Fire resistance of cold-formed steel walls with composite panels: Results from insulation rating (I) and loadbearing prediction rating (R)

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1. Introduction

Cold-formed steel structures using prefabricated panels are widely used in partition walls and loadbearing walls, with direct application in different types of buildings, such as multi-storey offices, educational buildings, health buildings, residential buildings and other types of public and private buildings. Fire protection is usually achieved by one or more layers of protective materials. Walls that meet fire resistance standards are the result of the proper combination of certain materials and elements. Sections of cold formed steel must be protected with a coating plate to prevent their properties from being damaged by the action of a fire. The "C" shaped structural section is the predominant shape, used for steel studs in loadbearing walls, but other sections may also be used. The U-shaped structural section is another possible shape used for tracks, as a profile at the base and at the top of the light steel frame. In this article only these two sections are used, but other sections could also be used (open, closed, composite or simple sections). The resistant capacity of steel decreases significantly when submitted to fire conditions, so this material should be protected with other materials. The plasterboards may be used as a simple protective material and may also be combined with other materials. 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 for room temperature use. 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. The service components can be installed in these walls, with the necessary protection of these components, according to the specialty involved.

To prevent the spread of fires to adjacent compartments or to the outside and to maintain the loadbearing capacity of this type of elements (structural stability), these walls must meet fire resistance requirements and may be classified according to their loadbearing capacity (R), sealing capacity to flame and hot gases (E) and thermal insulation capacity (I). The fire rating of construction products and building elements is regulated by the European standard EN13501-2 [1], using the results of the experimental tests.
The loadbearing capacity assessment must be carried out in accordance with EN1365-1 [2] and the compartmentation capacity assessment may be carried out in accordance with EN1364-1 [3].

The loadbearing capacity (R) is the ability of the element to withstand exposure to fire, under specified mechanical actions, on one exposed surface for a period of time, without any loss of structural stability. The criteria that provide for the evaluation of the loadbering capacity of axially loaded elements are specified by the actual displacement limit value (contraction $C = h / 100$ mm, where h is the height of the element) or by the rate of variation of the vertical displacement (contraction rate $dC/dt = 3.h / 1000$ [mm / min]).

The sealing or integrity capacity (E) is the ability of the element to maintain the separation function, to only withstand exposure to fire, without transmitting the fire to the unexposed side, due to the passage of flames or hot gases. These may 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 aspects: checking cracks or excessive opening of certain dimensions; existence of ignition of a cotton pad; existence of a permanent flame on the unexposed side. Failure of the loadbearing capacity criterion (R) should also be considered as a integrity failure (E). When an element is rated for both the E (integrity) and the I (insulation), the integrity value will be the one determined by any of the three aspects that fail first. When an element is rated (E), but without an (I) rating, the sealing value should be set to the aspect that first fails cracks / openings or 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 classification (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 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 maximum temperature, limited to 180°C above the initial average temperature. Failure of any loadbearing (R) or integrity (E) criteria also means insulation (I) failure, regardless of whether the specific insulation temperature limits have been exceeded or not.

In this article, two fire resistance criteria will be evaluated. The insulation criterion was applied based on experimental tests and the loadbearing criterion was determined on the basis of a hybrid method (experimental and numerical).

2. Experimental tests

The case presented is part of a larger study of materials for cold-formed steel walls. The case presented has a light steel frame structure made by 5 vertical studs and 2 tracks. The structure was built with profiles C90x43x15x1.5 for the studs and U93x43x1.5 for the tracks. Both profiles belong to material class S280GD, so the value of the 0.2% of proof strength is 280 GPa. 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 study. The dimensions of the sample do not correspond to the dimensions normally used in practice for these walls, and therefore these tests cannot be used for fire rating of common partition walls because they do not comply with point 6.1 of EN 1364-1 [3] .

