Research Programme of the Research Fund for Coal and Steel

FIre and Seismic performances of Hybrid fire WALLs in case of single-storey industrial and commercial steel buildings (FISHWALL)

Thermal Analysis of steel members protected by sandwich panels

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EFECTIS FRANCE

WP3: Fire behaviour of a hybrid fire wall solution associated with unprotected steel structure

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Contributing partners		
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ABSTRACT

It is well known that the intrinsic fire resistance of single-storey unprotected steel-framed buildings is sufficient to guarantee the evacuation of occupants in the event of fire. In consequence, for this type of building, the main concern of national fire regulations in Europe is how to prevent the spread of fire to the whole building. To achieve this objective, two performances shall be usually satisfied, namely, the appropriateness of constructive systems to ensure that there is no progressive collapse between fire compartments, and the efficiency of fire walls to stop the fire inside the initial compartment regardless of the state of structures exposed to fire. In practice, many constructional solutions can be implemented in order to preserve the integrity of the fire walls, while accepting that the fire exposed part of the structure may collapse. One of the most common solutions is to place a non-load bearing wall between two independent steel structures and to connect it to them by means of "fusible" links. In fire situation, these fusible links have to allow the wall to be disconnected from the structure affected by fire without endangering the separating function of the wall, which shall remain fixed to the steel structure on the other side of the wall and therefore not exposed to fire. However, due to the lack of corresponding scientific evidence, questions are being very often raised about the real efficiency of such systems in fire situation, which, in certain cases, have also to provide an adequate seismic resistance, if they are used in seismic areas.

Today, concrete or masonry wall solutions are frequently used for the compartmentation of buildings, predominately for low-rise commercial and industrial steel buildings. However, as an alternative, lightweight sandwich panels (comprising two thin flat metal faces and an insulated core) could become an appropriate steel fire wall solution, offering numerous benefits in comparison to other solutions, including fire resistance, durability, flexibility, easy dismounting and fast construction times. But, there is an evident lack of technical information about the adequate fire performance of such type of wall solutions when they are implemented in single-storey buildings with unprotected steel structure, which constitutes a major obstacle for their large use.

In this context, the overall goal of the FISHWALL project is to develop a design guidance and recommendations for an innovative hybrid fire wall solution based on lightweight steel-faced sandwich panels associated with unprotected steel structure under both fire and seismic actions, but considered individually. This will be achieved through the following specific tasks:

i) Establishing of a full range of experimental evidence about the fire and seismic behaviour of the investigated hybrid fire wall solution by carrying out a number of tests;

ii) Investigating intensively the fire and seismic performances of the above hybrid fire wall solution in combination with unprotected single-storey steel structures through a variety of parametric numerical studies by means of validated FE numerical models;

iii) Developing both cost-effective and innovative “fusible” connection systems for fire walls to be used in combination with unprotected steel structures of single-storey buildings;

iv) Developing a design guidance and practical recommendations for the studied hybrid fire wall and fusible links solutions, on the basis of above studies, from which engineers can carry out very efficient design.

The present report aims at summing up the results of the thermal analysis carried out by the Testing Laboratory of EFECTIS FRANCE according to the standard EN 13381-4 [3] on steel members fire-protected with sandwich panels provided by EUROCLAD using data coming from the fire test ([1], [2]) . The detailed report is provided in Appendix A of the report.

1 INTRODUCTION

In order to prevent the spread of fire inside buildings, fire safety regulations commonly require buildings to be divided into several zones of limited size and separated by means of partition fire walls. Among the possible wall solutions, the compartmentation of single-storey steel-framed buildings can be achieved by implementing directly the wall into the building and to solidly fix it to the main steel structure, which remains continuous at the position of fire wall. In such situation, any structural member supporting the partition fire wall solidly attached to the building structure should also have the same fire resistance as that required for the wall to preserve the integrity and insulation performance of the separating element. Fire resistance is frequently achieved by applying fire protection to the structural members but common passive fire protections, such as sprayed materials or intumescent coatings. In addition to aesthetic and maintenance problems, such fire protection can add significantly to the cost of the construction, in particular for high fire resistance rating. Due to an easy and fast implementation, sandwich panels forming the partition fire wall could also be used as a low-cost encasement fire protection system (which can be prefabricated by bending the panels) for its supporting steel members, as alternative to common passive fire protections, avoiding the involvement of any other subcontractor.

In this context, a set of two standard fire tests was carried out at the ISO 17025 accredited for Testing Laboratory of PAVUS on steel members fire-protected by an encasement system provided by EUROCLAD made of a single layer of sandwich panels to demonstrate that structural steel members could be adequately fire protected with such type of panels ([1], [2]). The tests were performed according to EN 13381-4 [3].

The current report aims at summing up the results of the thermal analysis carried-out on data coming from these tests for evaluating the contribution of the investigated encasement system to the fire resistance of structural members. The corresponding technical report provided by the ISO 17025 accredited for testing fire laboratory Efectis France is given in Appendix A.

2 TESTS SPECIMENS

Only a short description of both tests specimens and test arrangements is given hereafter. Further detailed information is specified in the fire test report Pr-23-2.025-En [1] provided by PAVUS and the corresponding deliverable 2.8 [2].

A sandwich panel is made of two opposite steel facings glued onto a core made of mineral (stone) wool.

During the test design, it was planned to test different panel thicknesses for the encasement system, ranging from 100 to 300 mm to cover most of thicknesses of the sandwich panel ranges selected for fire tests. In total, two pairs of loaded and unloaded I-shaped steel beams (with 3 fire exposed sides) as well as thirteen unloaded short I-shaped steel columns (with 4 fire exposed sides) with various section factors (from 51 to 220 m^{-1}) and different protection thickness were tested (as listed in Table 1). The specimens were selected according to EN 13381-4 [3].

It should be noted that sandwich panels were cut to the required dimensions according to the protected steel section. They were fixed either directly to the steel profiles (to the flanges) or using secondary supporting steel systems (mounted to the web) using stainless screws. Four screws were used per panel. The secondary supporting steel systems were made from steel U profiles and, when appropriate, with additional L-shaped profiles depending on the thickness of the panel and the size of the steel profile tested. Some glue was locally applied between the panel joints and between the sandwich panels and the steel profiles.

