



TEST&E 2019

Monitorizar e Preservar

2º Congresso de Ensaios e Experimentação
em Engenharia Civil

19-21 FEVEREIRO 2019
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Engenharia do Porto

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ATAS DO 2º CONGRESSO

DE ENSAIOS E EXPERIMENTAÇÃO EM ENGENHARIA CIVIL



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PREFÁCIO

O 2º Congresso de Ensaios e Experimentação em Engenharia Civil – TEST&E 2019 – foi realizado de 19 a 21 de fevereiro de 2019 no Instituto Superior de Engenharia do Porto, numa organização conjunta da RELACRE (Associação de Laboratórios Acreditados de Portugal), do ISEP (Instituto Superior de Engenharia do Porto) e do IST (Instituto Superior Técnico).

Este congresso pretendeu proporcionar um amplo fórum de divulgação e partilha de conhecimentos e experiências entre os seus participantes das áreas da investigação e ensino, indústria e serviços, sob o tema principal: Monitorizar e Preservar.

No atual ciclo de atividade com enfoque na preservação e valorização do património construído, este congresso pretendeu dar a devida importância à monitorização como ferramenta de apoio imprescindível à gestão desses mesmos ativos, com a finalidade última da sua melhor preservação no ciclo de vida. A monitorização assume ainda maior relevância no âmbito da utilização de novos materiais ou processos construtivos, sobretudo na reabilitação ou reconstrução, onde interessa aprofundar conhecimentos relativos ao seu comportamento em serviço. A implementação das mais variadas técnicas de monitorização, usufruindo com vantagem das tecnologias de informação e comunicação da atualidade, baseia-se em grande medida em ensaios e experimentação que estão em permanente evolução.

Neste livro são apresentados os 68 artigos de 204 autores, de acordo com os seguintes temas:

1. Reabilitação do património
2. Novos materiais
3. Hidráulica, ambiente e recursos naturais
4. Geotecnia e transportes
5. Inovação e tendências futuras
6. Ensaios não destrutivos
7. Vibrações e higrotérmica

Os editores expressam os seus maiores agradecimentos: aos autores, pela confiança na divulgação dos seus trabalhos neste congresso; à Comissão Científica, pela contribuição dada à qualidade técnica e científica dos artigos; à Comissão Organizadora Local e à Comissão Executiva, pela garantia de concretização do congresso com todo o sucesso. Um agradecimento geral é dirigido a todos os que direta ou indiretamente contribuíram para a excelência da qualidade deste congresso.

Lisboa, julho de 2019.

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FIRE RESISTANCE TESTS OF NON-LOADBEARING LSF WALLS

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RESUMO

Um conjunto de testes de resistência ao fogo de paredes sem carga, à escala real, é apresentado para avaliar o efeito da estrutura de aço (número e posição dos montantes e guias) e diferentes materiais de protecção. Os ensaios experimentais são desenvolvidos de acordo com as normas internacionais EN1364-1 para a preparação de amostras e condições de ensaio e de acordo com a norma genérica de teste de resistência ao fogo EN1363-1, utilizada para definir o critério de classificação deste tipo de elemento de construção. Modelos numéricos também são utilizados para comparar os resultados dos testes. O modelo numérico é validado, usando as condições limites definidas no Eurocódigo EN1991-1-2 e as condições específicas limites na cavidade da parede. Estas condições de contorno específicas são essenciais quando se assume que a transferência de calor flui por convecção e radiação, do lado exposto para o lado não exposto da parede. Os resultados permitem concluir sobre o comportamento de diferentes sistemas de protecção da estrutura de aço enformado a frio, sobre o efeito da estrutura e apresentar um modelo híbrido para validação dos resultados numéricos.

ABSTRACT

A set of full scale fire resistance tests of non-loadbearing walls is presented to evaluate the effect of the steel frame (number and position of studs and tracks) and different protection materials. The experimental tests are developed in accordance to the international standards EN1364-1 for the sample preparation and conditions for testing and in accordance with the generic standard fire test EN1363-1, used for the criterion to rate this type of building construction element under fire. Numerical models are also used to compare the results of the tests. The numerical model is validated, using the boundary conditions defined in Eurocode EN1991-1-2 and specific boundary conditions in the cavity of the wall. These specific boundary conditions are essential when assuming that the heat transfer flows by convection and radiation, from the exposed side to the unexposed side of the wall. The results allow to conclude on the behaviour of different systems of protection used for the cold formed steel structure, on the effect of the structure and to present the hybrid model to validate the numerical results.

1 - INTRODUCTION

The light steel framed (LSF) walls are usually made with prefabricated plates (homogeneous or composite) and are widely used as partition walls or loadbearing walls, with large application in buildings structures. The LSF construction method contributes to the sustainability of the built environment, due to the possibility of the material recycling and lower water consumption. This construction method presents also a high degree of freedom to the architects for new building solutions and retrofitting solutions. This construction method is easy and allows for modular construction, presenting building elements with small weight when comparing to traditional solutions and presenting also economy for transportation and handling. However, the high thermal conductivity of the steel structure can lead to significant thermal bridges at room temperature, which can affect the thermal performance of LSF assemblies and can lead to significant damage of the structure when submitted to accidental fire conditions. The LSF is usually made with studs and tracks that require fire protection, normally achieved with a single plasterboard, or a double plasterboard, composite layer or insulation material inside the cavity. The partition walls can be fire rated for the integrity (E) and insulation (I) criteria.

Previous investigation related with the fire behaviour of LSF walls has been developed around the world, but with more emphasis in countries that are using this building construction method for long time ago. One of the first reported fire test was developed in the US, in 1973, by B. C. Son and H. Shoub (Son & Shoub, 1973), explaining in detail two fire-endurance tests on double LSF wall assemblies. Later on in 1985, Kenneth J. Schwartz and T. T. Lie (Schwartz & Lie, 1985) studied the effect of the heat transmission to prevent materials ignition in contact with the unexposed side of the

