EXPERIMENTAL AND ANALYSIS OF PRECAST CONCRETE SANDWICH PANELS FAÇADE (PCSPF) SYSTEMS AT ELEVATED TEMPERATURES

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ABSTRACT

Like most structural members, the physical characteristics and resistance of the precast concrete sandwich panels deteriorate at elevated temperatures. These changes promote a considerable loss in the stiffness of the structural system and compromises the integrity of the stainless-steel ties which is a major concern. Therefore, it is imperative to investigate the precast concrete sandwich panels under the fire condition. To understand this concern and to propose an engineering solution, finite element modelling was conducted to simulate the behaviour of precast concrete sandwich panel system under fire conditions using SAFIR which is an advanced computational tool. The mechanical and thermal material nonlinearities of the structural members, such as the concrete walls and reinforcing bars were included in the model. The model used is based on the frame analogy considering a strip of wall to investigate the fire performance focusing on the integrity of the stainless-steel ties of the external wall cladding. The reinforcement stainless-steel tie connectors are considered based on the publication [1] to check the minimum satisfaction of the PCSPF system existing in construction. The model used demonstrated encouraging results for different cases considered during the study and the results from the computational modelling were well aligned with the experimental results.

Keywords: Experimental tests; fire and structures; finite element modelling; precast façade panels

1 INTRODUCTION

Precast concrete sandwich panels Façade (PCSPF) systems are known for their good inherent thermal and acoustic insulating properties. This technology allows the fast construction of energy-efficient and durable buildings. Due to these advantages and the growing need for sustainable solutions, sandwich panels have gained in popularity in industrial and residential construction. Precast concrete sandwich panels are usually composed of two steel- reinforced concrete walls and an insulation layer in between. The outer concrete layer usually does not play any structural role and serves solely as a form of aesthetic protection for the insulating layer. On the other hand, the inner layer concrete layer is load-bearing. The inner and the outer concrete walls are mechanically linked together by means of connectors. The connectors and insulation together constitute the so-called core layer. The inner, load-bearing concrete wall is designed to carry all

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the vertical and bending loads. The design of the connecters in the PCSPF system must be robust and checked at ultimate limit state to satisfy strength, stability, stiffness, serviceability, soundness.
In fire situation, the insulation layer should first ensure the thermal protection of the load- bearing inner layer, stay firm during the fire, and not contribute to fire spread. Further, especially for sandwich walls, the effectiveness of shear transfer during fire, provided by the insulation and connectors, should be assessed, since this gives information about their contribution to the PCSPF system action. Additionally, since the concrete precast walls are produced with different thicknesses, the side of the wall being exposed to fire could potentially impact the behaviour of the connectors.

1.1 Assumptions and objectives

To obtain comprehensive information on the fire resistance of the PCSPF systems used in construction, the worst-case scenario is considered with the following assumptions:

1) The base of the study is the experimental test conducted by FireSERT on the heat transfer of a thinner bearing PCSPF wall with 80 mm thickness.
2) The representative limiting insulation layer thickness of 200mm is considering based on the heat transfer test conducted at FireSERT and the computational modelling is conducted for a period of 120minutes for a bearing wall with 80mm concrete thickness (FireSERT fire test simulation, figure 10).
3) Thicker thermal insulation, as shown in figure 10, can expose larger lengths of the connector to high temperatures. Such exposure conditions result in the deteriorated mechanical properties over longer lengths in connectors which can lead to more severe damage to the shear connection between the inner and the outer concrete precast walls. Hence for longer connector ties with higher thickness of the insulation, more server damage may be encountered as compared to the case with short connectors resulting from lesser thickness of the insulation.
4) Due to the wide range of connector types available on the market [1,2], the minimum reinforcement steel tie connectors [1] are considered to check the minimum satisfaction of the PCSPF system existing in practice.

