of common partition walls EN 1364-1 [42].



a) LSF specimen with composite panels.

b) LSF wall specimen fixed to the testing frame (1), with studs (2) and layer plates (3), along with the main disc thermocouples (DT).

Figure 1: LSF walls under investigation.

2.1 Specimens

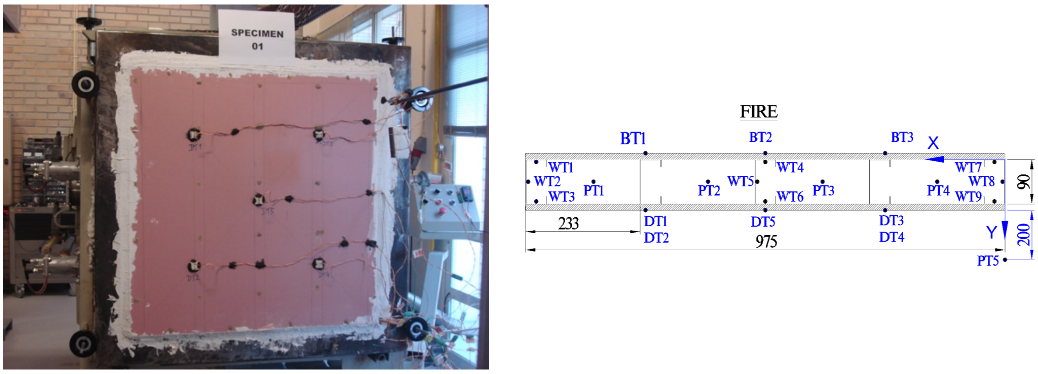
5 specimens were tested under fire conditions to evaluate the insulation effect of the layer plates and cavities. Two different types of plasterboards were used (Gypsum 1 is fired proof with two layers of multilayer paper, with high purity natural gypsum inner core reinforced with fiberglass filaments and duly added with thermo-expandable minerals with density of 770 kg/m^3; and gypsum 2 is normal gypsum, made with laminated gypsum board consisting of two layers of multilayer paper, with high purity natural gypsum inner core reinforced with fiberglass filaments and with density of 760 kg/m^3).

The fire resistance was determined in complete minutes for all the specimens, using the criterion for the maximum temperature (DT), average temperature (DT) and average temperature (IR). All the specimens have the same LSF structure, see Table 1. Specimen 01 is made with a single layer gypsum 1, Specimen 02 is made with double layer gypsum 1, both with 12.5 mm. Specimen 03 is made with a single layer gypsum 1 using Rockwool with 75 kg/m^3 as insulation material for the cavity. Specimen 04 is made with a composite solution with 10 mm of cork and 12.5 mm of gypsum 2. Specimen 07 is also a composite solution made with 10 mm OSB wood and 12.5 mm gypsum 2.

Table 1: Specimens characteristics.

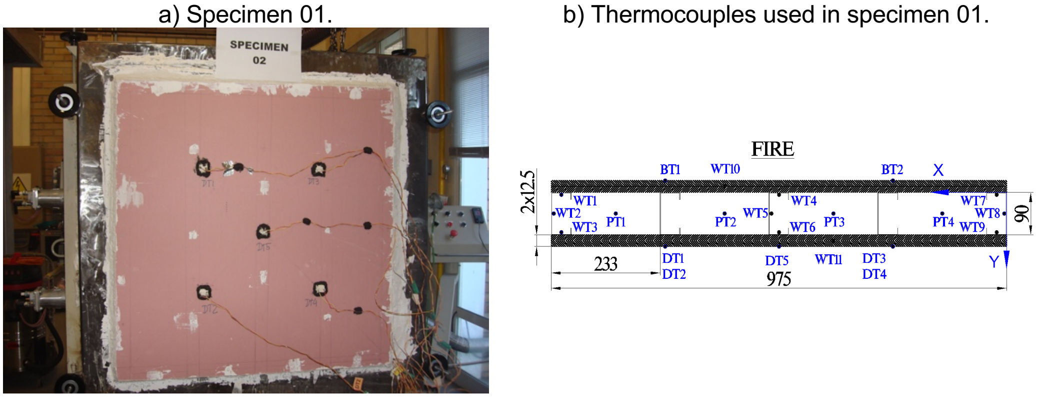
Specimen ID	Material / thickness [mm] Layer 1	Material / thickness [mm] Layer 2	Cavity /density [kg/m^3] Insulation
01	Gypsum 1/ 12.5	-	-
02	Gypsum 1/ 12.5	Gypsum /12.5	-
03	Gypsum 1/ 12.5	-	Rockwool / 75
04	Cork / 10	Gypsum 2 / 12.5	-
07	Wood OSB / 10	Gypsum 2 / 12.5	-

Type K thermocouples were used in different formats for temperature measurement: copper disk with plasterboard protection - DTi for unexposed surface temperature measurement; welded joint applied on cold formed steel profiles - WTi for temperature measurement in 3 different regions (hot flange , web and cold flange); PTi plate for measuring the temperature developed in the 4 cavities and also the ambient temperature (located 200 mm away from the unexposed surface); sheath thermocouples - BTi for temperature measurement on the exposed surface. The number of thermocouples depends on the specimen to be tested, see Figure 2.



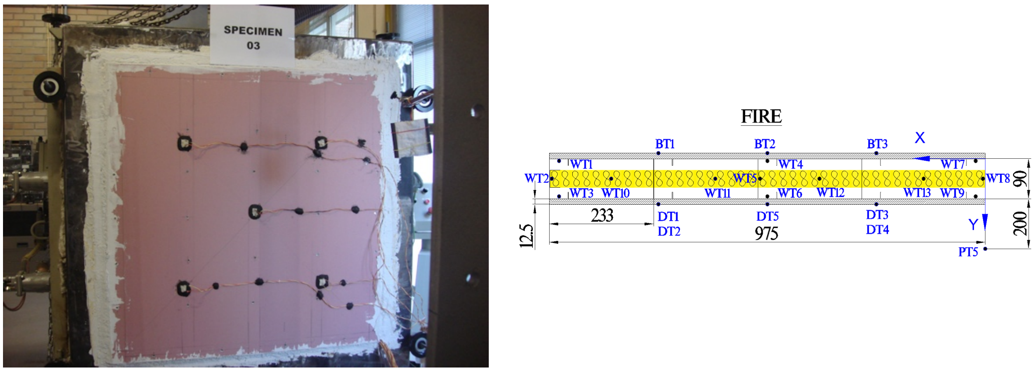
a) Specimen 01.

b) Thermocouples used in specimen 01.