partition wall, assessing the temperature criterion of the American standard ASTM E119. In 1996, Mohamed A. Sultan (Sultan, 1996) presented a one-dimensional heat transfer model with the possibility to determine the temperature evolution across the wall thickness. This author summarised the results obtained from the numerical simulation and experimental tests for predicting the fire resistance of non-insulated and unloaded steel-stud wall assemblies with gypsum. The results obtained by numerical simulation were conservative with respect to the experimental tests but with very good agreement. In 2002, Geoff Thomas (Thomas, 2002) investigated the thermal properties of gypsum plasterboard at high temperatures and developed a finite element heat transfer model for LSF walls. The model was conservative for fast and hot fires and less accurate for specimens subjected to abrupt temperature changes. The heat transfer model was not able to predict the motion of moisture and pyrolysis reaction products. In 2009 K. Ghazi Wakili and E. Hugi (Ghazi Wakili & Hugi, 2009) developed an experimental investigation regarding the thermal properties of the materials, comparing the performance of four different types of gypsum. Depending on the amount and types of carbonates, different endothermic reactions occurred between room temperature and 900 °C, leading to different values of thermal conductivity, effective specific heat and density. Authors also investigate the time-temperature evolution comparison for a box protected steel column, finding more than 100 °C of maximum difference on the steel temperature after 90 minutes of fire exposure, when considering different these types of gypsum materials. Poologanathan Keerthan and Mahen Mahendran in 2012 (Keerthan & Mahendran, 2012) 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 and new simple formulas were developed to estimate the temperature in the unexposed side of the walls. In 2013, the same authors (Keerthan & Mahendran, 2013) 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 (Kolarkar, 2010). Authors concluded that the use of this composite solution led to lower temperature evolution in the unexposed side, increasing the fire resistance. In 2014, Ayman Y. Nassif et al. (Nassif, Yoshitake, & Allam, 2014) presented an investigation with experimental tests and numerical modelling of the transient thermo-mechanical behaviour of partition wall with Rockwool insulation, using ABAQUS. The predicted temperature results agree well with the experimental results and the displacements due to thermal bowing were quite similar. In 2016 Jonathan Vallée (Jonathan Vallée, 2016) 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 demonstrated that insulation material in the cavity can improve the fire resistance, when considering the insulation criterion, especially when ablation of the gypsum plates occurs. In 2017 Anthony Ariyanayagam and Mahen Mahendran (Ariyanayagam & Mahendran, 2017) 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. 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 higher than the traditional gypsum plates, probably due to the high-level content 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. 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 (Piloto, Khetata, & Gavilán., 2017), validate the numerical models with experimental tests developed elsewhere (Khetata et al., 2017); analysing the fire performance of LSF using the simplified one dimensional heat flow (Piloto, Khetata, & Gavilán, 2017); and presenting a sequential numerical model to study the fire resistance of LSF walls made with composite panels (Piloto, 2018).

The fire rating of the LSF walls requires the development of experimental fire tests in accordance to the final application of materials and LSF structure. For this purpose, nine experimental tests are presented to evaluate the fire resistance with respect to insulation (I) criterion. The fire insulation of a single plasterboard is compared to fire resistance of composite materials and also with the insulation of stone wool. The thermal behaviour of the LSF structure is also compared, using different number of studs. All the tests were simulated using the hybrid 3D finite element model. The results agree well, which allows to develop future parametric analysis.

2 - EXPERIMENTAL TESTS

Nine experimental tests were developed under standard fire conditions, ISO834 (International Organization for Standardization, 1999), using the general requirements for fire tests (CEN- European

Committee for Standardization, 2012) and the particular procedures for partition walls (CEN-European Committee for Standardization, 2015). The partition walls under analysis present three different light steel frames, using 3, 4 and 5 studs, see figure 1.

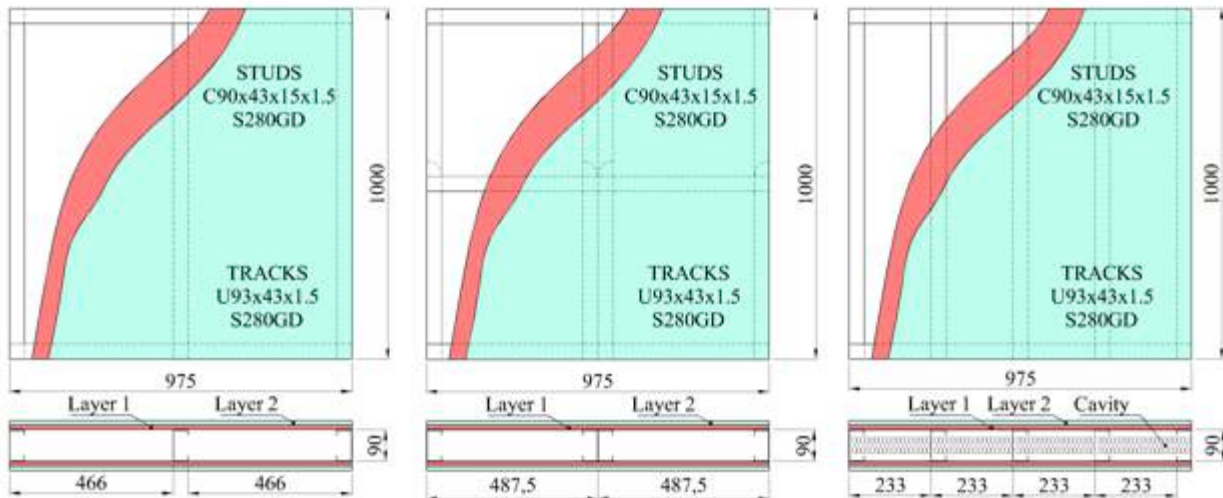


Figure 1 – Partition walls with different LSF structure.

These LSF walls are made with cold formed steel profiles, using stud profiles C90x43x15x1.5 and track profiles U93x43x1.5, forming a cavity thickness of 90 mm. Both profiles have the steel grade S280GD and should be protected with different types of layers and materials, to evaluate the effect of the fire, see table 1. A composite panel with cork and gypsum is compared with a composite panel using OSB and gypsum. Both composite solutions are compared with single and double gypsum panels and with cavity insulation Rockwool. Two different types of plasterboards materials 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, colour pink; and Gypsum 2 which is normal gypsum, made with laminated gypsum board consisting of two layers of multilayer paper, with same purity natural gypsum inner core reinforced but only with fiberglass filaments, colour white).

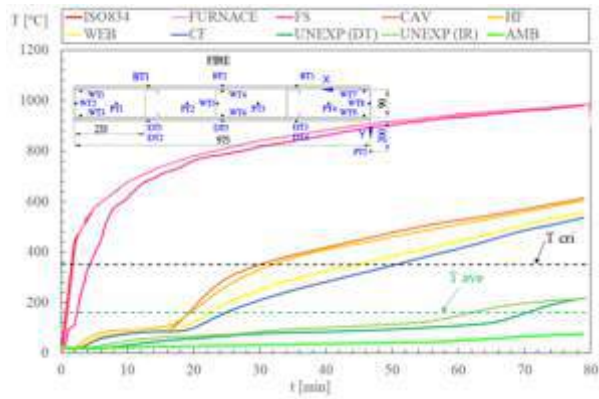
Table 1 – LSF walls: Materials and geometry.