To solve this problem finite element model is proposed to simulate the PCSPF system behaviour under fire conditions using SAFIR, an advanced computational modelling tool [3]. The mechanical and thermal material nonlinearities of the structural members, such as the concrete walls and steel reinforcement, insulation are included in the model. The model is validated at the early stages by conducting a comparative analysis of the numerical modelling results with the precast panel test conducted at FireSERT. The methodology used in this work is listed below as:

- Objective 1: Analysis of fire resistance test precast concrete facade system conducted FireSERT, Ulster University, using ISO834 fire curve.
- Objective 2: Computational studies on the tested façade systems from Objective 1 using SAFIR software to validate the computational (finite elements, FE) models to further understand their fire and structural performance focusing on the stainless-steel ties integrity.
- Objective 3: To extend the thermal and structural models from Objective 2 to other potential parametric study to cover an analysis based on worst case scenario with assumptions discussed previously with the goal to verify the fire safety level of the stainless-steel tie integrity using the ISO834 Fire curve.

The analyses conducted during this research is based on the recommendations and principles from the Eurocodes [4,5] listed as references.

2 GENERAL EXPERIMENTAL ON PRECAST SANDWICH PANEL

The experimental details of the fire test conducted at FireSERT Ulster University are shown in Figure1. This experimental investigation was aimed at assessing the fire resistance of reinforced concrete sandwich walls with thermal insulating materials (see Figure 2). The adopted dimensions (1500mm by 1500mm – width by height) of the half scale sandwich walls followed by the BS EN 1363-1, 2012 [7]. The testing specimen was constructed out of three layers: internal reinforced precast wall exposed to elevated temperature, a core layer of mineral wool thermal insulating non-combustible material and the external concrete layer. The furnace internal temperature was monitored and regulated with four standard- plate thermocouples placed approximately 100 mm away from the fire-exposed surface of the specimen. The fire test provided a useful data set on the recorded thermal distribution across the cross-section of the wall system which will be used to achieve objectives 2 and 3 mentioned in the previous section.

Figure 1. Precast sandwich Panel tested at Ulster University using ISO834 for 1 hour fire resistance

Figure 2 illustrates the cross-sectional details of the sandwiched concrete wall panel used during the experimental fire test. The instrumentation comprised of 3 thermocouples in the Structural Face side (SF) exposed to the fire, 2 thermocouples in the unexposed Architectural Face side (AF), and an additional TC at the cooler face.