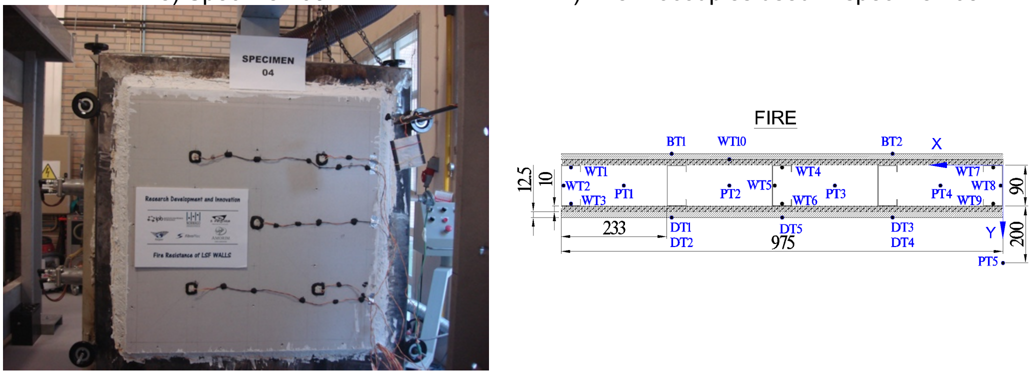


c) Specimen 02.

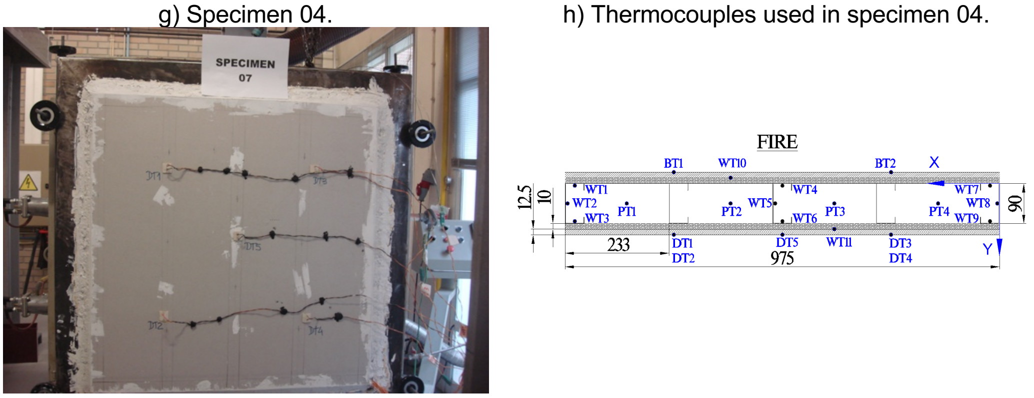
d) Thermocouples used in specimen 02.



e) Specimen 03. f) Thermocouples used in specimen 03.



g) Specimen 04. h) Thermocouples used in specimen 04.

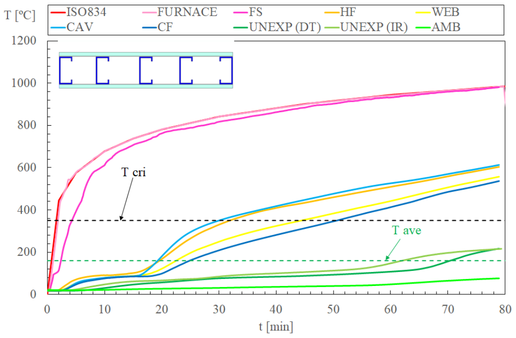


i) Specimen 07. j) Thermocouples used in specimen 07.

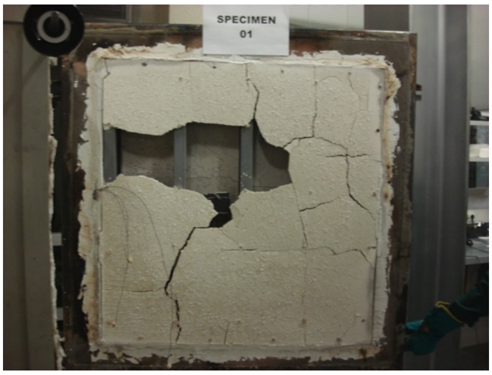
Figure 2: Specimens and thermocouples.

2.2 Experimental results

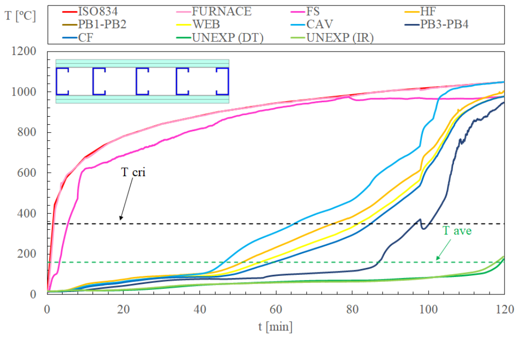
All the specimens were submitted to standard fire [43]. Different failure modes were achieved due to local and global instabilities and identified as the ultimate limit state of the frame, see Figure 3. For some specimens (specimen 04 and specimen 07), the furnace temperature presented two moments with some instability, related with the ignition of the combustible material (cork and OSB). The cork layer located on the exposed side ignited at minute 20, while the cork layer on the unexposed side ignited at minute 36. Both plates made of OSB layer start ignition for the same time instants. All other specimens kept the real furnace temperature close to the ISO834 standard [43]. Average temperature is depicted for each specimen, using the results of individual measurements, to represent the evolution on the hot flange (HF), web (WEB) and cold flange (CF). The unexposed temperature was measured with standalone disc thermocouples UNEXP (DT) and with a FLIR infrared thermal camera located at 3m distance from the unexposed surface, UNEXP (IR). Special measurements were also developed for some specimens, such as: the average temperature of the cavity (CAV), the room temperature (AMB) and the interface temperature between the composite layers (PBi-PBj).



a) average temperature results for specimen 01.

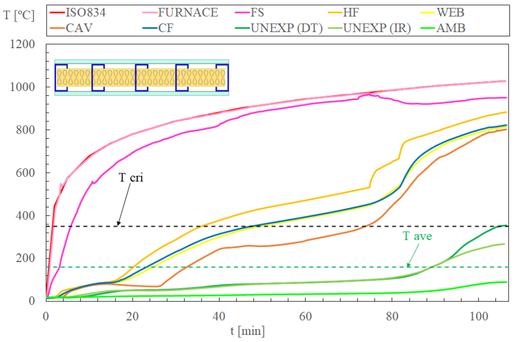


b) Final state of the LSF wall specimen 01.