SPECIMEN	LSF (NUMBER OF STUDS)	MATERIAL / THICKNESS FOR LAYER 1 [mm]	MATERIAL / THICKNESS FOR LAYER 2 [mm]	CAVITY / DENSITY [kg/m ³]
01	5	Gypsum 1/ 12.5	-	-
02	5	Gypsum 1/ 12.5	Gypsum /12.5	-
03	5	Gypsum 1/ 12.5	-	Rockwool / 75
04	5	Cork / 10	Gypsum 2 / 12.5	-
05	3	Cork / 10	Gypsum 2 / 12.5	-
06	4	Cork / 10	Gypsum 1 / 12.5	-
07	5	Wood OSB / 10	Gypsum 2 / 12.5	-
08	3	Gypsum 1 / 12.5	-	-
09	4	Gypsum 1 / 12.5	-	-

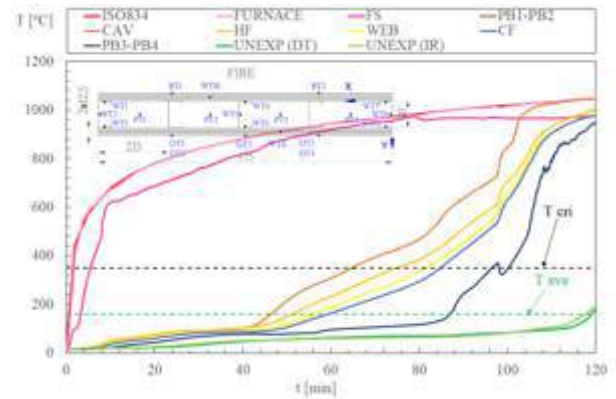
The plates were fixed to the LSF structure, using self-drilling screws of diameter 4.2 and 4.8 mm, spaced every 152 mm. The LSF was fixed to the testing frame around 3 edges (left side, bottom and top) allowing a free edge, properly filled with ceramic fibre on the right side (gap size equal to 25 mm). All the wall borders were filled with gypsum.

Several thermocouples Type K were installed into the specimen. Thermocouples were installed in different formats for temperature measurement: copper disk with plasterboard protection - DTi for measuring the unexposed surface temperature; welded hot joint applied on cold formed steel profiles - WTi for measuring the temperature of the steel profiles in three different regions (hot flange-HF , web- WEB and cold flange - CF); plate thermocouples PTi were applied for measuring the bulk temperature developed inside the cavities defined by the studs and tracks and also the ambient temperature (located 200 mm away from the unexposed surface; sheath thermocouples - BTi were used for measuring the temperature on the exposed surface. The number of thermocouples depends on the configuration of the specimen, see Fig. 2. The time history of the temperature measurements is presented in Fig. 2 for all the positions, using the average results of similar thermocouples. The

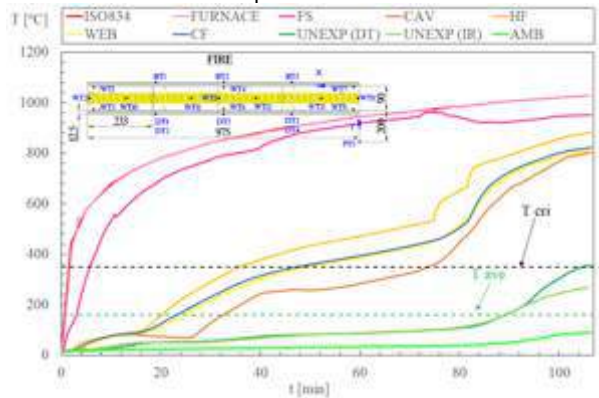
steel temperature is characterized by the hot flange (HF), always presenting the highest temperature, and characterized by the central web temperature (WEB) and the temperature of the cold flange (CF). The results of specimen 03 are quite different from the others, because the cavity is filled with Rockwool. The average temperature inside this material (CAV) was determined by the average values of WT10-WT13, which explains the smaller value with regard to the temperature measurements of HF, WEB and CF.