Fire tests were conducted according to EN 13381-4 [3], recording two sets of data during the tests: temperatures of fire and steel profiles and deflection of loaded steel beams according to the standard provisions. The overall behaviour of test specimens (steel members and protection system) was also monitored visually.

Table 1: List of test specimens

Specimen	Cross-section size	Section factor A_p/V (m^{-1})	Section Range factor k_s	Range of k_s	Panel thickness d_p (mm)	Thickness range factor k_d	Range of k_d
LBmin	IPE 400	121.0	0.414	0.2 to 0.8	100.0	-	-
RBmin	IPE 400	121.0	0.414	0.2 to 0.8	100.0	-	-
LBmax	IPE 400	121.0	0.414	0.2 to 1.0	300.0	-	-
RBmax	IPE 400	121.0	0.414	0.2 to 1.0	300.0	-	-
SIC1	HEM 280	51.0	0.000	0.0	100.0	0	0
SIC2	HEM 280	51.0	0.000	0.0	175.0	0.375	0.2 to 0.5
SIC3	HEM 280	51.0	0.000	0.0	240.0	0.700	0.5 to 0.8
SIC4	HEA 300	110.0	0.349	0.2 to 0.5	100.0	0.000	0.0
SIC5	HEA 300	110.0	0.349	0.2 to 0.5	240.0	0.700	0.5 to 0.8
SIC6	HEA 300	110.0	0.349	0.2 to 0.5	300.0	1.000	1.0
SIC7	HEA 220	140.0	0.527	0.5 to 0.8	100.0	0.000	0.0
SIC8	HEA 220	140.0	0.527	0.5 to 0.8	175.0	0.375	0.2 to 0.5
SIC9	HEA 220	140.0	0.527	0.5 to 0.8	240.0	0.700	0.5 to 0.8
SIC10	HEA 220	140.0	0.527	0.5 to 0.8	300.0	1.000	1.0
SIC11	IPE 200	220.0	1.000	1.0	175(100*)	0.375	0.2 to 0.5
SIC12	IPE 200	220.0	1.000	1.0	240.0	0.700	0.5 to 0.8
SIC13	IPE 200	220.0	1.000	1.0	300.0	1.000	1.0

LB : loaded beam – RB : Reference unloaded beam – SIC : Short unloaded I column

*) Thickness change agreed by partners

k_s and k_d are defined in the test method EN 13381-4 [3]

3 TESTS RESULTS

Detailed test results are reported in the fire test report Pr-23-2.025-En [1] provided by PAVUS and the corresponding deliverable 2.8 [2].

Based on first test results discussed during the meeting held at Trento in February 2023, it should be noted that partners indicated that unanticipated or unforeseen shadow effects could have affected advantageously the heating of steel profiles during the first fire test, by limiting it, because of the small space separating the steel specimens protected with the highest panel thicknesses (as illustrated in Figure 1). Thus, partners expressed doubts about the accuracy of temperatures recorded for the specimens protected with 300mm thick panels and judged the results as inoperable. Consequently, partners agreed that some changes were needed for the second test in order to be able to conduct a thermal analysis of test results according to the standard EN 13381-4 [3], as planned. Since the specimens were already mounted and taking into account that a complete modification of the setup was impossible, it was decided to only change the panel thickness applied around some specimen, changing the thickness to 100 mm on one specimen in order to fit the requirement of the standard EN 13381-4 [3], ensuring also sufficient spacing between specimens.

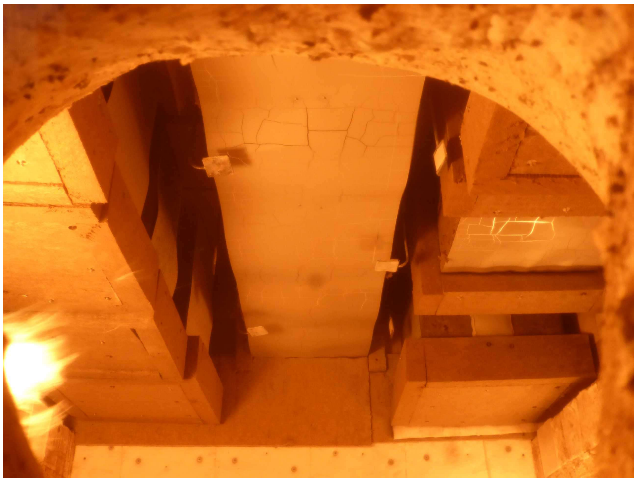

Figure 1: Views of the test specimens during the first fire test

It can be remembered that during the test no significant damage of the tested encasement system were noted on short specimens, only disbonding of the fire-exposed steel sheets from mineral wool of the sandwich panels during both tests. In addition, a detachment of wool from the bottom flange of the loaded beam protected with the minimum panel thickness, namely 100mm was observed due to the large beam deflection at 140 minutes which occurred after the removal of the load on the loaded beam as it reach its loadbearing capacity at 122 mm.

a) Disbonding of the fire-exposed steel sheets of sandwich panels

b) Falling down of protection from the bottom flange of the loaded beam

Figure 2: Views of test specimens after the tests

4 THERMAL ANALYSIS

The thermal analysis was done according to the standard EN 13381-4 [3] and its detailed results are reported in Appendix of the present report. As already mentioned, the modifications that had to be made to the second test of Task 2.3 don't allow to take account all temperatures data recorded during the tests as originally planned, but only those recorded for steel members fire protected with the 100mm thick panels. Thus, only a limited part of test data was used in the analysis corresponding to the test specimens listed in the following table:

Table 2: List of test specimens

Specimen	Cross-section size	Section factor A_p/V (m^{-1})	Section Range factor k_s	Range of k_s	Panel thickness d_p (mm)	Thickness range factor k_d	Range of k_d
LBmin	IPE 400	121.0	0.414	0.2 to 0.8	100.0	-	-
RBmin	IPE 400	121.0	0.414	0.2 to 0.8	100.0	-	-
SIC1	HEM 280	51.0	0.000	0.0	100.0	0	0
SIC4	HEA 300	110.0	0.349	0.2 to 0.5	100.0	0.000	0.0
SIC7	HEA 220	140.0	0.527	0.5 to 0.8	100.0	0.000	0.0
SIC11	IPE 200	220.0	1.000	1.0	175(100*)	0.375	0.2 to 0.5

LB : loaded beam – RB : Reference unloaded beam – SIC : Short I column

*) Thickness change agreed by partners

The thermal analysis was done in three steps according to the standard EN 13381-4 [3]:

1. A correction of the data based on the comparison between results of the loaded beams and results of the unloaded beams tested which gives the stickability factor to correct the time to reach a steel temperature coming from the short specimens,
2. Then, a thermal analysis, based on one of the available methods of the standard EN 13381-4 [3], using the thermal data, corrected or uncorrected depending on the analysis method used, coming from the short sections.
3. And to finish, the result of the thermal analysis from step 2 are compared to the corrected data coming from step 1 and have to fit some acceptability criteria. If the criteria are not fitted, modification of the analysis should be made until the criteria of acceptability are met.

First, to take into account the "stickability" performance of the tested encasement system, the thermal data for the selected short samples (SIC1, SIC4, SCI7 and SIC11) were corrected with the stickability factor issued from the comparison between the results from the loaded beam and its reference beam tested (LBmin and RBmin). This has been done using stickability factors according to Annex D of EN 13381-4 [3], which have been determined by comparing the time for the loaded beam to reach a specified temperature with the time for the equivalent short reference beam (RBmin). The correction (stickability) factor k was calculated as the ratio between the time for the unloaded beam to reach a specified temperature and the time for the loaded beam to reach the same temperature. As the beams have not exactly the same section factor, the difference of section factor was taken into account in the calculation.

According to the standard EN 13381-4, the stickability factor is calculated using the formula:

$$k = \frac{t_l}{t_1 \times \frac{S_1}{S} \times \frac{D}{D_1}}$$

where

- t_l is the time for the loaded section to reach the design temperature.
- t_1 is the time for the reference section to reach the design temperature;
- S is the section factor of the loaded section;
- S_1 is the section factor of the reference section;
- D is the protection thickness for the loaded section;
- D_1 is the protection thickness for the reference section.

Where the stickability factor is greater than one, a stickability factor of one is used.

The stickability factors for all design temperatures above the temperature at which the loaded section lose its loadbearing capacity is based on a lowest value derived as follows:

- Calculation of the factor at a temperature equal to 100 °C below that at which loadbearing capacity failure occurred;
- Calculation of factors for intermediate temperatures at intervals of 10 °C in the same way;
- Selection of the lowest value, which is used for the data correction for design temperatures above that at which loadbearing capacity failure occurred.

The corrections factor thus calculated are reported in Figure 3.

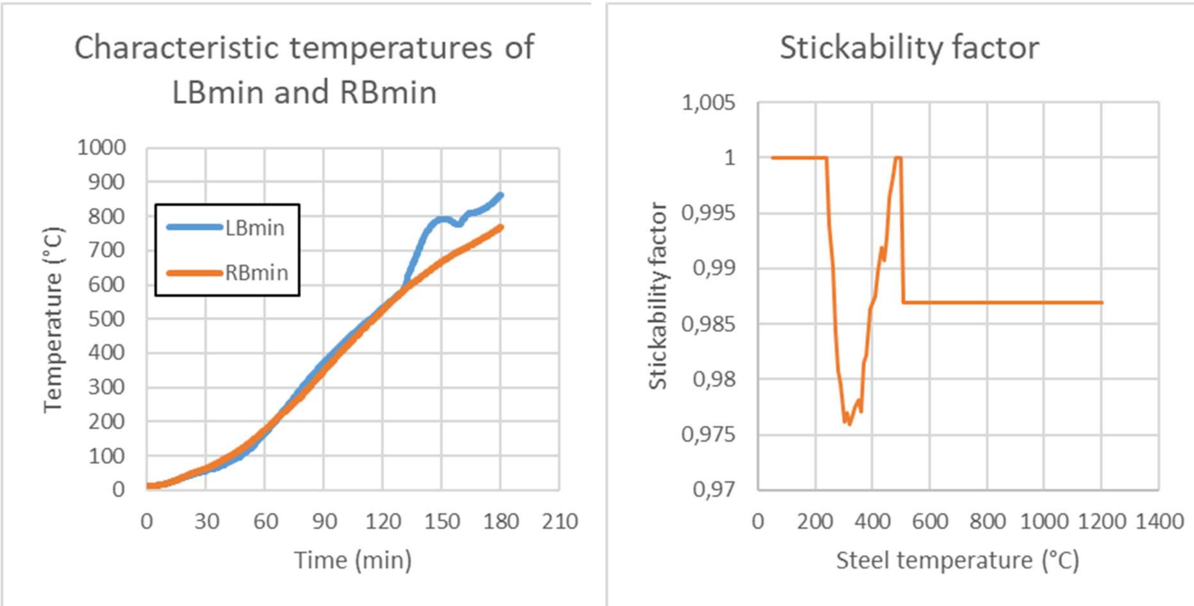

Figure 3: Temperatures of LBmin and RBmin and stickability factor obtained.