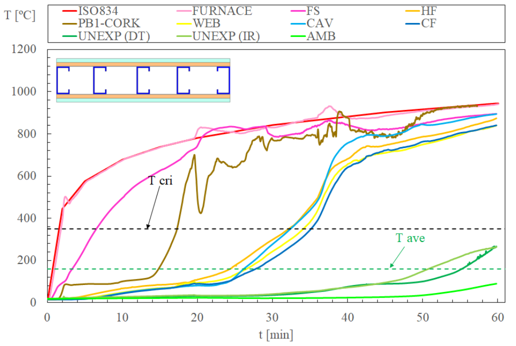
c) average temperature results for specimen 02.

d) Final state of the LSF wall specimen 02.



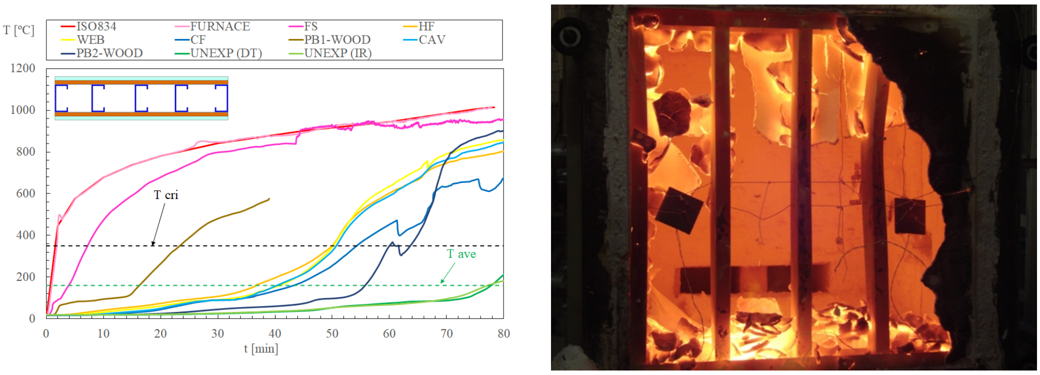
e) average temperature results for specimen 03.

f) Final state of the LSF wall specimen 03.



g) average temperature results for specimen 04.

h) Final state of the LSF wall specimen 04.



i) average temperature results for specimen 07. j) Final state of the LSF wall specimen 07.

Figure 3: Temperature history and limit state for the specimens.

The temperature evolution on the unexposed side allows to determine the fire resistance time (I). The critical time was determined for every specimen, taking into consideration all the possible criteria and measuring methods. The traditional and standard method, using disk thermocouples (DT), allows to verify the insulation criterion, looking for the maximum temperature and average temperature. The infrared thermal camera, non-standard method, allowed for the calculation of the average temperature (IR) in a wide predefined area. Both measurement methods agree very well with respect to the definition of the fire resistance, see Table 2.

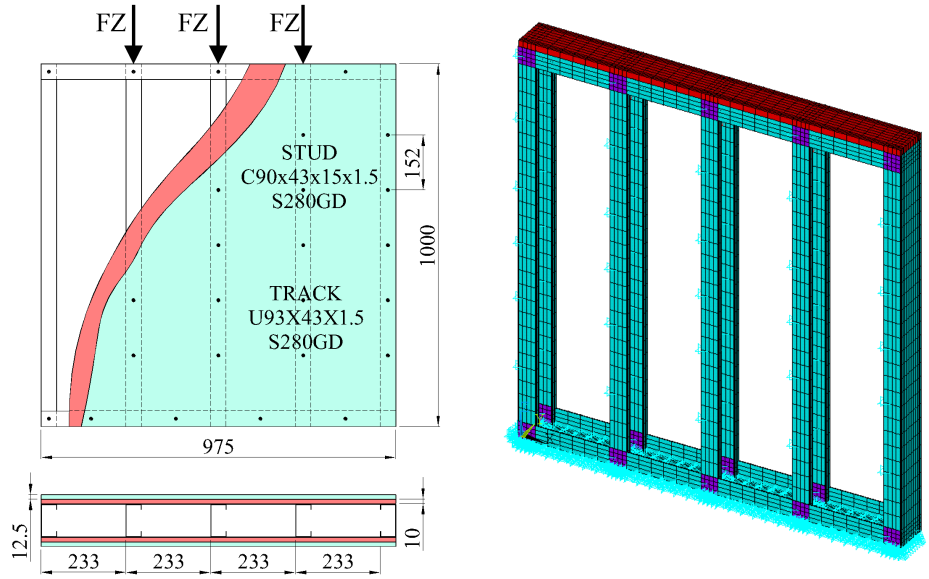
Table 2: Fire resistance for insulation criteria (I).

Specimen ID	T max=200 (DT) [min]	T ave=160 (DT) [min]	T ave=160 (IR) [min]
01	70	71	62
02	119	118	117
03	89	87	89
04	55	51	50
07	77	75	77

3. NUMERICAL SIMULATION

The computational model uses the thermal model, representative of the fire effect, duly validated to allow the determination of the loadbearing capacity of the wall. The finite element model uses shell and solid finite elements with linear interpolating functions from ANSYS. To achieve this goal, a four steps analysis is required.

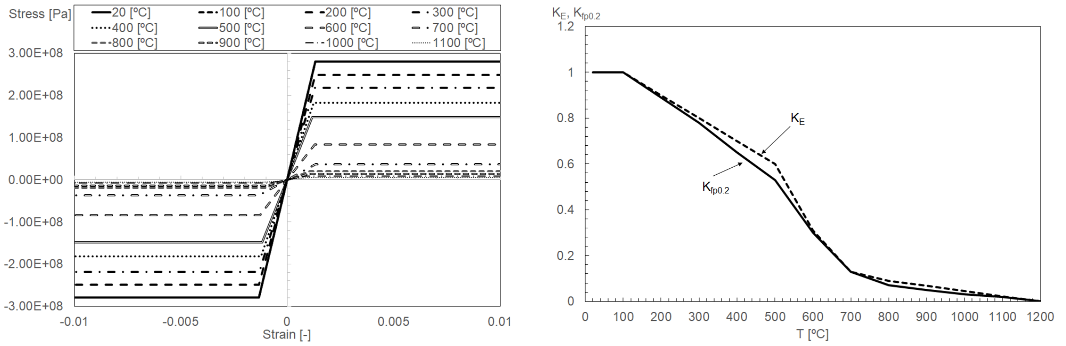
In the first step, a three dimensional linear elastic stability model is defined to determine the critical load and the corresponding mode of instability. The boundary conditions are defined according to Figure 4, fixing the bottom surface of the wall (web of the bottom track) and restraining some screw positions in the parallel direction to the base of the wall (direction X). The web of the upper track was modelled with a bigger thickness to simulate the interface beam, normally used on experimental tests to distribute the load over the top surface of the wall. The interface beam will be responsible for the distribution of 3 vertical forces (FZ) applied on the top surface of the top track and coincident with the direction of the three central vertical studs. The Block Lanczos method was used to extract the first 10 modes of instability. In this case the first eigenvalue was selected, corresponding to a local instability mode (local buckling of the web). The maximum displacement value was also considered for the definition of the scale factor to update the geometric imperfections of the structure [44].



a) Loadbearing LSF wall specimen with composite panels.
b) Finite element mesh and boundary conditions.