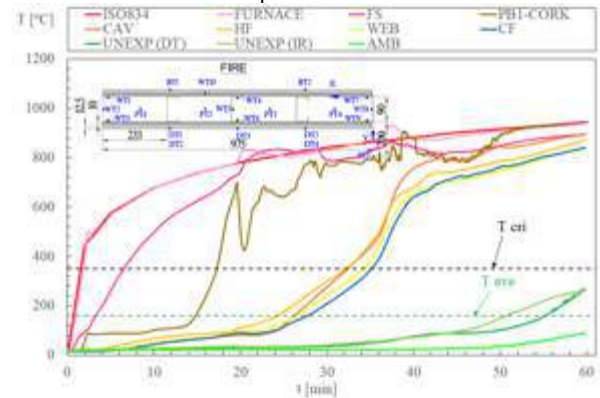
Specimen 01



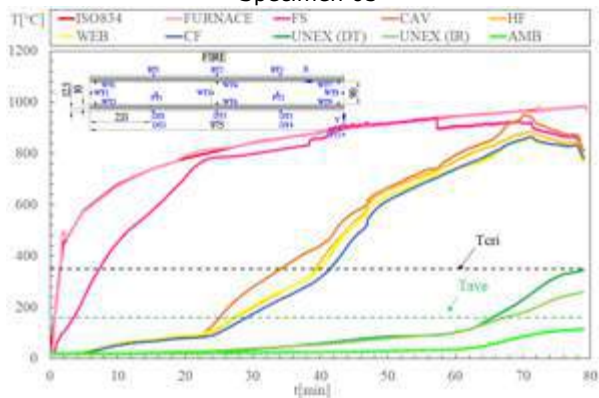
Specimen 02



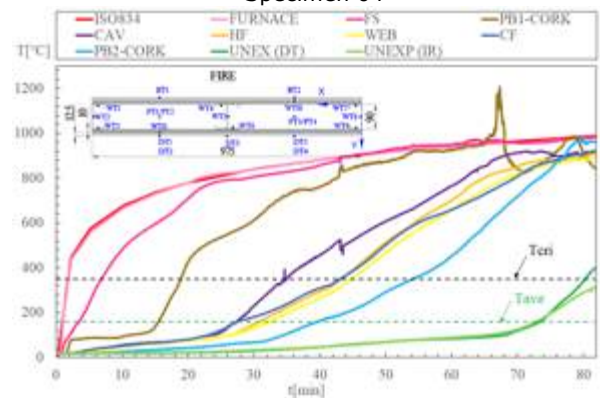
Specimen 03



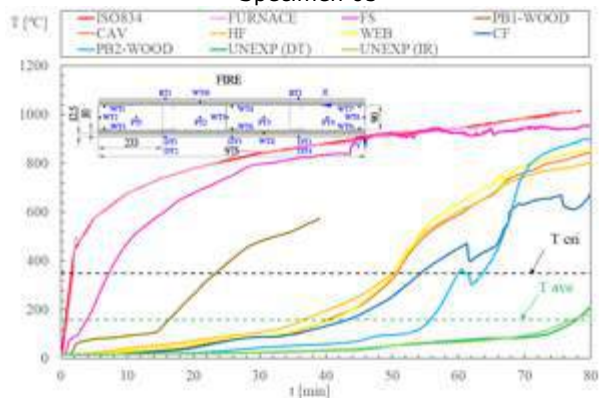
Specimen 04



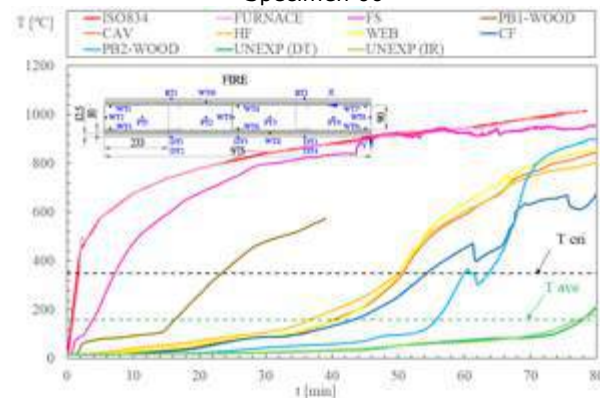
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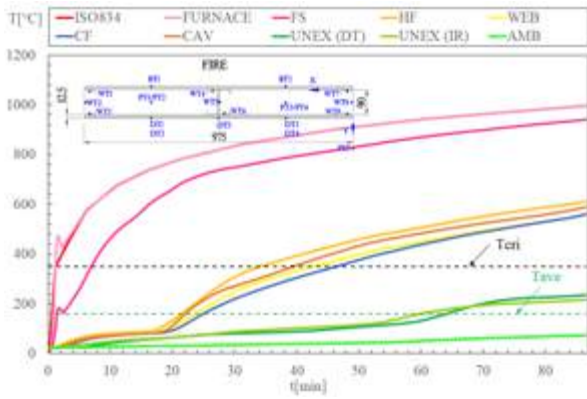
Specimen 06



Specimen 07



Specimen 08

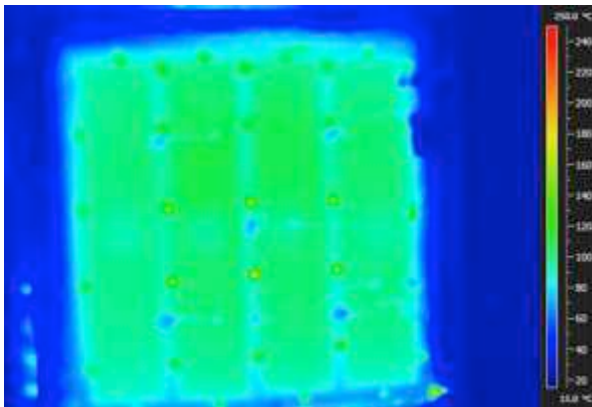


Specimen 09

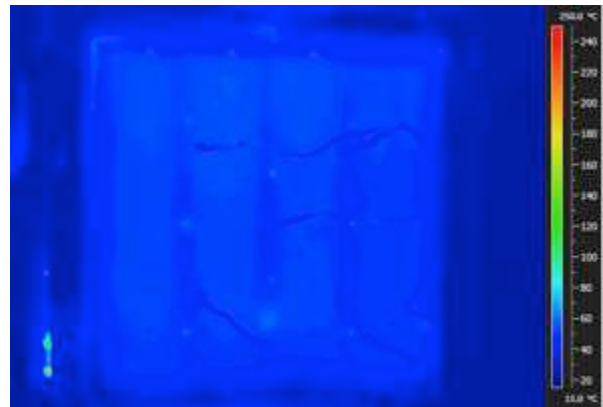
Specimen 07

Figure 2 – Temperature evolution during fire test.

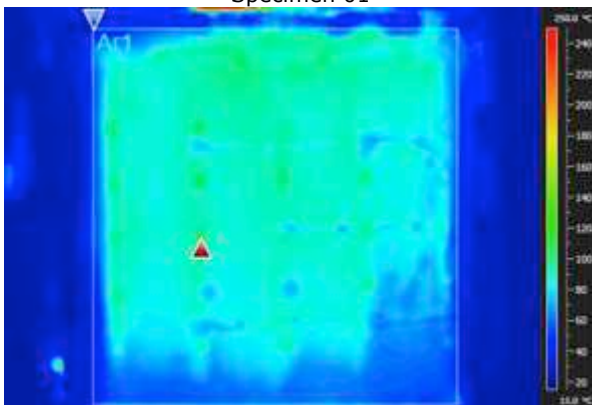
Different failure modes were achieved due to local and global instabilities. These instabilities are also associated with the formation of local plastic hinges. These modes are due to the thermal expansion and also due to the restrain effect of the portal frame. For some specimens (specimens 04, 05, 06 and 07), the furnace temperature goes beyond the temperature curve of ISO834 standard due to the heat release effect of the combustible materials (cork and OSB). Some specimens have combustible material, such as cork and wood. This type of material is localised in internal layer (layer 1) and is first protected by the layer 2 of the exposed side. When flames or hot gases are in contact with layer 2 or when temperature exceeds a certain level, this material starts ignition and starts to burn. In all the other specimens, the furnace temperature was kept close to the ISO834 because there was no combustible material. The unexposed temperature was measured with disc thermocouples UNEX (DT), obtained from the individual measurements of DTi; and with a FLIR infrared thermal camera located at 3m distance from the unexposed surface, UNEX (IR), see Fig. 3 for the corresponding temperature field at minute 50, using the same scale for $T_{min}=15^{\circ}\text{C}$ and $T_{max}=250^{\circ}\text{C}$.