Then, the times for the short sections to reach the specified temperatures are corrected using the appropriate stickability factor and the corrected times are used as input data in the analysis:

$$Corrected\ time\ for\ the\ short\ section\ =\ k_i\ \times\ time\ to\ reach\ the\ design\ temperature$$

Based on the measurements recorded during the test, the uncorrected time to reach the steel temperature was:

Nr	**Profile**	**Section factor (m^{-1})**	**Th (mm)**	**Uncorrected time (min) to reach the steel design temperature (°C)**								
				350	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
SIC 11	IPE 200	224,7	100	43,8	47,5	51	54,8	59	63,7	69,3	75,3	83
SIC 7	HEA 220	143,3	100	73,5	82	90,5	99,7	109,8	120,5	132	145,2	163,3
SIC 4	HEA 300	115,1	100	95,5	106,8	118,8	131	144,5	158,8	174		
SIC 1	HEM 280	52,2	100	109,3	122,8	136,3	150,3	165				

Applying the stickability factor coming from the relation between the loaded beam and its reference beam, the correction times are:

Nr	**Profile**	**Section factor (m^{-1})**	**Th (mm)**	**Corrected time (min) to reach the steel temperature (°C)**								
				350	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
SIC 11	IPE 200	224,7	100	42,9	46,9	50,6	54,8	58,2	62,8	68,4	74,3	81,9
SIC 7	HEA 220	143,3	100	71,9	80,9	89,9	99,7	108,4	118,9	130,3	143,3	161,2
SIC 4	HEA 300	115,1	100	93,4	105,4	118	131	142,6	156,8	171,7		
SIC 1	HEM 280	52,2	100	106,9	121,2	135,4	150,3	162,8				

Then, the thermal analysis could be done using one of the four existing methods described in the standard EN 13381-4 [3]. Each of them was discussed during the 2nd meeting held in February 2023, and all partners agreed that linear regression and variable thermal conductivity approaches should be used and compared in order to select the final one. During the conference call dated 12th of June, 2023, the linear regression approach was selected as the results of each method were not so different and this method seems to be the most used in all fire laboratories in Europe despite the variable thermal conductivity approach has more common points with the Eurocode 3 part 2, EN 1993-1-2 [4].

The numerical analysis according to "Numerical Regression Analysis" approach was performed according to Annex E.5 of the standard EN 13381-4 [3]. The inputs for the analysis were :

- the design temperatures;
- the corrected times to reach the design temperatures of short specimens;
- the calculated section factor of the steel members;
- the thickness of the protection material only.

The multiple linear numerical regression analysis was conducted using Formula (F.1):

$$t = a_0 + a_1 d_p + a_2 \frac{d_p}{A_m/V} + a_3\theta_a + a_4 d_p \theta_a + a_5 d_p \frac{\theta_a}{A_m/V} + a_6 \frac{\theta_a}{A_m/V} + a_7 \frac{1}{A_m/V} \qquad [F.1]$$

Where:

t	is the time to reach the design temperature (min);
d_p	is the thickness of the protection material (mm);
A_m/V	is the measured section factor (m^{-1});
a_0 to a_7	are the regression coefficients;
θ_a	is the steel temperature

Regression coefficients were obtained by solving the regression formula using all the test data for the design temperatures for which the analysis was carried-out, ranging from 350°C to 750°C with 50°C intervals.

Coefficients	Values
a_0	61,43814308
a_1	0
a_2	-76,38309891
a_3	0
a_4	-0,000276279
a_5	0,28535786
a_6	0
a_7	0

It should be noted that having a value "0" for some coefficients is normal as the analysis was made for the thickness 100 mm only.

Using the formula F.1, the calculated (predicted) time to reach the design temperature were:

Nr	Profile	Section factor (m^{-1})	Th (mm)	Predicted time (min) to reach the steel temperature (°C) without modification								
				350	400	450	500	550	600	650	700	750
SIC 11	IPE 200	224,7	100	62,2	67,2	72,2	77,1	82,1	87,1	92	97	102
SIC 7	HEA 220	143,3	100	68,2	76,7	85,3	93,9	102,5	111	119,6	128,2	136,8
SIC 4	HEA 300	115,1	100	72,2	83,2	94,2	105,2	116,2	127,3	138,3	149,3	160,3
SIC 1	HEM 280	52,2	100	96,8	122,7	148,7	174,6	200,6	226,5	252,5	278,4	304,4

The results coming from the correction of the short section and the thermal analysis are then compared according to criteria given by the standard EN 13381-4 [3]. If the comparison does not fit the requirements of the criteria, the thermal analysis must be modified accordingly.

The acceptability of the analysis within the range of steel section temperature and duration of the test shall be assessed up to the maximum temperature tested on the following basis:

a) For each short section, the predicted time in minutes to reach the design temperature calculated to one decimal place shall not exceed the corrected time by more than 15 %.

b) The mean value of all percentage differences as calculated in a) shall be less than zero.

c) A maximum of 30 % of individual values of all percentage differences as calculated in a) shall be more than zero.

d) The results of the analysis which satisfy a) to c) above shall also comply with the following "logic" rules provided all other parameters remain constant:

  1) The thickness of fire protection material increases with fire resistance duration.

  2) As the section factor increases the fire resistance time decreases.

  3) As fire resistance time increases the temperature increases.

  4) As thickness increases temperature decreases.

  5) As section factor increases the temperature increases.

Before any modification of the regression coefficients a_0 to a_7, the results of the comparison were not suitable:

Nr	Profile	Section factor (m^{-1})	Th (mm)	Deviation, in %, between predicted times and corrected test times								
				350	400	450	500	550	600	650	700	750
SIC 11	IPE 200	224,7	100	45,12	43,33	42,51	40,66	40,99	38,57	34,50	30,47	24,49
SIC 7	HEA 220	143,3	100	-5,19	-5,18	-5,05	-5,80	-5,47	-6,63	-8,18	-10,52	-15,16
SIC 4	HEA 300	115,1	100	-22,73	-21,10	-20,15	-19,68	-18,49	-18,82	-19,48		
SIC 1	HEM 280	52,2	100	-9,51	1,24	9,84	16,16	23,18				

And from all the deviations above:

Criterion	Description	Value	Result
a)	Predicted time for each element ≤ 15% larger than corrected time	45,12 %	FAILED
b)	Mean value of all percentage differences < 0%	5,80 %	FAILED
c)	Maximum of 30% of values > 0%	43,3 %	FAILED
d)	Results must be "logic"		PASSED

The regression coefficients must be modified using a modification factor X lower than 1 which, when applied to all the regression coefficients , leads the predicted times to just meet the acceptance criteria. "X" must be determined by iteration and with X=0.792, new regression coefficients were obtained as well as new predicted times and deviations.