Figure 4: Loadbearing LSF wall. Geometric and finite element model.

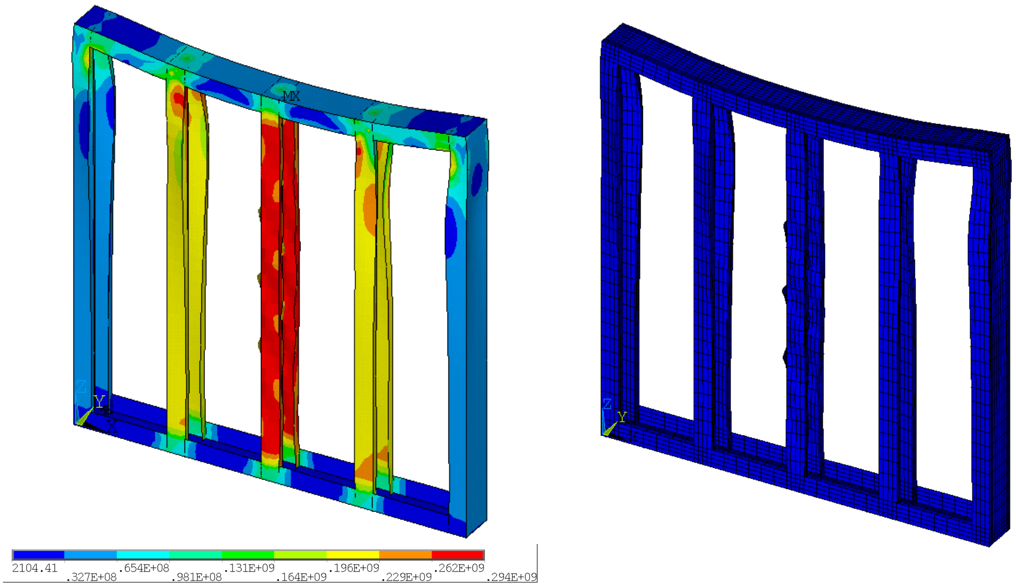
In the second step, the geometry (position of the nodes) is updated, to include the geometric imperfection. The mechanical properties of cold formed steel at room temperature are also defined for room temperature, see Figure 5. At this stage, the cold steel is the only material considered for the loadbearing capacity of the wall. All other materials, that may contribute to the strength and collapse mode of the structure [30], will not be considered for the calculation of the loadbearing capacity. An incremental and iterative solution method was applied to determine the loadbearing capacity. The arc-length method was used with a maximum load increment of 800 N and with a minimum load increment of 8 N, applied at each of the 3 load points (FZ). The convergence criterion for the solution was defined for displacement with a zero reference value and with a tolerance of 5%. This solution method allows to determine the potential mode of collapse of the wall structure and its loadbearing capacity. The deformed shape and the equivalent stress are represented in Figure 6 for the maximum loadbearing condition. The deformed mode shape confirms the existence of local buckling mode of the web for the central stud and also a distortional buckling mode in the upper part of the other studs. The yield stress of the material was reached in some parts of the LSF structure.



a) Stress strain under tension and compression.
b) Reduction coefficients for the elastic modulus and 0.2% proof strength.

Figure 5: Mechanical properties of cold formed steel at room and elevated temperature.

These results allow to define the maximum loadbearing capacity of the wall. This structure is capable of supporting a maximum point load of FZ = 78612 N, at room temperature.

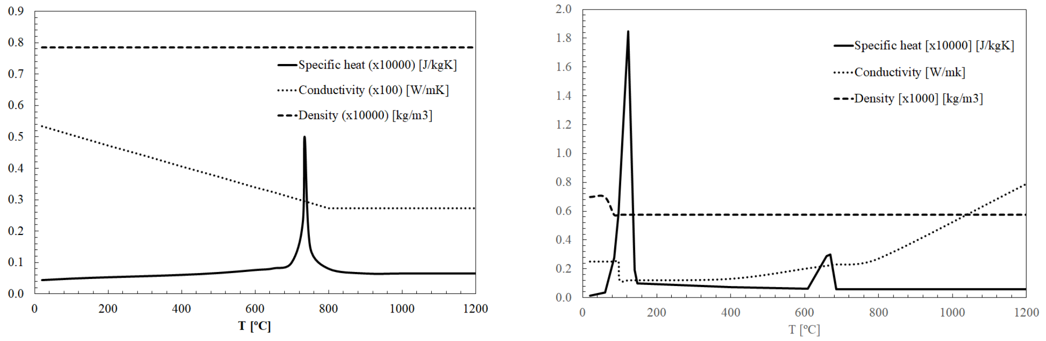


a) von Mises stress for the maximum loadbearing capacity.

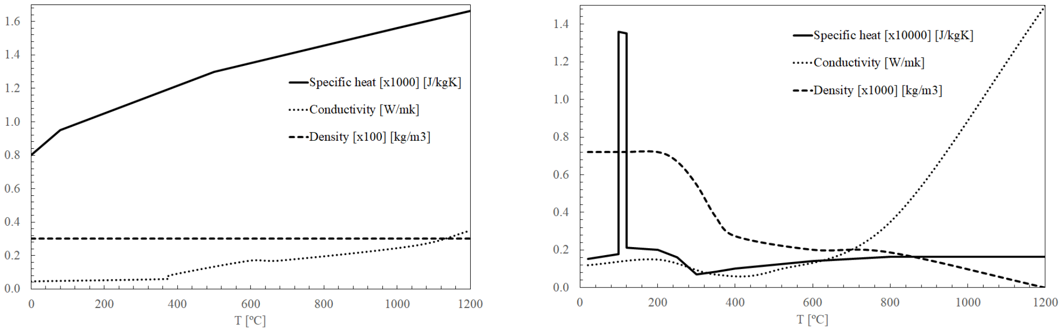
b) Deformed mode shape for the maximum loadbearing capacity.