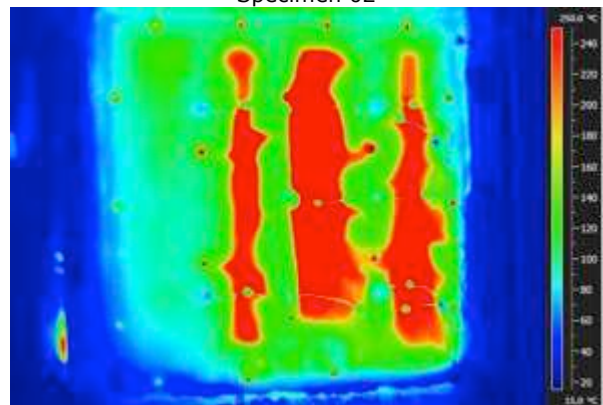
Specimen 01



Specimen 02



Specimen 03



Specimen 04

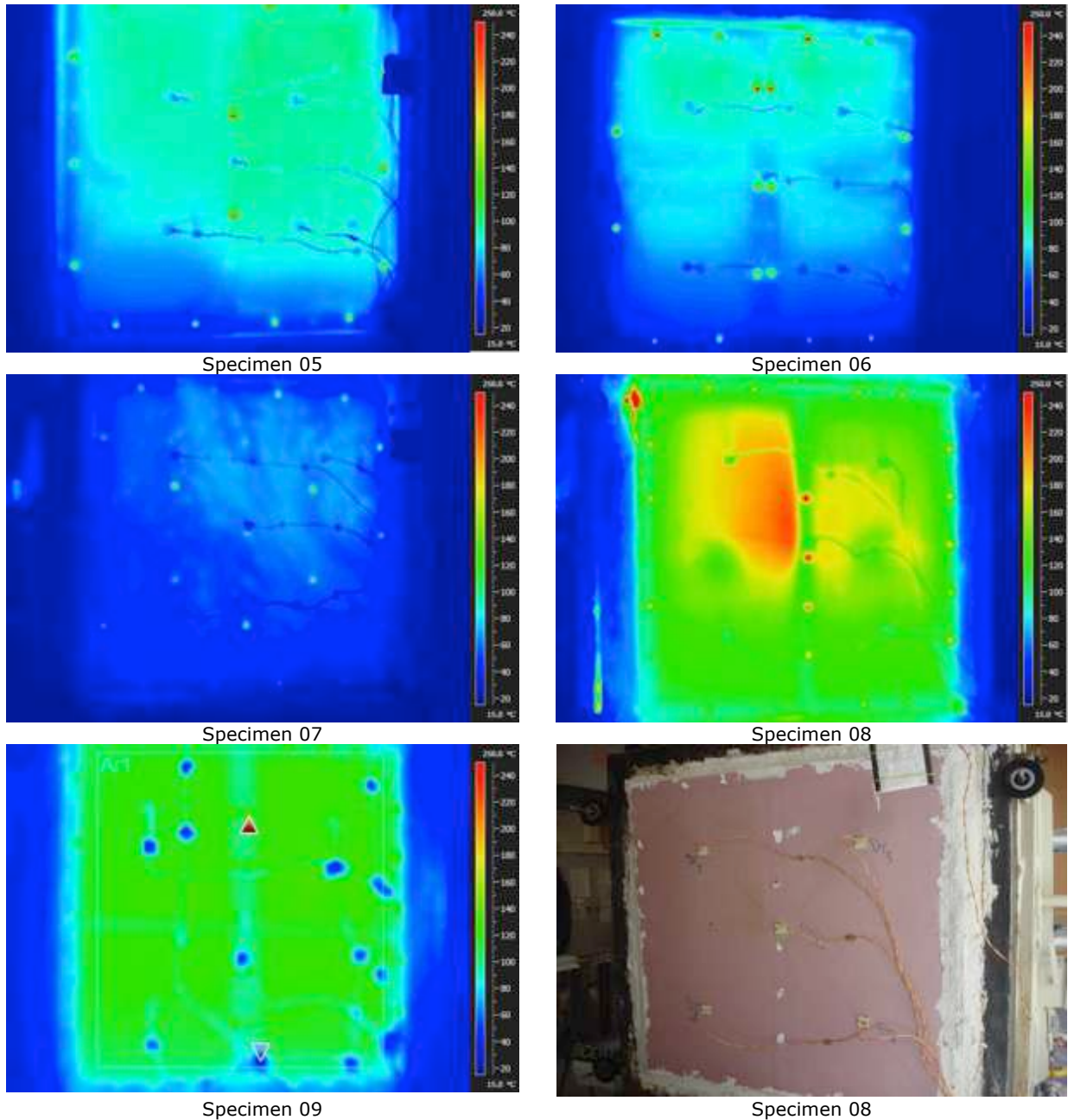


Figure 3 – Infrared temperature field for minute 50.

Special measurements were also developed for some specimens, such as: the average temperature of the cavity (CAV), obtained from the individual measurements of PTi; the room temperature (AMB) measured 200 mm away from the unexposed side of the LSF wall, see Fig. 3 for specimen 08, and the interface temperature (PBi-PBj) between the composite layered plates, obtained from the individual measurements of WTi.

The temperature evolution on the unexposed side defines the fire resistance time (I). The critical time was also determined for every specimen, taking into consideration all the possible criteria and measuring methods. The traditional and standard measuring method, using disk thermocouples (DTI), allows to determine the fire resistance, using the criterion for insulation, looking for the maximum temperature in any location or looking for the average temperature, above the initial average temperature (20 °C), in more than 180 °C or 140°C, respectively. The infrared thermal camera (non-standard measuring method) allowed for the calculation of the average temperature (IR) in the total unexposed area of the specimen (see example of the region A1 for specimen 03 or 09). Both measurement methods agree very well with respect to the definition of the fire resistance, see Table 2. The infrared thermography for the maximum temperature was not considered due to the existence of hotspots, special developed at the screw positions.

Table 2 – LSF walls: Fire resistance for insulation criteria (I) in completed minutes.

SPECIMEN	LSF (NUMBER OF STUDS)	T MAX=200 (DT) [MIN]	T AVE=160 (DT) [MIN]	T AVE=160 (IR) [MIN]
01	5	70	71	62
02	5	119	118	117
03	5	89	87	89
04	5	55	51	50
05	3	63	65	67
06	4	70	73	72
07	5	77	75	77
08	3	53	53	52
09	4	65	64	60

The fire resistance of LSF walls increases with the number of studs, see the comparison between specimen 01, 08, 09 or the comparison between specimen 05, 06. This may be justified by the higher number of cavities that are created and the bigger number of screws that are applied to the layered plates. Increasing the thickness of the gypsum also increases the fire resistance, see the comparison between specimen 01 and 02, being justified by the increase of the thermal resistance. Previous numerical investigation also allows the authors to conclude that for each additional 1 mm in gypsum thickness the fire resistance increases 8 minutes (Khetata et al., 2017). The comparison of the fire resistance of specimen 01, 02 and 03 also allows to conclude that doubling the number of layers of gypsum is a better solution in comparison to the use of insulation material in the cavity. The composite solution with gypsum and OSB presented better fire resistance when compared to composite solution with gypsum and cork, probably due to the higher stiffness presented by the wood plate and maybe also due to the higher heat released rate of the cork.