Coefficients	Initial values	Modified values
a_0	61,43814308	48,65900932
a_1	0	0
a_2	-76,38309891	-60,49541434
a_3	0	0
a_4	-0,000276279	-0,000218813
a_5	0,28535786	0,226003425
a_6	0	0
a_7	0	0

Nr	Profile	Section factor (m^{-1})	Th (mm)	Calculated time (min) to reach the steel temperature (°C) with modification								
				350	400	450	500	550	600	650	700	750
SIC 11	IPE 200	224,7	100	49,3	53,2	57,2	61,1	65	69	72,9	76,8	80,8
SIC 7	HEA 220	143,3	100	54	60,8	67,6	74,4	81,2	87,9	94,7	101,5	108,3
SIC 4	HEA 300	115,1	100	57,2	65,9	74,6	83,3	92,1	100,8	109,5	118,2	127
SIC 1	HEM 280	52,2	100	76,6	97,2	117,8	138,3	158,9	179,4	200	220,5	241,1

Nr	Profile	Section factor (m^{-1})	Th (mm)	Deviation, in %, between predicted times and corrected test times								
				350	**400**	**450**	**500**	**550**	**600**	**650**	**700**	**750**
SIC 11	IPE 200	224,7	100	14,94	13,52	12,87	11,40	11,67	9,74	6,52	3,33	-1,41
SIC 7	HEA 220	143,3	100	-24,91	-24,90	-24,80	-25,39	-25,13	-26,05	-27,28	-29,14	-32,80
SIC 4	HEA 300	115,1	100	-38,80	-37,51	-36,76	-36,38	-35,45	-35,71	-36,23		
SIC 1	HEM 280	52,2	100	-28,33	-19,82	-13,01	-8,00	-2,44				

Criteria	Description	Value	Result
a)	Predicted time for each element ≤ 15% larger than corrected time	14,94 %	PASSED
b)	Mean value of all percentage differences < 0%	-16,21 %	PASSED
c)	Maximum of 30% of values > 0%	26,7 %	PASSED
d)	Results must be "logic"		PASSED

Once the analysis is acceptable according to the requirements of the standard EN 13381-4 [3], tables specifying the minimum required thickness required for a given section factor for each required fire resistance period and for each steel design temperature were developed using a transposition of the formula [F.1]:

$$d_p = \frac{t - a_0 - a_3\theta_a - \left(\frac{a_6\theta_a}{A_m/V}\right) - \left(\frac{a_7}{A_m/V}\right)}{a_1 + a_4\theta_a + \left(\frac{a_2}{A_m/V}\right) + \left(\frac{a_5\theta_a}{A_m/V}\right)}$$

The final tables coming from the analysis are given in the technical report EFR-21-003868 provided by the fire laboratory Efectis France, see Appendix A.

5 CONCLUSIONS

The present report aims at summing up the results of the thermal analysis carried out by the Testing Laboratory of EFECTIS FRANCE according to the standard EN 13381-4 [3] on steel members fire-protected with sandwich panels using data coming from the fire test Pr-23-2.025-En [1],[2].

The thermal analysis confirmed that the encasement system with sandwich panels supplied by EUROCLAD provides an efficient fire protection of steel members. However, it had to be limited to the protection encasement system with 100 mm thick panels only, because of suspicions that unforeseen shadow effects may have happened during the fire test on thicker panels.

From test data, the thermal analysis allowed to provide several tables to easily determinate for steel members fire-protected with the 100 mm thick panels encasement system, the steel section factors to meet the wanted fire resistance rating according to the defined design temperature (i.e. the critical temperature of the considered steel members). Results of the undertaken assessment are valid for the following conditions:

- both three or four sided protections;
- Steel section factor until 247 m^{-1};
- Steel temperature ranging between 350 to 750°C;
- Fire resistance rating ranging from R15 to R120;

It should be noted that a wider scope including thicker protection panels could be easily possible by performing an additional fire resistance test.

6 REFERENCES

[1] Fire resistance test report n° Pr-23-2.025-En for determining the contribution to the fire resistance of steel members by applied passive protection - single-layer fire protection system made of sandwich panels Eurobond Rockspan Extra, Rainspan and Firemaster Extra, 27-02-2023, PAVUS.

[2] Jiří Vaněk, Deliverable D2.8: Fire test report on steel members fire protected by sandwich panels, RFSC project FISHWALL, 2023.

[3] EN 13381-4 Test methods for determining the contribution to the fire resistance of structural members — Part 4: Applied passive protection to steel members, Brussels, Belgium, CEN, 2013.

[4] EN 1993-1-2 Eurocode 3 - Design of steel structures - Part 1-2: general rules - Structural fire design, Brussels, Belgium, CEN, 2005.

APPPENDIX A. TECHNICAL REPORT N°EFR-21-003868

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TECHNICAL REPORT

TECHNICAL REPORT n°

According to EN 13381-4:2013

Reference test reports
- Pavus Pr-23-2.025-En

Scope
Thermal analysis of steel structures protected by sandwich panels reference FIREMASTER EXTRA :
- Thickness of protection : 1 x 100 mm
- Section factor : from ≤ 47 to 247 m^{-1}

Sponsors

This document does not represent type approval or certification of the product.

1. SCOPE

Determination, according to the characterization methodology of protective materials as indicated by the European standard EN 13381-4 "Test method for determining the contribution to the fire resistance of structural members - Part 4: Applied passive protection to steel members", of the temperatures of steel members exposed to the conventional fire according to their section factors, the thickness of protective material and the duration of the exposure.

2. DESCRIPTION

2.1. GENERALITY

The steel members are protected by by a boxed protection system made with sandwich panels reference FIREMASTER EXTRA and 100 mm thickness.