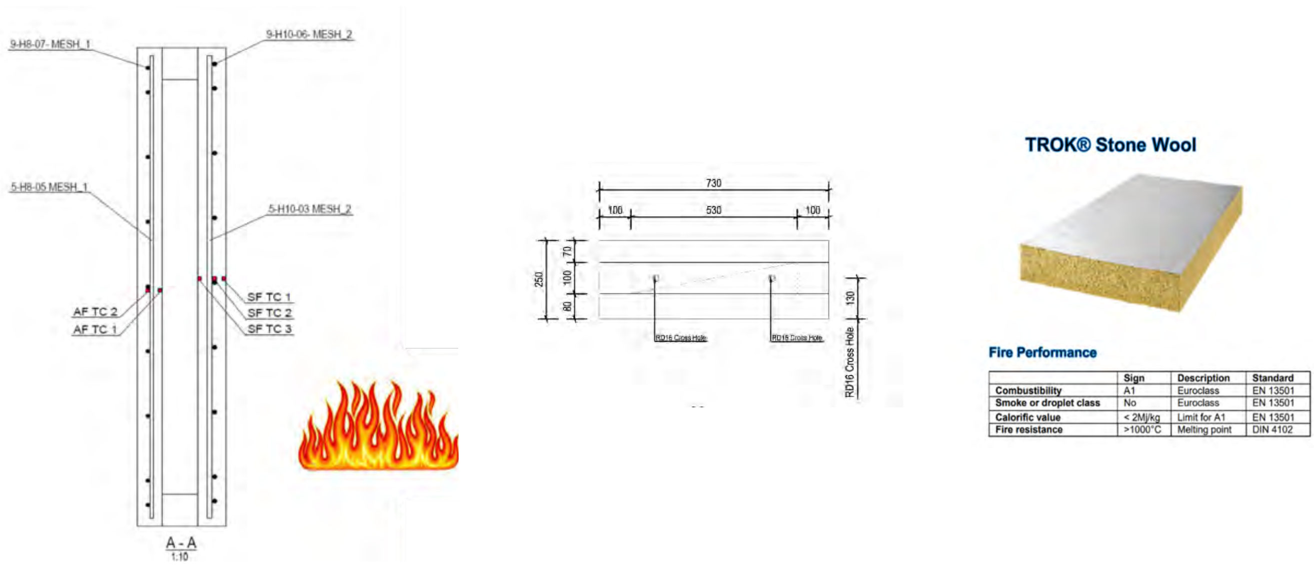


Figure 2. Details of the PCSPF system used during the experimental work

3 COMPUTATIONAL VALIDATION OF THE EXPERIMENTAL FIRE TEST USING SAFIR

3.1 Experimental test results

The fire exposure conditions during the test were in accordance with the standard temperatures time curve. This is seen in Figure 3 where the furnace temperatures recorded by all 6 thermocouples used have been