3 - NUMERICAL MODEL AND SIMULATIONS

The three dimensional thermal analysis is validated from experimental results, based on the hybrid solution method and based on the traditional solution method. This hybrid method uses the temperature evolution in the cavity (average PTi value) as bulk temperature for the heat transfer due to convection and radiation. The traditional solution method was used for specimen 03, using perfect contact between materials. The cavity region is fully filled with Rockwool in this specimen.

The finite element model uses shell and solid finite elements with linear interpolating functions and full integration methods from ANSYS. Solid finite elements are only used to model the layer plates and the insulation material (Rockwool). All the LSF model uses shell finite elements. The joints between studs and tracks are assumed to be in perfect contact, using superposed thin flanges, modelled as one shell region with double thickness (3 mm). The contact between solids and shells is also perfect, see Fig. 4.

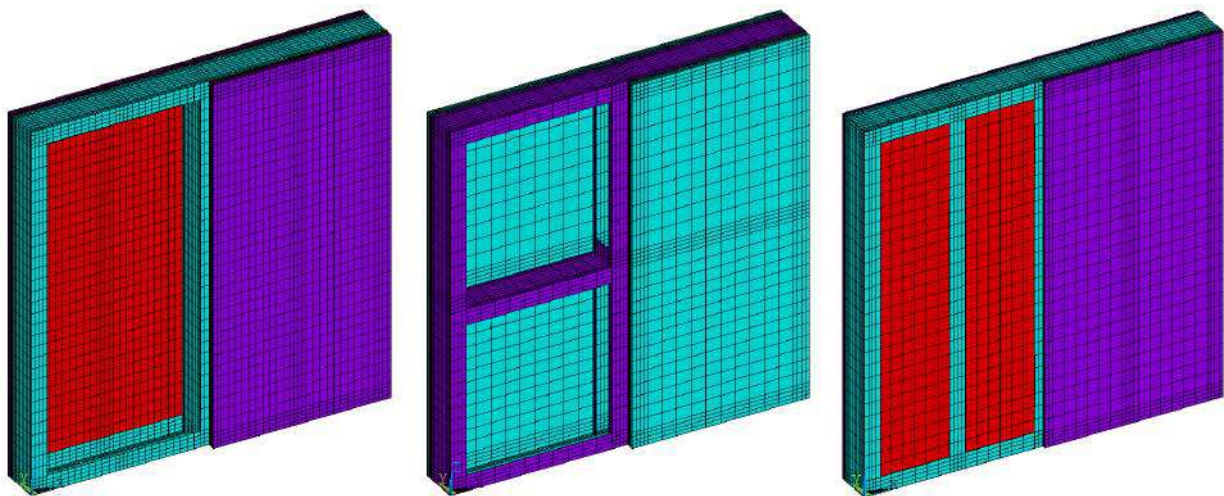
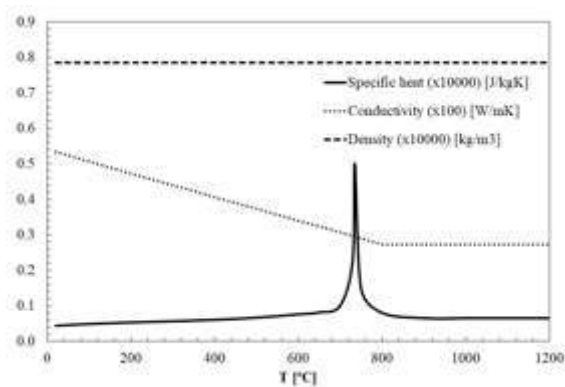


Figure 4 – Finite element mesh used for the simulation of some specimens.

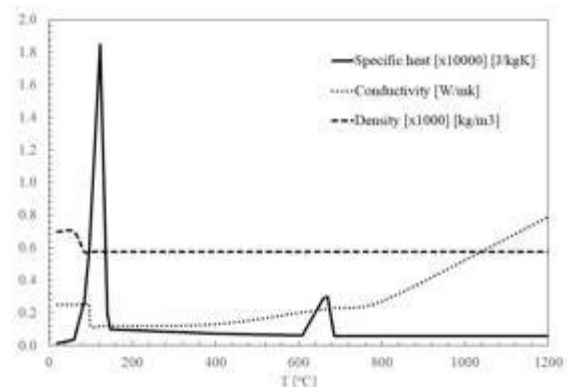
The hybrid solution method considers the temperature variation inside the cavity region, to take into consideration any sudden increase of temperature due to cracks, openings or the heat release from the combustible materials (see temperature measurements for CAV in Fig. 2). The heat flow

parameters were calibrated to be applied for all the simulations with the same values, considering the bulk temperature in this region, specimen dependent and defined by the average value of the measurements made by the plate thermocouples (TPI). The standard boundary conditions were used according to the document on actions in structures submitted to standard fire EN 1991-1-2 (CEN-European Committee for Standardization, 2002), for the exposed side and unexposed side. The heat flow by convection was considered in the exposed surface using a heat transfer coefficient of 25 W/m²K and the heat flow by radiation with an emissivity for the flames equal to 1. In both cases the temperature inside the furnace was considered to rise according to the ISO834 (International Organization for Standardization, 1999). On the unexposed surface, only the convective heat flow was considered, with a heat transfer coefficient of 9 W/m²K to include the effect of radiation. The bulk temperature outside the furnace was considered equal to the initial mean temperature (20 °C). The extra flow parameters were applied in the cavity region, assuming heat transfer by convection and radiation, considering heat transfer coefficient of 17.5 W/m²K and a flame emissivity value of 1.

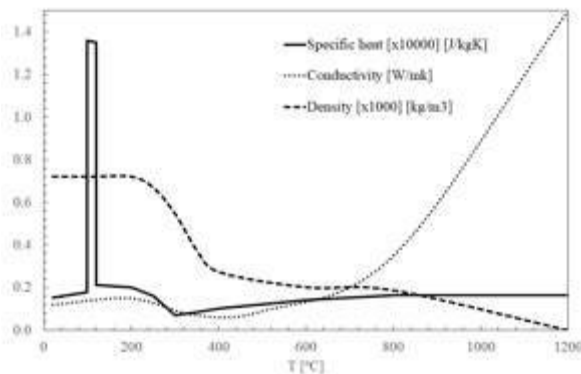
The thermal properties of all the materials were considered temperature dependent. Fig. 5 depicts all the major properties that were used to solve the energy equation. The steel properties were retrieved from EN1993-1-2 (CEN- European Committee for Standardization, 2005) and the gypsum properties were retrieved from the work developed by Mohamed Sultan (Sultan, 1996). The thermal properties of the cork and OSB assumed the same type of temperature dependence in accordance to the proposal of EN1995-1-2 (CEN- European Committee for Standardization, 2004), but small modifications were applied to the properties of cork, due to the material characteristics (elimination of the specific heat peak value for the OSB and adjusting the values measured at room temperature by the hot disk method (International Organization for Standardization, 2015)). The thermal properties for the Rockwool were obtained from Steinar Lundberg (Lundberg, 1994), duly adapted to the corresponding material density. The emissivity of steel and cork was considered equal to 0.7, the emissivity of gypsum and OSB equal to 0.8.