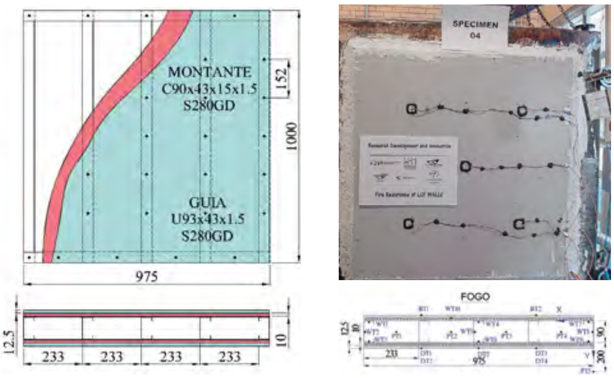
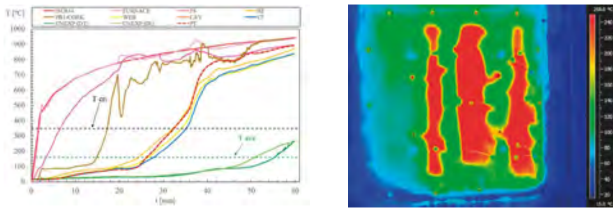


Figure 1. Model of the wall under study.

This wall is protected by a first layer of cork with 10 mm of thickness and by a second layer of plaster with 12.5 mm. Self-drilling screws spaced 152 mm apart were used. The joint connection of the frame with the wall was filled with gypsum. K-type thermocouples with various shapes were used for measurements performed at different locations, see figure 1.

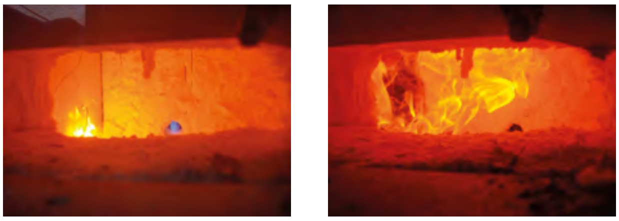
The sample was subjected to an ISO834 standard fire curve [4] for 60 minutes. The structure was screwed to the frame on 3 sides (left side, bottom and top) allowing a free edge (right side with 25 mm), properly protected with ceramic fiber. The temperature evolution was determined at all measurement points. Average values were determined for temperature measurement in the following regions: FS – average value of the temperature measured on the exposed face; HF – average value of the temperature measured in exposed flanges; PB1-CORK – WT10 single measurement value; WEB – average value of the temperature measured in the web of the studs; CF – average value of the temperature measured in the unexposed flanges; UNEXP (DT) – average value of temperature measured on the unexposed surface; UNEXP (IR) – average value of the temperature measured on the unexposed surface with infrared thermographic camera; PT – average value of the temperature in the cavities, see figure 2.



a) b)

Figure 2. Experimental temperature results. (a) evolution during the test. b) Result of the temperature field on the unexposed face for the time equal to t = 50 minutes.

The furnace temperature presented two moments with some instability, related to the ignition of the combustible material (cork). The cork layer on the exposed side ignited at minute 20, while the cork layer on the unexposed side ignited at minute 36, see photos of figure 3.



a) b)

Figure 3. Photograph from inside the furnace. a) Ignition of the exposed cork board at minute 20. b) Ignition of the cork unexposed board at minute 36.

The wall was submitted to the indirect effect of this action due to materials expansion. Different failure modes due to local and global instabilities were identified as the ultimate limit state, see figure 4.

a) b)

Figure 4. Final state of the wall and the steel structure (after 60 minutes of fire exposure).

3. Computer simulation

This computational model uses the thermal model, representative of the action of the fire duly validated to allow the determination of the loadbearing capacity of the wall. To achieve this goal, 4 steps were defined.

In the first step, a linear elastic stability model is defined to determine the critical load and its critical mode of instability. The boundary conditions are defined according to figure 5, and it is important to emphasize the use of a high thickness surface of the web of the track to simulate an interface beam normally used at the top of the wall and also the restraints of the screws in the parallel direction to the base of the wall (direction X). The 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. In this case the first eigenvalue was selected, with a mode of local instability (local buckling of the web). The maximum displacement value was also considered for the definition of the scale factor to stablish the geometric imperfections of the structure [5].