Figure 6: Equivalent stress and deformed shape for the maximum loadbearing of the LSF.

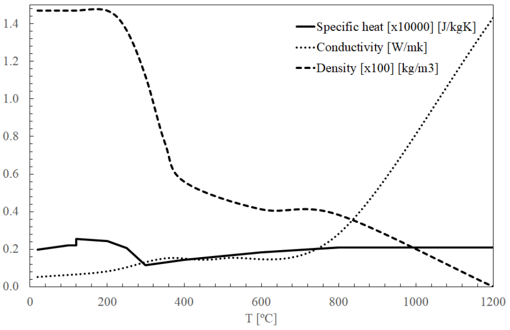
In the third step, the thermal part model of the wall was validated. Finite elements of multilayer shell were used to model the LSF and solid elements were used to represent the protection layers. The appropriate boundary conditions were used according to each test and according to the document on actions in structures submitted to standard fire [45]. For all the specimen models, with exemption to specimen 03, boundary conditions of convection and radiation were applied inside the empty cavity. The bulk temperature of the cavity region is determined with the average value of the measurements made by the plate thermocouples, from TP1 to TP4. In this way and with high accuracy, the effect of the cracks or other type of failure of the plasterboards is considered, including also the effect of the ignition and heat release rate of the combustible material. The other common boundary conditions were applied to the exposed side and unexposed side. Heat flow by convection was considered in the exposed surface using a heat transfer coefficient of 25 W/m^{2}K and the heat flow by radiation with an emissivity of the flames equal to 1. In both cases the temperature inside the furnace was considered to rise according to the ISO834 standard [43]. In the unexposed surface, only the convective heat flow was considered, with a heat transfer coefficient of 9 W/m^{2}K to include the effect of radiation. The temperature outside the furnace was considered equal to the initial mean temperature (20 °C). In the internal region of the cavity, the conditions of heat flow by convection and radiation were considered, assuming a heat transfer coefficient of 17.5 W/m^{2}K and a flame emissivity value of 1. The cavity temperature was determined according to the average value of the measurements made by the plate thermocouples TP1 to TP4. The thermal properties of the materials were considered temperature dependent, see Figure 7. The thermal properties of the cork were assumed as closed as possible to the variation of the thermal properties of the wood with the temperature [46], but duly adjusted to the values measured at room temperature [47]. The variation of the thermal properties for the steel were assumed in accordance to Eurocode EN1993-1-2 [48].



a) steel b) gypsum



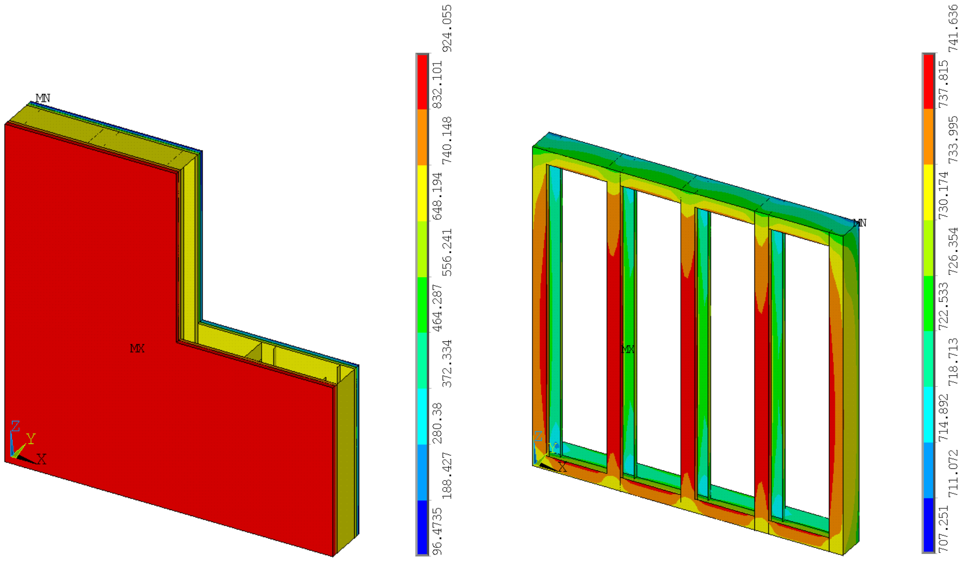
c) Rockwool d) Wood



e) cork

Figure 7: Thermal properties for all the materials involved in heat flow analysis.

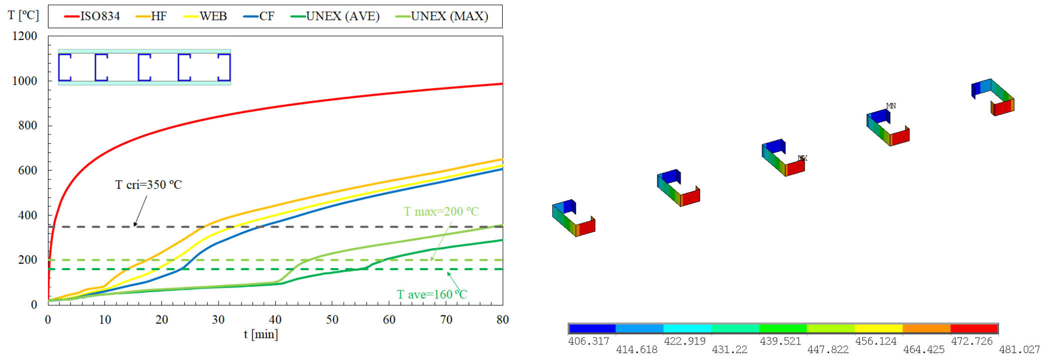
The thermal properties of the gypsum were considered from Mohamed A. Sultan [6] and the thermal properties for the Rockwool were adapted from Steinar Lundberg [49], duly adapted to the corresponding material density. The thermal solution was considered transient and nonlinear, using an incremental procedure with a time step of 60 s, with the possibility to be reduced to 1 s. Figure 8 shows the temperature field for the critical time of the complete model of the wall and on for the LSF structure.



a) Temperature in the Wall set. b) Temperature in the steel structure.