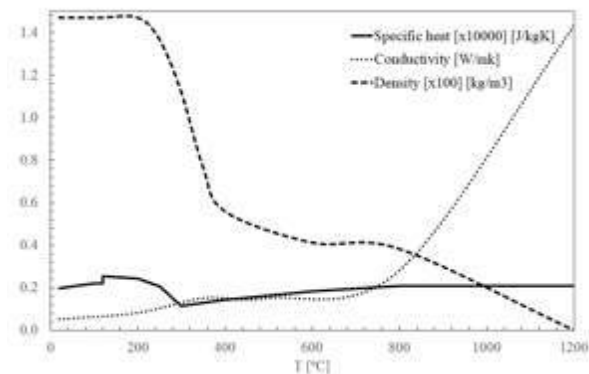
Thermal properties for steel



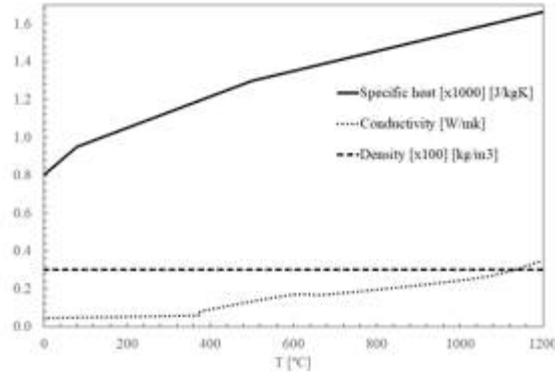
Thermal properties for gypsum



Thermal properties for OSB



Thermal properties for cork

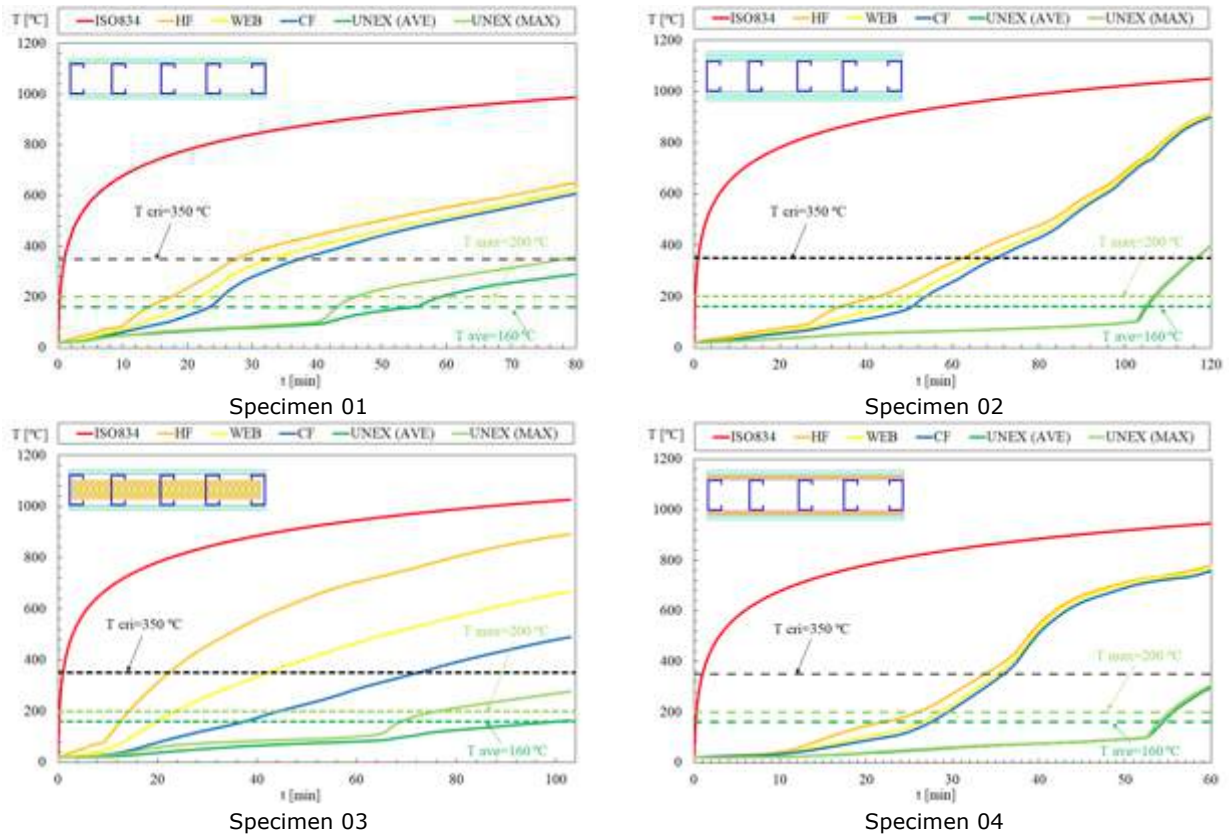


Thermal properties for Rockwool

Figure 5 – Thermal properties for all the materials involved in thermal simulation.

The thermal solution was considered transient and nonlinear, using an incremental time step of 60 s, with the possibility to be reduced to 1 s. The convergence criterion was based on the heat flow, with a tolerance value of 1E-03 and a minimum reference value 1E-06. The ideal ISO834 was adopted for the simulation instead of the furnace temperature evolution.

Fig. 6 depicts the time history evolution for the temperature, collecting the nodal temperatures in the same regions where the thermocouples were located. The results agree well for the most part of the experiments. The specimen 03 presents higher temperature difference between hot flange (HF) and the cold flange (CF), being justified by the assumption of perfect contact between the Rockwool and all other materials in contact with. This perfect contact is responsible for a temperature delay during time. All the other specimens present similar trend and the main difference between the experimental results and the numerical results can be justified by the localised effect of a crack, opening or the ignition of any combustible material.