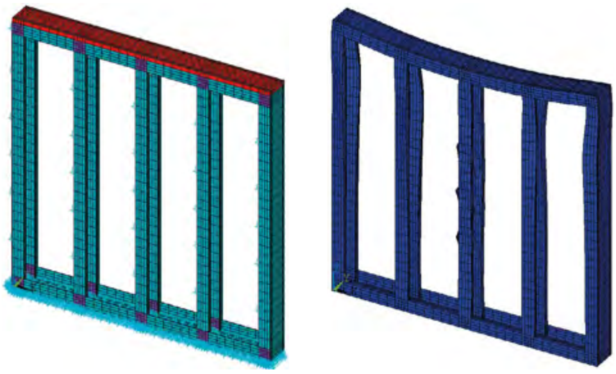

a) b)

Figure 5. a) Finite element model. b) Mode of instability.

In the second step, the geometric imperfection is included into the model as well as the law of mechanical behaviour of the resistant materials. At this stage, only the light steel frame is responsible for the

loadbearing capacity of the wall. All other materials, that may contribute to the strength and collapse mode of the structure [6], will not be considered for the determination of the loadbearing capacity. An incremental and iterative method was applied to determine the loadbearing capacity. This solution allows to determine the potential mode of failure of the wall structure and the value of its loadbearing capacity. In figure 6 the deformed shape is shown for the maximum value of the loadbearing capacity. The deformed mode confirms the existence of local instability mode in the web and also a distortional instability mode in the upper part of the studs. The yield stress of the material was reached in some parts of the steel structure. 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.

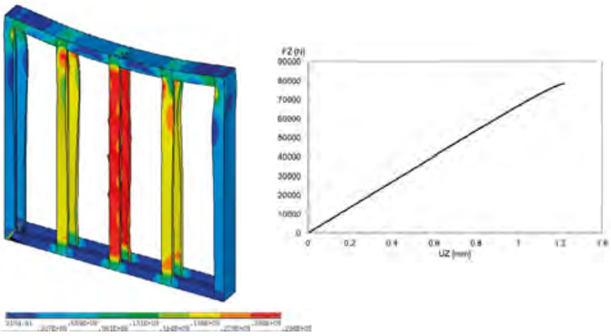
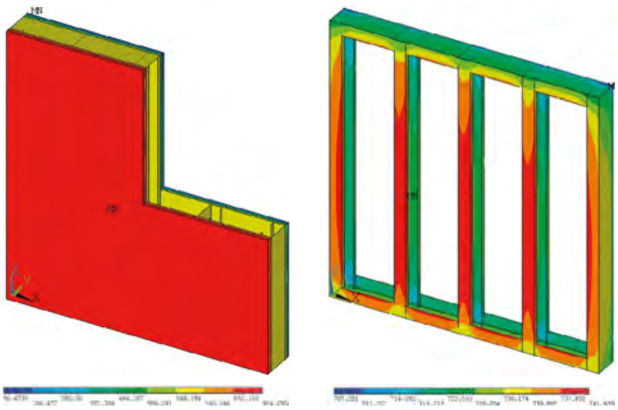


Figure 6. Equivalent von Mises stress for the maximum load value.

In the third step, the thermal model of the wall was validated. Finite elements of multilayer shell and solid elements were used to represent the protection layers. The appropriate boundary conditions were used according to the test and according to the document on actions in structures submitted to standard fire [7]. In the inner zone of the cavity, the conditions of heat transfer by convection and radiation were considered, being the cavity temperature determined with the average value of the measurements made by the plate thermocouples TP1 to TP4. In this way and with high accuracy, the effect of the cracking or damage of the plaster boards is considered and also the effect of the ignition of the combustible material. The thermal properties of the materials were considered temperature dependent t. 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 [8], but duly adjusted with the values determined at room temperature [9]. The variation of the thermal properties of the steel were assumed to vary with the temperature according to Eurocode 3 part 1.2 [10]. The thermal solution was considered transient and nonlinear, using an incremental process in the time step of 60 s, with the possibility of reduce to 1 s. Figure 7 shows the temperature field for the critical time in the complete model of the wall and on the steel structure.