2.2. COMPONENTS LIST

Description	Reference	Material	Characteristics	Supplier
Sandwich panel	FIREMASTER EXTRA	Stone wool core and metal sheets	Th= 100 mm d= 186 kg/m^3	EUROCLAD
Screws	DrillFast DF12-SSA4-HT-6.3	Stainless steel	Ø 6.3 mm	FIXFAST LTD
U steel profile		Steel		
L-shaped profile		Steel		
Glue	FIREPRO Glue			ROCKWOOL LIMITED

Th = Thickness --- d = Density

2.3. STEEL MEMBERS

Protection system can be applied on steel profiles:

- Any structural grade of steel (S designation) to EN 10025-1 (excluding S185)
- With section factors between ≤ 47 and 247 m^{-1}
- Kind of profile:
  - I/H shaped steel members;
  - Hollow sections (SHS) (rectangular, square or circular sections) with protective material required thicknesses for the same section factor;
  - Angles, channels or T-sections for the same section factor, whether used as individual elements or as bracing.

2.4. Application of the protective material

The panels can be installed in single layers only.

The installation of the protection depends on the number of sides to be protected.

Sandwich panels are cut to the required dimensions according to the protected steel section.

They are fixed either directly to the steel profiles (to the flanges) or either using secondary supporting steel systems (to the web), with stainless steel selfdrilling screws DrillFast DF12-SSA4-HT-6.3 (FIXFAST LTD) with a Ø of 6.3 mm.

A minimum of 4 screws are used per panels.

The secondary supporting steel systems are mounted between the flanges of tested steel profiles.

They are made from steel U profiles with section 100 x 60 x 2 mm and, with additional L-shaped profiles depending on the thickness of the panel and the size of the steel profile tested.

Sandwich panels are locally glued with adhesive FIREPRO Glue (ROCKWOOL LIMITED) inside the joints between sandwich panels themselves and also between the sandwich panels and the steel profiles.

2.5. Characteristics of the protection product

Characteristics	Data
Thickness of protection	▪ 1 x 100 mm
Mean density	▪ 186 kg/m^3

3. ASSESSMENT METHOD

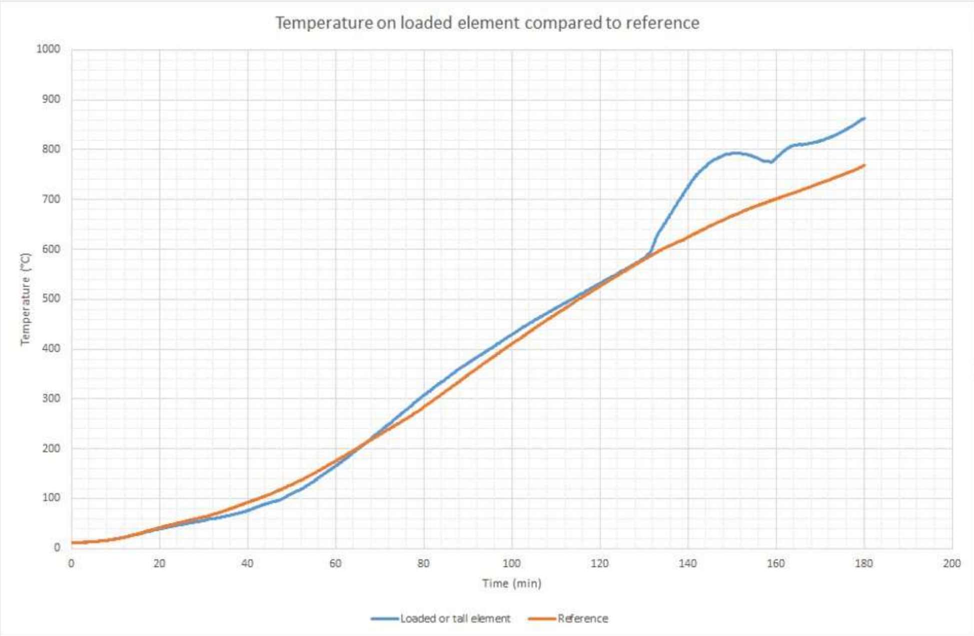
The assessment method used to assess the protective material is « Numerical regression », as described in Annex E.5 of standard EN 13381-4:2013.

3.1. List of tested elements

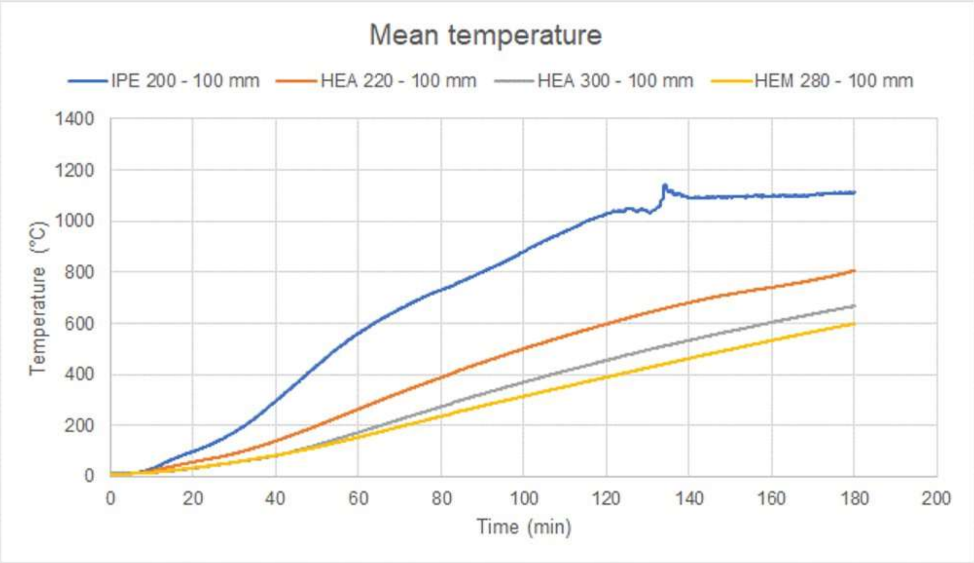
Elements	Test n°	Date of the test	Section	Protection	Section factor (m^{-1})
Loaded beam	Pr-23-2.025-En	13/02/2023	IPE 400	1 x 100 mm	127.7
Reference beam	Pr-23-2.025-En	13/02/2023	IPE 400	1 x 100 mm	125
Column 1	Pr-23-2.025-En	13/02/2023	IPE 200	1 x 100 mm	224.7
Column 2	Pr-23-2.025-En	13/02/2023	HEA 220	1 x 100 mm	143.3
Column 3	Pr-23-2.025-En	13/02/2023	HEA 300	1 x 100 mm	115.1
Column 4	Pr-23-2.025-En	13/02/2023	HEM 280	1 x 100 mm	52.2