provided. Further, the average temperatures recorded in the furnace have been presented as a thick black line which are on accordance with ISO834 curve, which is presented as a thick red line in Figure 3. The data presented in Figure 3 shows that the heating conditions during the test were in accordance with the standard temperatures time curve, ISO834.

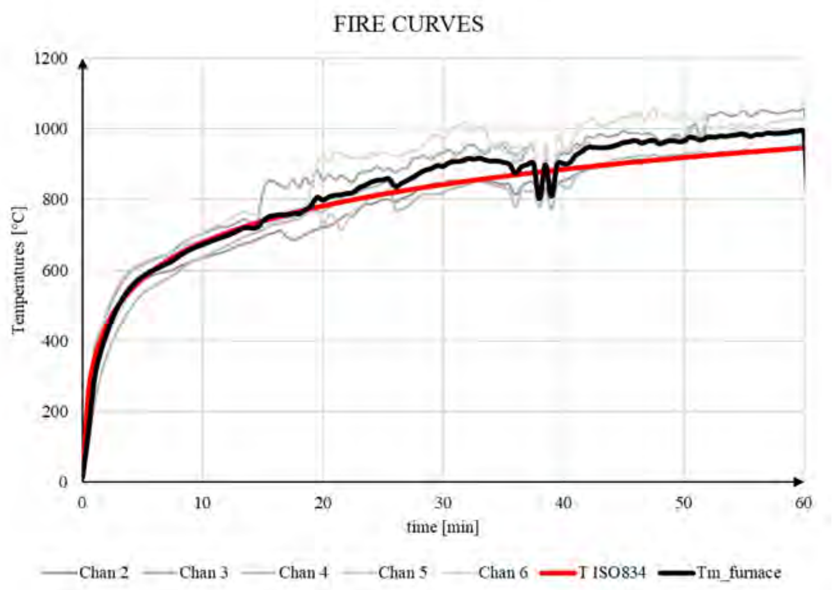
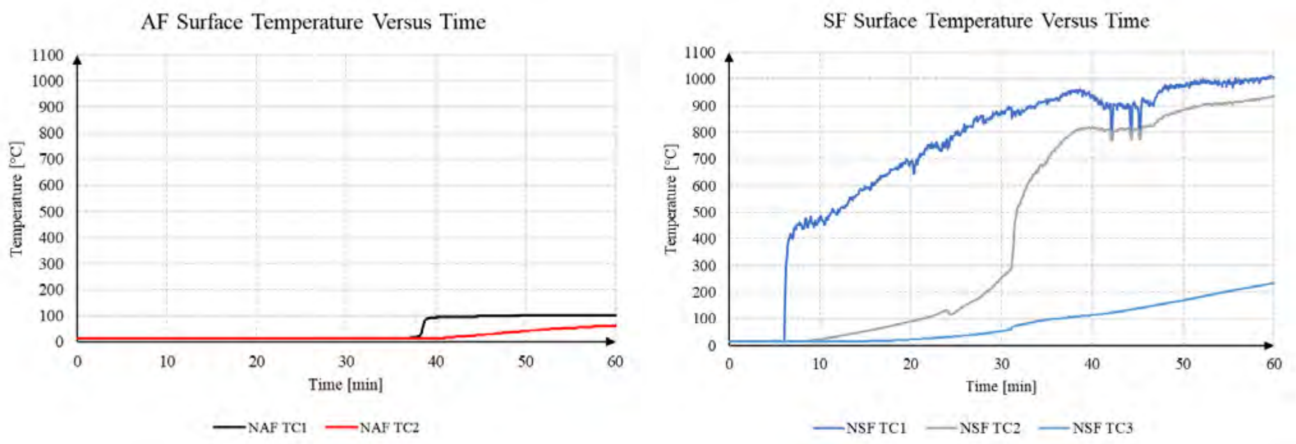