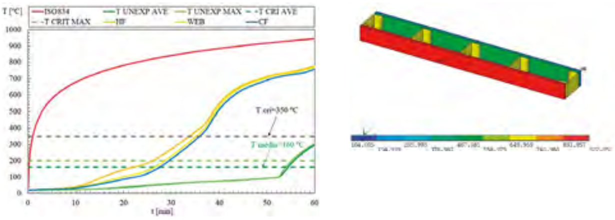


a) Wall temperature.

b) Temperature in the steel structure.

Figure 7. a) temperature fields for critical time (t=54.4 min).

The temperature evolution on the unexposed surface allows to validate the numerical model and the fire resistance time (I). The critical time value obtained in the experimental trial for the maximum temperature was 51 min and for the average temperature was 55 min. The numerical model presents a critical time of 54 min when the average value is used and 55 min when the maximum value is used. Figure 8 shows the temperature evolution on the unexposed surface and also the average values of the exposed flanges (HF), web (WEB) and unexposed flanges (CF) temperatures. This figure also shows the temperature of the wall for the region (Z = 0.5 m).



a) b)

Figure 8. Numerical temperature results. a) Simulation for 60 min. b) Temperature in the profile and in the plasterboard for the critical time (54 min).

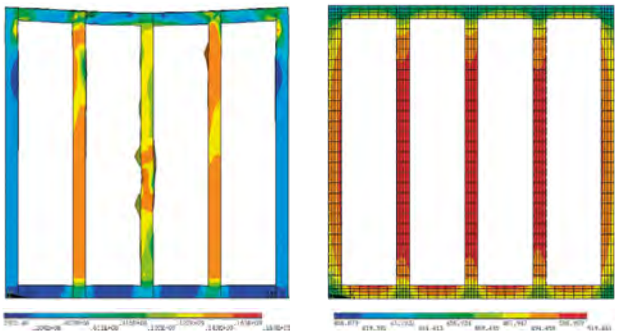
In the fourth step, an estimate of the fire resistance (R) for different load levels, corresponding to a degree of utilization variable between 40 and 80%, is made in relation to the value of the loadbearing capacity of the steel structure at room temperature. The model uses an iterative and incremental static analysis, based on a nonlinear, geometric and material model. The restraints for the displacements are exactly the same as those considered in the previous structural steps. It is assumed that plaster and cork boards do not contribute to the determination of loadbearing capacity. A perfectly elastic plastic material behaviour model is also used at elevated temperatures [11].

The time of fire resistance decreases with the increase of the load level to which is the wall is submitted. Results include the time in complete minutes and the average critical temperature value in the steel structure, see table 1.

Table 1. Fire resistance of the loadbearing wall submitted to different load levels.

LOAD LEVEL [%]	Critical time [min]	Steel minimum temperature [ºC]	Steel maximum temperature [ºC]	Steel average temperature [ºC]
40	41	513	612	562
50	39	445	557	501
60	38	406	519	462
70	36	333	433	383
80	32	238	341	289

The ultimate limit state of the wall is shown In figure 9, for a load level of 60% FZ and when submitted to a standard fire curve.



a) b)

Figure 9. Numerical results for a load level of 60%. a) The von Mises stress for critical time (38 min). b) Temperature in the steel structure for the critical time (38 min).

4. Conclusions

An experimental method was presented to determine the fire resistance for walls built with cold – formed steel, protected by composite materials of plasterboard and cork. The fire resistance time and the fire rating to the insulation capacity (I) was determined.

A hybrid method was also presented for determining fire resistance for the same type of walls in the loadbearing domain. This method requires the use of the heating curves developed in the cavities of the structure and a validation of the numerical model. The fire resistance time and the fire rating (R) were demonstrated. This hybrid method has the great advantage of enabling the prediction of the cracking of the materials and the ignition of the combustible materials. ■

Acknowledgments

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