3.2. Reference steel temperatures

3.2.1. Characteristic temperatures of IPE 400 beams



3.2.2. Mean temperature of short columns



3.3. Correction factors

Steel temperature (°C)	Correction factor determined according to paragraph 13.3. of standard EN 13381-4
	100 mm panel
50	1
60	1
70	1
80	1
90	1
100	1
110	1
120	1
130	1
140	1
150	1
160	1
170	1
180	1
190	1
200	1
210	1
220	1
230	1
240	1
250	0,99398919
260	0,99016615
270	0,98433133
280	0,98082185
290	0,97947216
300	0,97619556
310	0,97700635
320	0,97588638
330	0,97667304
340	0,97743308
350	0,97816784
360	0,977102
370	0,98146571
380	0,98216982
390	0,98631157
400	0,9869107
410	0,98748982
420	0,98972742
430	0,99189273
440	0,99074086
450	0,99282254
460	0,99641418
470	0,99838182
480	1
490	1
500	1
510 to 1000	0,9869107

3.4. CORRECTED TIME TO REACH THE STEEL TEMPERATURE

Nr	Profile	Section factor	Th	Corrected time (min) to reach the steel temperature (°C)								
				350	400	450	500	550	600	650	700	750
1	IPE 200	224,7	100	42,9	46,9	50,6	54,8	58,2	62,8	68,4	74,3	81,9
2	HEA 220	143,3	100	71,9	80,9	89,9	99,7	108,4	118,9	130,3	143,3	161,2
3	HEA 300	115,1	100	93,4	105,4	118	131	142,6	156,8	171,7		
4	HEM 280	52,2	100	106,9	121,2	135,4	150,3	162,8				

3.5. NUMERICAL REGRESSION

The numerical regression used has been determined on the basis of the following equation in accordance with requirements of EN 13381-4 - Annex E.5:

$$t = a_0 + a_1 \times d_p + a_2 \times \frac{d_p}{A_i/V} + a_{\cdot 3} \times \vartheta_{sc} + a_4 \times d_p \times \vartheta_{sc} + a_5 \times d_p \times \frac{\vartheta_{sc}}{A_i/V} + a_6 \times \frac{\vartheta_{sc}}{A_i/V} + a_7 \times \frac{1}{A_i/V}$$

With:

- d_p : thickness of the protection product (mm)
- A_i/V : Section factor of the steel profile (m^{-1})
- ϑ_{sc} : Temperature of the steel profile (°C)

Constants from the analysis are:

Constants	Values
a_0	48,65900932
a_1	0
a_2	-60,49541434
a_3	0
a_4	-0,000218813
a_5	0,226003425
a_6	0
a_7	0

The acceptability of the analysis within the range of steel section temperature and duration of the test shall be judged up to the maximum temperature tested on the following basis:

§ of standard 13381-4	Criteria	Result
		Single layer
13.5 a)	For each short section, the predicted time in minutes to reach the design temperature calculated to one decimal place shall not exceed the corrected time by more than 15 %.	14.94 % *
13.5 b)	The mean value of all percentage differences as calculated in a) shall be less than zero.	-16.21 %
13.5 c)	A maximum of 30 % of individual values of all percentage differences as calculated in a) shall be more than zero.	26.7 %

** maximum of all deviation.*

3.6. Predicted time to reach the steel temperature

Nr	Profile	Section factor	Th	Corrected time (min) to reach the steel temperature (°C)								
				350	400	450	500	550	600	650	700	750
1	IPE 200	224,7	100	49,3	53,2	57,2	61,1	65	69	72,9	76,8	80,8
2	HEA 220	143,3	100	54	60,8	67,6	74,4	81,2	87,9	94,7	101,5	108,3
3	HEA 300	115,1	100	57,2	65,9	74,6	83,3	92,1	100,8	109,5	118,2	127
4	HEM 280	52,2	100	76,6	97,2	117,8	138,3	158,9	179,4	200	220,5	241,1

3.7. Required thickness of protective material

The minimum required thickness of protective material is determined according to:

- The section factor Hp/A (m^{-1}) of the steel members;
- The standard steel limit temperature comprise between 350 and 750 °C;
- The duration of the thermal exposure under the conventional thermal program.

3.7.1. Required minimal thicknesses of protective material to justify R15

Section factor (m^{-1})	Minimum required thickness to reach R15 (mm) — Standard steel temperature (°C)								
	350	400	450	500	550	600	650	700	750
≤ 47	100	100	100	100	100	100	100	100	100
50	100	100	100	100	100	100	100	100	100
60	100	100	100	100	100	100	100	100	100
70	100	100	100	100	100	100	100	100	100
80	100	100	100	100	100	100	100	100	100
90	100	100	100	100	100	100	100	100	100
100	100	100	100	100	100	100	100	100	100
110	100	100	100	100	100	100	100	100	100
120	100	100	100	100	100	100	100	100	100
130	100	100	100	100	100	100	100	100	100
140	100	100	100	100	100	100	100	100	100
150	100	100	100	100	100	100	100	100	100
160	100	100	100	100	100	100	100	100	100
170	100	100	100	100	100	100	100	100	100
180	100	100	100	100	100	100	100	100	100
190	100	100	100	100	100	100	100	100	100
200	100	100	100	100	100	100	100	100	100
210	100	100	100	100	100	100	100	100	100
220	100	100	100	100	100	100	100	100	100
230	100	100	100	100	100	100	100	100	100
240	100	100	100	100	100	100	100	100	100
247	100	100	100	100	100	100	100	100	100