Figure 3. ISO fire curve and comparison with furnace temperatures



(a) **(b)**

Figure 4. Temperatures recorded during the fire test in the unexposed (AF) and exposed (SF) concrete walls

The thermal data recorded in the insulated concrete wall panel is presented in Figure 4 for both unexposed and exposed sides. It is seen in Figure 4 (a) that the temperatures in the exposed concrete wall (AF) remain below or around 100^0C for the while duration of the fire test. On the other hand, temperatures recorded in the exposed concrete wall are significantly higher reaching around 1000^0C in some thermocouples. Further, the results in Figure 4 (b) show that the results near the exposed surface (TC1) are highest and with the increase in the distance from the exposed surface, recorded temperatures reduce (TC2 and TC3).
The average temperatures recorded on the unexposed surface have been presented in Figure 5 which are around15^0C. Considering the insulation requirements of structural members which should serve as fire walls, the mean temperature on the unexposed side must not exceed 180^0C [8].

Although testing standards do not set requirements for the temperature increase within the cross sections of the wall to the side not exposed to fire enables a better understanding of the thermal and mechanical performance of insulation and the steel tie connectors.

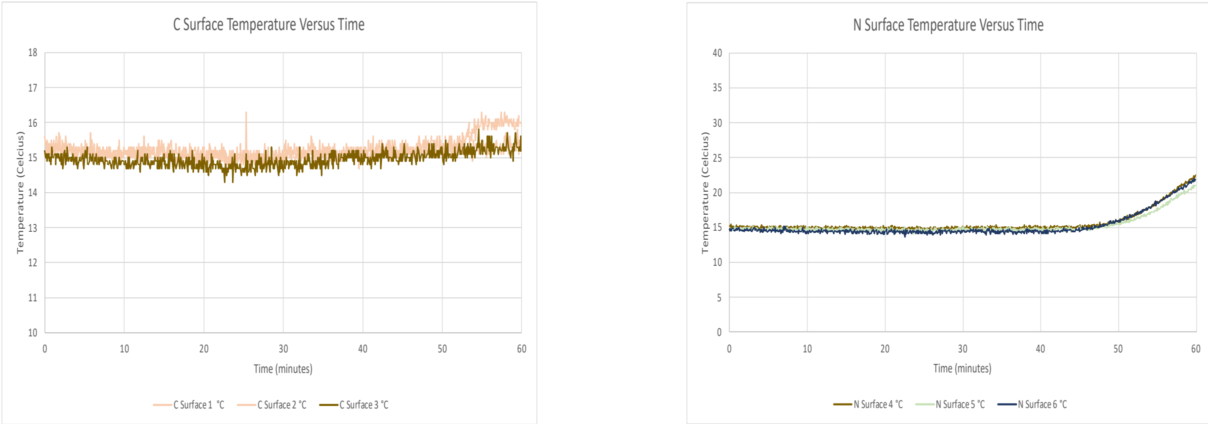


Figure 5. Temperatures recorded at the surface of the unexposed side

3.2 Validation of the Experimental fire test with SAFIR

As mentioned earlier, SAFIR is a computer program that models the behaviour of buildings and structures subjected to fire. The structure can be made of a 3D skeleton of linear elements such as beams and columns, in conjunction with planar elements such as slabs and walls. Volumetric elements can be used for analysis of details in the structure such as connections. Different materials such as steel, concrete, timber, aluminium, gypsum, or thermally insulating products can be used separately or in combination in SAFIR for numerical studies. Keeping in view the advantages, SAFIR software was employed to conduct the finite-element simulation of the temperature field of PCSPF system cross sections (see Figure 6). This was done through the validation of the test conducted by FireSERT and later the validated model was used to conduct further studies. During the FE analysis, nonlinear elements were considered, taking in account mechanical and geometrical non linearities.

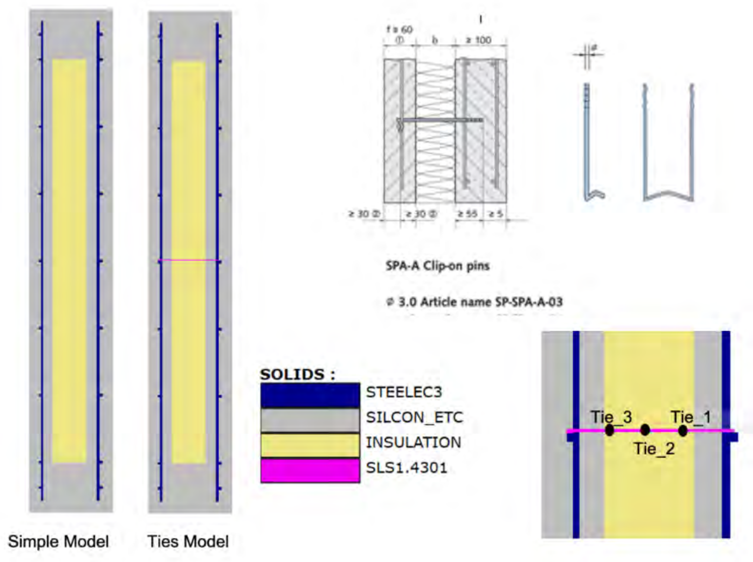


Figure 6. Computational modelling details (SAFIR Models)

The computational modelling was conducted for two PCSPF systems:

1) The precast wall with wool rock insulation.

2) The precast wall with wool rock insulation with steel ties element.

Details of both models can be seen in Figure 6 where simple and the tie model are shown adjacent to each other. Further, the elements of the models in terms of the clip-on pins, details of ties and materials have also been shown.

The results from the computational modeling are presented against the test data in Figures 7 and 8. The results presented are in terms of temperatures and there is a good agreement between the test and the analysis results from SAFIR modelling. As the computational model applied is efficient and can replicate the test conducted by FireSERT, it will be employed to conduct further studies in the proceeding sections.