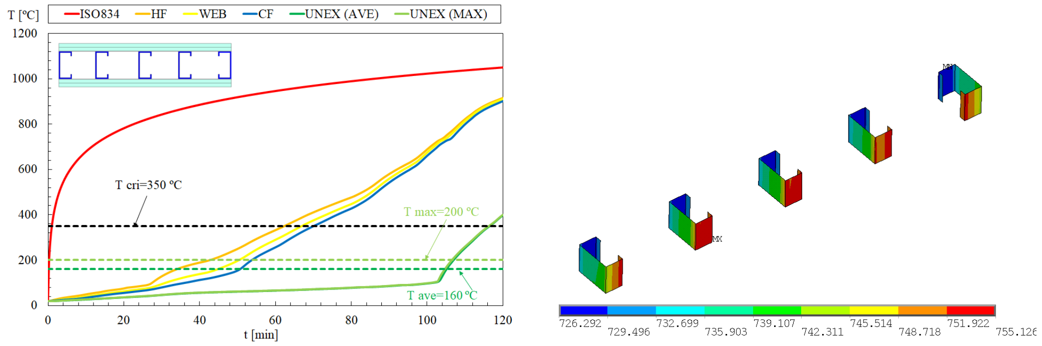
Figure 8: Temperature fields for the critical time (t=54.4 min) of specimen 04.

Figure 9 shows the temperature evolution on the unexposed surface (UNEXP) and also the average temperature values of the hot flange (HF), web (WEB) and cold flange (CF). This figure also shows the temperature of LSF for the region (Z = 0.5 m).



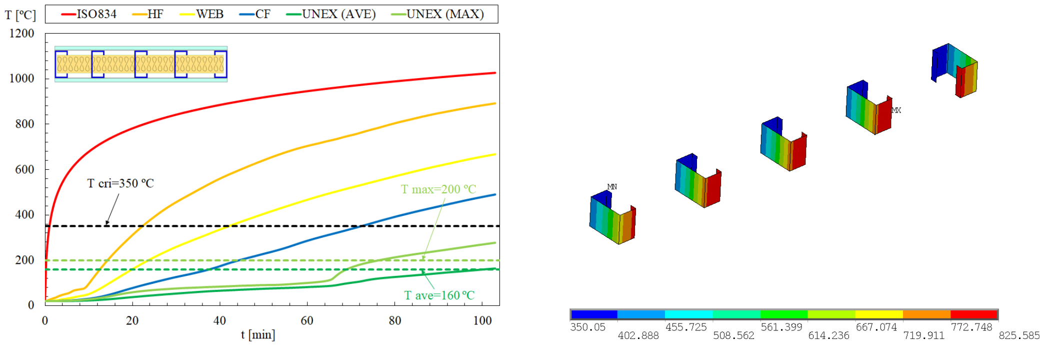
a) Time temperature history for specimen 01.

b) Temperature in the LSF, at half height, for the critical time of 45 min.



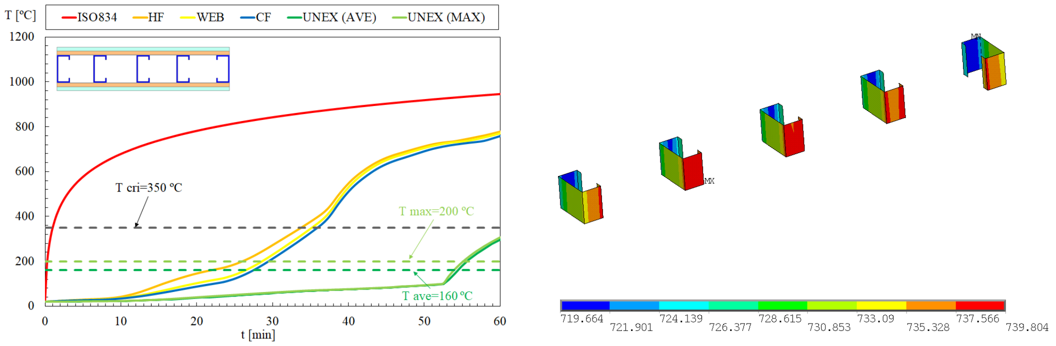
c) Time temperature history for specimen 02.

d) Temperature in the LSF, at half height, for the critical time of 105 min.



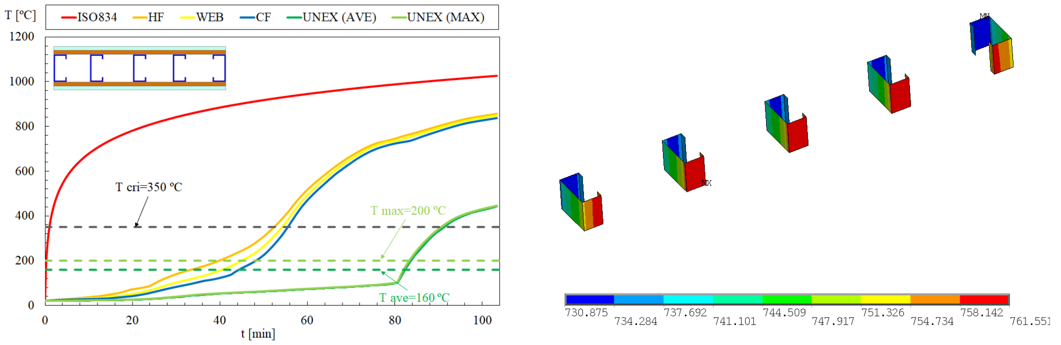
e) Time temperature history for specimen 03.

f) Temperature in the LSF, at half height, for the critical time of 76 min.



g) Time temperature history for specimen 04.

h) Temperature in the LSF, at half height, for the critical time of 54 min.



i) Time temperature history for specimen 07.

j) Temperature in the LSF, at half height, for the critical time of 82 min.

Figure 9: Numerical results for the thermal analysis for all the specimens.

Table 3 presents a comparison between the numerical and experimental results. The difference between the results are in between 9.7% and 35%. The comparison was made between the criteria applied for DT, using the smallest time to reach each condition, in completed minutes.

Table 3: Fire resistance determined using the insulation criteria.