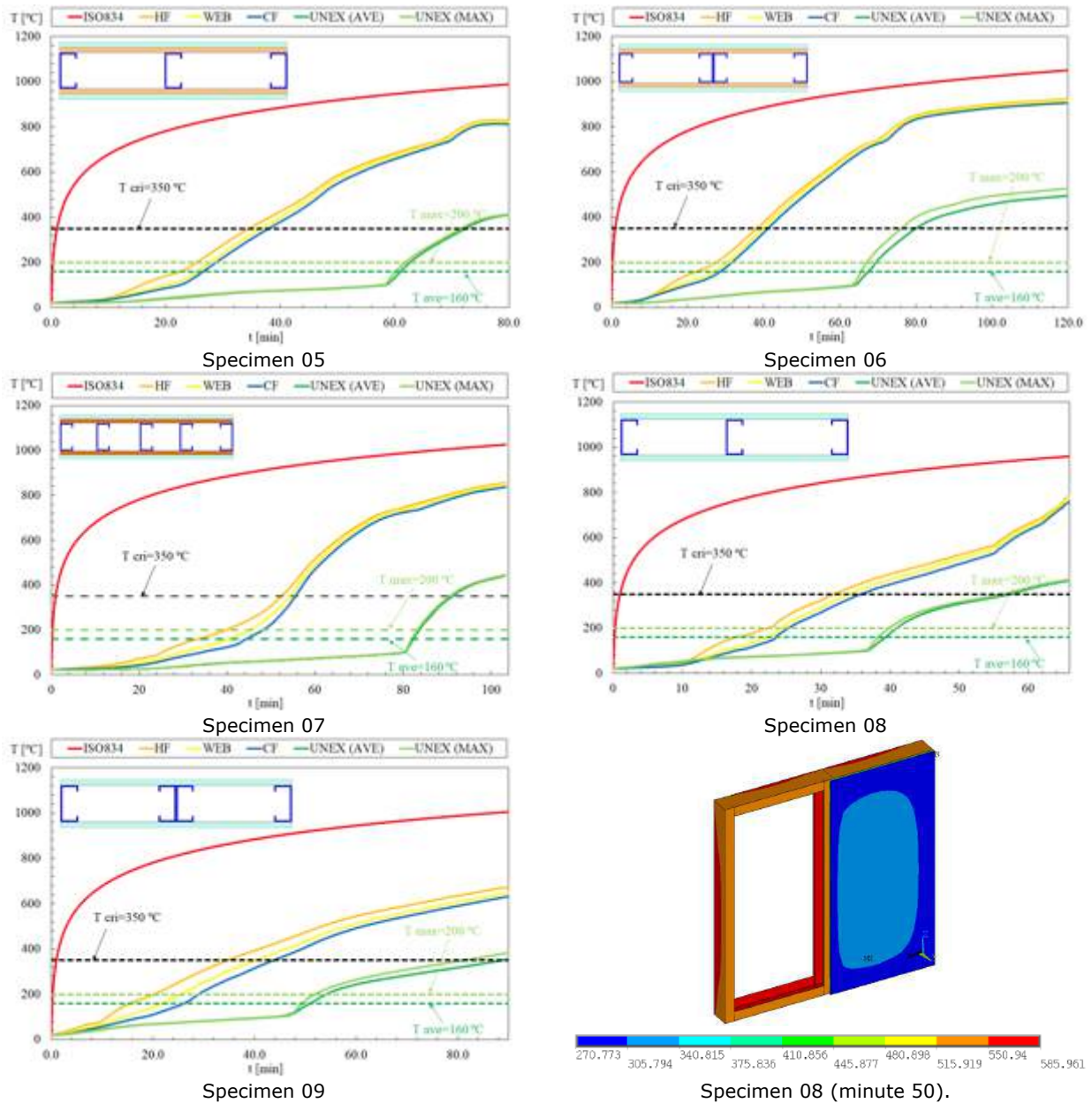


Figure 6 – Temperature evolution during fire simulation.

The critical time was determined with the same criteria used for experimental tests. A specific number of nodes were selected to determine the unexposed surface temperature (UNEX), being representatives of the unexposed surface at mid height of the wall, being some of them aligned with steel studs. The critical time was determined for both conditions [T max] and [T ave], being the fire rating always determined by the first to achieve each condition (smallest critical time in completed minutes in agreement with the fire rating scales available (CEN- European Committee for Standardization, 2016)).

4 - COMPARISON OF RESULTS

Table 3 presents the comparison between the fire resistance (I) determined by numerical simulation and experimental tests. The difference between the results obtained for the fire resistance criteria are in between 1% and 36%. The comparison was made using the criteria (maximum temperature [T max] and average temperature [T ave]) applied to measure the insulation fire performance, using DT measurements from experiments and a representative number of nodal results from the unexposed side of the model, in completed minutes. The results agree well not only when using the criteria but also when comparing the time history of the temperature results. The main difference can be justified by the localised effect of special phenomena's that are very difficult to predict. The numerical model uses the hybrid method, but takes into consideration the average phenomena's of all the cavities

available in the LSF walls, which means that the same phenomenon is reproduced in each cavity in the numerical simulation. This is not exactly what was determined during the experimental test, see for example the Infrared thermal image of specimen 04, 06 or 08, after 50 minutes of fire exposure.

Table 2 – LSF walls: Fire resistance for insulation criteria (I) in completed minutes

SPECIMEN ID	LSF (NUMBER OF STUDS)	T MAX=200 (DT) [MIN]	DIFFERENCE T MAX [%]	T AVE=160 (DT) [MIN]	DIFFERENCE T AVE [%]
01	5	54	22	45	36
02	5	105	11	106	10
03	5	99	11	76	12
04	5	54	1	55	7
05	3	61	3	61	6
06	4	67	4	67	8
07	5	82	6	83	10
08	3	39	26	39	26
09	4	51	21	50	21

5 - CONCLUSIONS

Nine experimental fire tests were developed to define the fire resistance of the partition walls, comparing the behaviour of composite plates with respect to the traditional gypsum protection plates.

The fire resistance of the LSF wall increases with the number of studs in the LSF and also with the thickness of the protection layers. Doubling the gypsum layer has a better fire performance in comparison to the use of insulation material inside the cavity. The composite layer using gypsum and OSB presented better fire resistance when compared to the composite layer using gypsum and cork, due to the higher stiffness of the OSB.

The hybrid solution method can be used to predict the fire resistance of partition walls. This solution method requires an extra temperature measurement for the evolution of the bulk temperature 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 may occur during tests (cracks and ignition of combustible materials).

The non-linear transient fire analysis was validated with experimental results, allowing for the fire rating (I) of the LSF wall.

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