3.7.2. Required minimal thicknesses of protective material to justify R30

Section factor (m^{-1})	Minimum required thickness to reach R30 (mm)								
	Standard steel temperature (°C)								
	350	400	450	500	550	600	650	700	750
≤ 47	100	100	100	100	100	100	100	100	100
50	100	100	100	100	100	100	100	100	100
60	100	100	100	100	100	100	100	100	100
70	100	100	100	100	100	100	100	100	100
80	100	100	100	100	100	100	100	100	100
90	100	100	100	100	100	100	100	100	100
100	100	100	100	100	100	100	100	100	100
110	100	100	100	100	100	100	100	100	100
120	100	100	100	100	100	100	100	100	100
130	100	100	100	100	100	100	100	100	100
140	100	100	100	100	100	100	100	100	100
150	100	100	100	100	100	100	100	100	100
160	100	100	100	100	100	100	100	100	100
170	100	100	100	100	100	100	100	100	100
180	100	100	100	100	100	100	100	100	100
190	100	100	100	100	100	100	100	100	100
200	100	100	100	100	100	100	100	100	100
210	100	100	100	100	100	100	100	100	100
220	100	100	100	100	100	100	100	100	100
230	100	100	100	100	100	100	100	100	100
240	100	100	100	100	100	100	100	100	100
247	100	100	100	100	100	100	100	100	100

3.7.3. Required minimal thicknesses of protective material to justify R45

Section factor (m^{-1})	Minimum required thickness to reach R45 (mm)								
	Standard steel temperature (°C)								
	350	400	450	500	550	600	650	700	750
≤ 47	100	100	100	100	100	100	100	100	100
50	100	100	100	100	100	100	100	100	100
60	100	100	100	100	100	100	100	100	100
70	100	100	100	100	100	100	100	100	100
80	100	100	100	100	100	100	100	100	100
90	100	100	100	100	100	100	100	100	100
100	100	100	100	100	100	100	100	100	100
110	100	100	100	100	100	100	100	100	100
120	100	100	100	100	100	100	100	100	100
130	100	100	100	100	100	100	100	100	100
140	100	100	100	100	100	100	100	100	100
150	100	100	100	100	100	100	100	100	100
160	100	100	100	100	100	100	100	100	100
170	100	100	100	100	100	100	100	100	100
180	100	100	100	100	100	100	100	100	100
190	100	100	100	100	100	100	100	100	100
200	100	100	100	100	100	100	100	100	100
210	100	100	100	100	100	100	100	100	100
220	100	100	100	100	100	100	100	100	100
230	100	100	100	100	100	100	100	100	100
240	100	100	100	100	100	100	100	100	100
247	100	100	100	100	100	100	100	100	100

3.7.4. Required minimal thicknesses of protective material to justify R60

Section factor (m^{-1})	Minimum required thickness to reach R60 (mm)								
	Standard steel temperature (°C)								
	350	400	450	500	550	600	650	700	750
≤ 47	100	100	100	100	100	100	100	100	100
50	100	100	100	100	100	100	100	100	100
60	100	100	100	100	100	100	100	100	100
70	100	100	100	100	100	100	100	100	100
80	100	100	100	100	100	100	100	100	100
90	100	100	100	100	100	100	100	100	100
100	-	100	100	100	100	100	100	100	100
110	-	100	100	100	100	100	100	100	100
120	-	100	100	100	100	100	100	100	100
130	-	100	100	100	100	100	100	100	100
140	-	100	100	100	100	100	100	100	100
150	-	-	100	100	100	100	100	100	100
160	-	-	100	100	100	100	100	100	100
170	-	-	100	100	100	100	100	100	100
180	-	-	100	100	100	100	100	100	100
190	-	-	100	100	100	100	100	100	100
200	-	-	-	100	100	100	100	100	100
210	-	-	-	100	100	100	100	100	100
220	-	-	-	100	100	100	100	100	100
230	-	-	-	100	100	100	100	100	100
240	-	-	-	-	100	100	100	100	100
247	-	-	-	-	100	100	100	100	100

"-" means non applicable

3.7.5. Required minimal thicknesses of protective material to justify R90

Section factor (m^{-1})	Minimum required thickness to reach R90 (mm)								
	Standard steel temperature (°C)								
	350	400	450	500	550	600	650	700	750
≤ 47	-	100	100	100	100	100	100	100	100
50	-	100	100	100	100	100	100	100	100
60	-	-	100	100	100	100	100	100	100
70	-	-	100	100	100	100	100	100	100
80	-	-	100	100	100	100	100	100	100
90	-	-	-	100	100	100	100	100	100
100	-	-	-	100	100	100	100	100	100
110	-	-	-	-	100	100	100	100	100
120	-	-	-	-	-	100	100	100	100
130	-	-	-	-	-	100	100	100	100
140	-	-	-	-	-	-	100	100	100
150	-	-	-	-	-	-	100	100	100
160	-	-	-	-	-	-	-	100	100
170	-	-	-	-	-	-	-	100	100
180	-	-	-	-	-	-	-	-	100
190	-	-	-	-	-	-	-	-	-

"-" means non applicable

3.7.6. Required minimal thicknesses of protective material to justify R120

Section factor (m^{-1})	Minimum required thickness to reach R120 (mm)								
	Standard steel temperature (°C)								
	350	400	450	500	550	600	650	700	750
≤ 47	-	-	100	100	100	100	100	100	100
50	-	-	100	100	100	100	100	100	100
60	-	-	-	100	100	100	100	100	100
70	-	-	-	-	100	100	100	100	100
80	-	-	-	-	-	100	100	100	100
90	-	-	-	-	-	-	100	100	100
100	-	-	-	-	-	-	100	100	100
110	-	-	-	-	-	-	-	100	100
120	-	-	-	-	-	-	-	-	100
130	-	-	-	-	-	-	-	-	-

"-" means non applicable

Maizières-lès-Metz, December 12th, 2023

X Clifford CHINAYA

Project leader
Signé par : Clifford CHINAYA

X Roman CHIVA

Supervisor
Signé par : Roman CHIVA