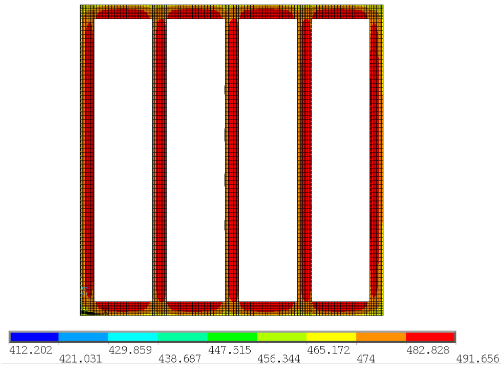
Specimen ID	T max=200 (DT) [min]	T ave=160 (DT) [min]	T ave=160 (IR) [min]	T max=200 (DT) [min]	T ave=160 (DT) [min]
	Experimental	Experimental	Experimental	Numerical	Numerical
01	70	71	62	54	45
02	119	118	117	105	106
03	89	87	89	99	76
04	55	51	50	54	55
07	77	75	77	82	83

In the fourth step, an estimate of the fire resistance (R) is presented for different load levels, corresponding to different degrees of utilization, between 40 and 80%, see Table 4. This load level is calculated with respect to the maximum loadbearing capacity of the LSF structure at room temperature (FZ = 78612 N). The model uses an incremental and iterative static analysis, based on a nonlinear and geometric material model. The time step is equal to 60 s with the possibility to be reduced to 0.1 s. The Newton Raphson method uses a displacement-based convergence criterion with a zero reference value and a tolerance of 5%. This step forces a modification of finite shell element, from SHELL131 to SHELL181, while solid elements are removed from the model. The restraints for the displacements are exactly the same as those considered in the previous structural step (first and second step). It is assumed that gypsum, cork and OSB boards do not contribute to the calculation of the mechanical loadbearing capacity, but these materials are considered during the thermal effect of the fire. A perfectly elastic-plastic material behaviour model is also assumed at elevated temperature, see Figure 5 [50].

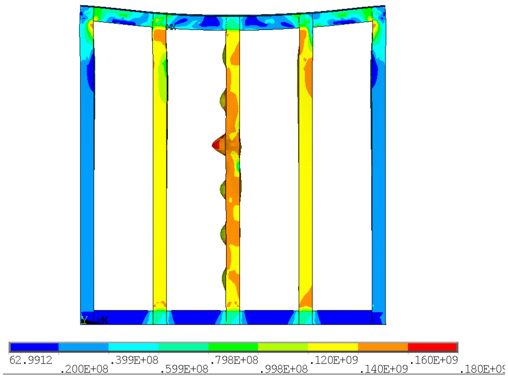
Table 4: Fire resistance of loadbearing LSF walls.

Specimen ID	Load level [%]	Steel min. temperature [ºC]	Steel max. temperature [ºC]	Steel average temperature [ºC]	Fire resistance (R) [min]
01	40	527	584	556	65
	50	484	548	516	57
	60	412	491	452	46
	70	307	414	361	34
	80	199	341	270	25
02	40	536	592	564	90
	50	485	547	516	86
	60	429	495	462	81
	70	334	414	374	69
	80	251	344	298	60
03	40	211	698	455	51
	50	178	645	412	44
	60	143	593	368	38
	70	125	540	333	33
	80	97	457	277	26
04	40	513	612	563	41
	50	445	557	501	39
	60	406	519	463	38
	70	333	433	383	36
	80	238	341	290	32
07	40	506	588	547	63
	50	467	556	512	61
	60	423	522	473	59
	70	324	434	379	55
	80	258	367	313	52

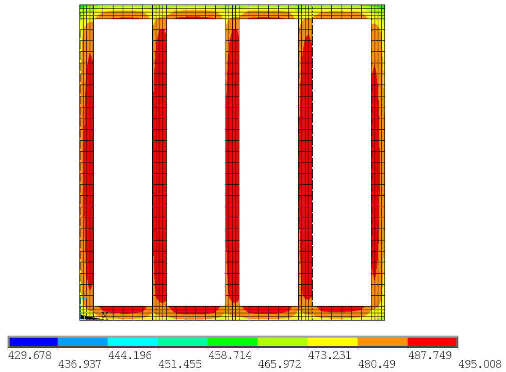
Results include the time in complete minutes and the critical temperature for the LSF structure. The results for the specimen 03 are quite different from all other results. The LSF of specimen 03 is submitted to a higher temperature gradient due to the effect of the cavity insulation material (Rockwool). This gradient can be justified by the use of the perfect contact between all the materials involved in simulation. Figure 10 represents the critical results for all the specimens, loaded with 60% of the loadbearing capacity or room temperature. The results include the critical temperature field for the LSF structure and also the deformed shape mode with the von Mises stress for the critical time. Local buckling of the web and distortional buckling modes are the potential failure modes for this type of LSF walls.



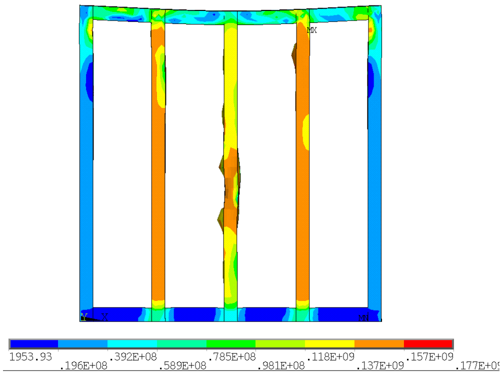
a) LSF temperature for the critical time of specimen 01, with 60% load level.



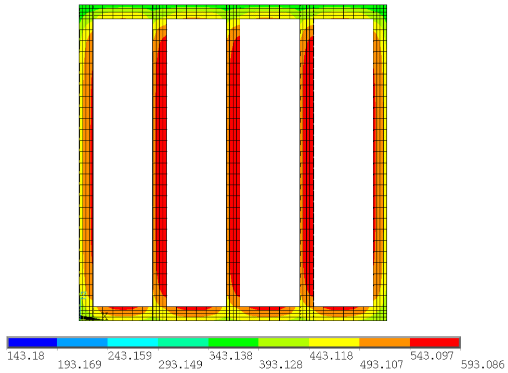
b) von Mises stress for the critical time of specimen 01, with 60% load level.



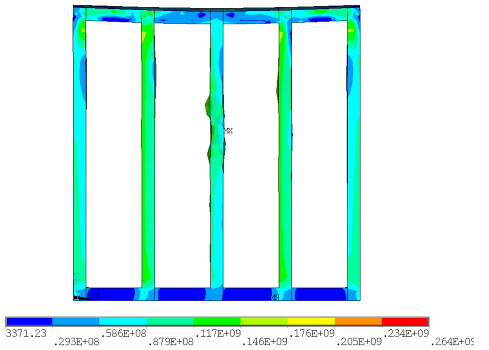
c) LSF temperature for the critical time of specimen 02, with 60% load level..



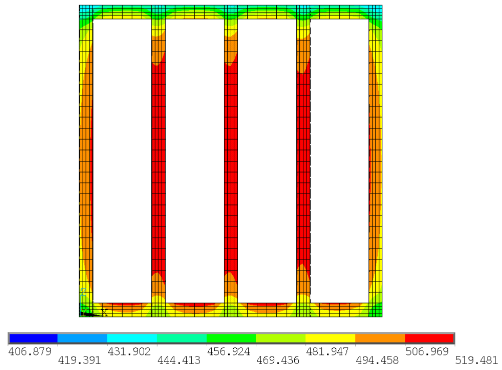
d) von Mises stress for the critical time of specimen 02, with 60% load level.

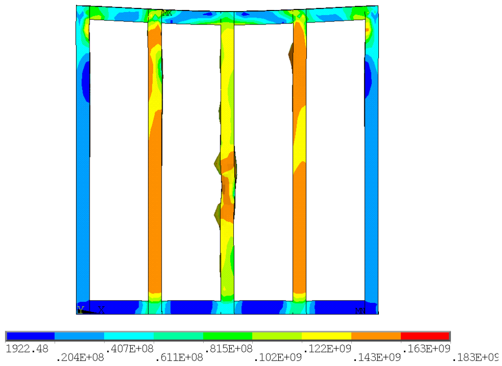


e) LSF temperature for the critical time of specimen 03, with 60% load level..



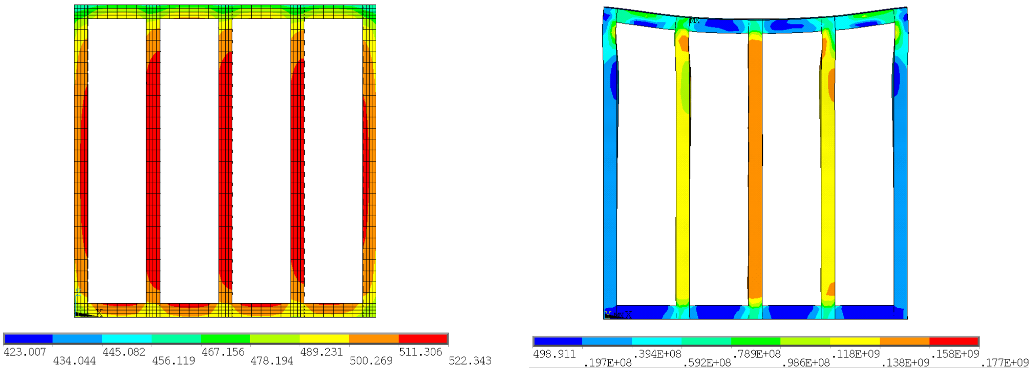
f) von Mises stress for the critical time of specimen 03, with 60% load level.





g) LSF temperature for the critical time of specimen 04, with 60% load level..

h) von Mises stress for the critical time of specimen 04, with 60% load level.

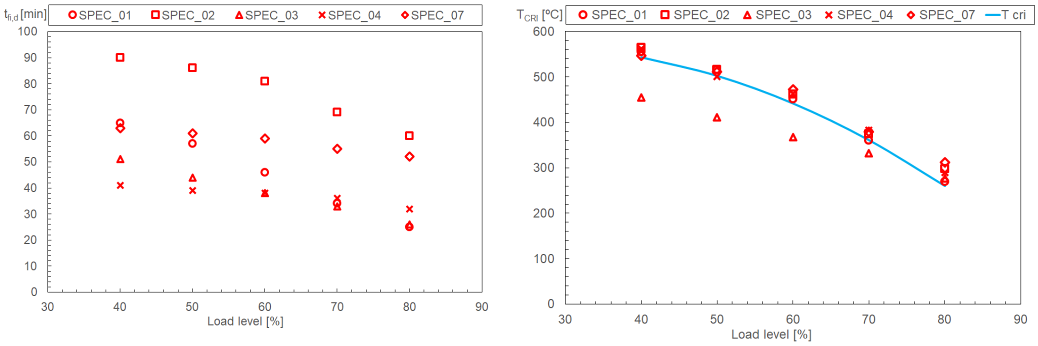


i) LSF temperature for the critical time of specimen 07, with 60% load level.

j) von Mises stress for the critical time of specimen 07, with 60% load level.

Figure 10: Critical temperature and equivalent stress for the critical time.

The fire resistance decreases with the increase of the load level, see Figure 11. With the exception to the specimen 03, the average critical temperature of all the specimens is approximately the same for each load level.



a) Fire resistance for all the specimens.

b) Average critical temperature of the LSF.

Figure 11: Fire resistance and average critical temperature for all simulated specimens.

The fire resistance depends on the load level μ and the critical temperature can be approximated by Eq. 1, for this type of LSF frame structure and for all the composite layer solutions presented herein and without any kind of insulation material in the cavity.

$$T_{CRI} = -0.0997 \times \mu^2 + 4.0935 \times \mu + 506.35 \qquad (1)$$

This critical temperature demonstrates that the simple calculation method presented in Eurocode EN1993-1-2 [48], which states that the fire resistance could be verified, for a specific time, when the temperature of the cross section is not more than 350 ºC, when applied to this type of elements (class 4 cross sections) is over conservative for the majority of the tested cases and unsafe for the case of the load level higher than 70%.

4. CONCLUSIONS

This investigation presents a hybrid solution method to predict the fire resistance of loadbearing walls, after the development of experimental tests on partition walls with the same type of geometry. This solution method requires an extra measurement for the temperature evolution in the cavity and the selection of the appropriate heat flow coefficients. This measurement is of extreme importance to account for all the major events that occur during experimental tests (cracks and ignition of combustible materials).

The results of five experimental tests are presented. All specimens were made with the same LSF structure. The fire resistance of a LSF wall protected with a single plasterboard can be improved by filling the cavity with low density Rockwool. Specimen 07 presents higher fire resistance when compared with specimen 04, demonstrating the worst fire performance of the composite solution using cork material in comparison with a composite solution using OSB. The LSF wall with double layer of gypsum almost reached the fire rating of 2 hours.

The numerical simulation model includes a four step solution method. The first step was developed with a linear elastic buckling analysis to find the critical load of the LSF structure and also the main instability mode shape. This mode of instability is currently used to define the imperfection of the LSF structure. The second step allowed for the calculation of the loadbearing capacity of the LSF wall. The mechanical resistance of the gypsum, cork and OSB was neglected. The third step used a non-linear thermal analysis, with all materials included, to predict the thermal effect of the fire into the LSF structure. This analysis was validated with experimental results and allows for the fire rating (I) of the LSF wall structure. The fourth step used a geometric and material non-linear analysis to predict the fire resistance of loadbearing walls made with the same materials as the ones tested without load. The fire resistance decreases with the increase of the load level and the average critical temperature of the steel structure is approximately the same, with exception to the specimen 03. A new formula is proposed for the definition of the critical temperature, depending on the load level.

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