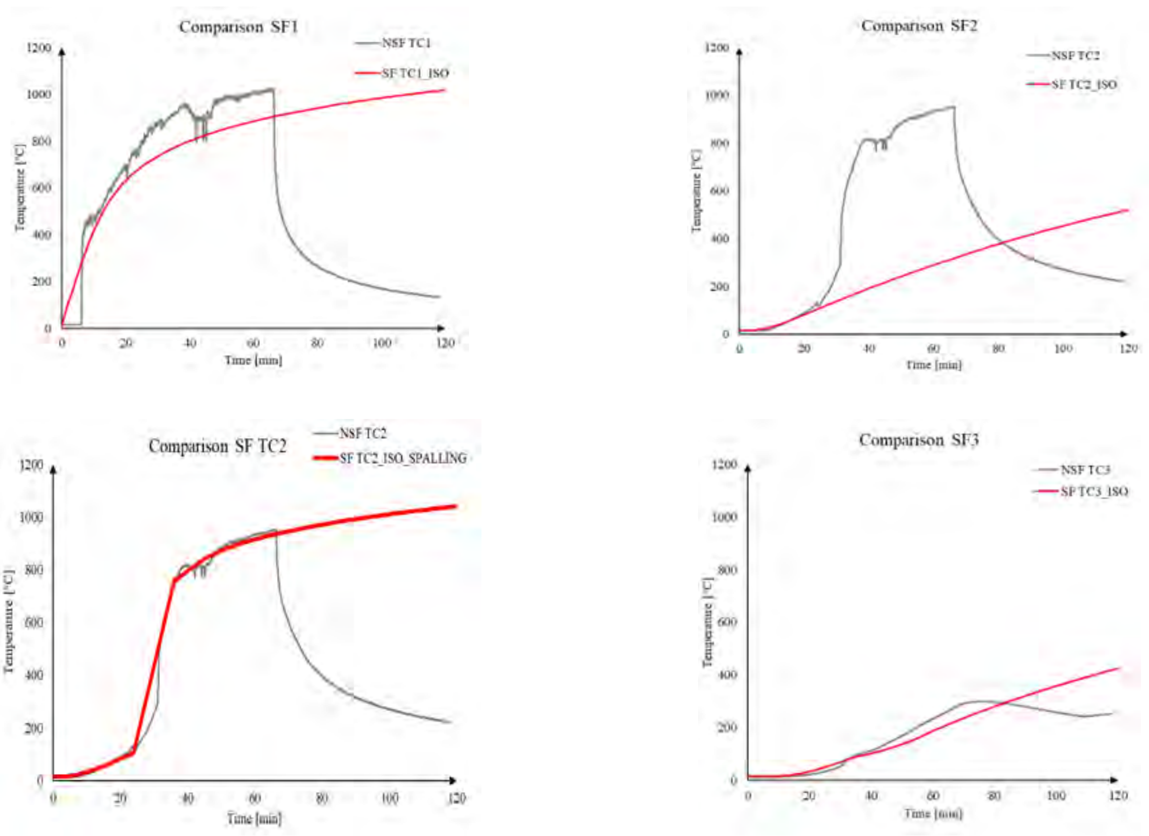


Figure 7. Comparison between computational and experimental temperatures for PCSPF panel exposed to the ISO834

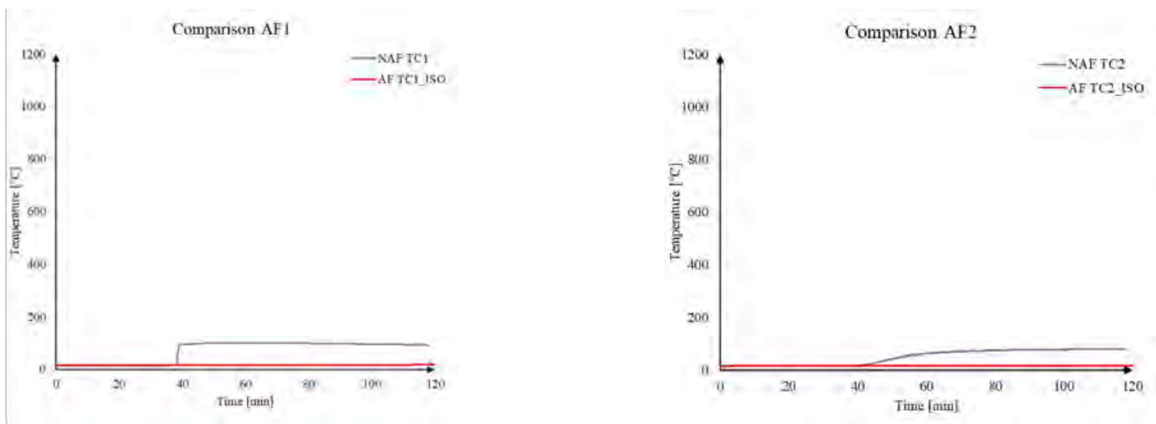


Figure 8. Comparison between SAFIR and experimental temperatures in an exposed panel to the ISO834

3.3 Connectors Behaviour

The validated analyses approach was repeated to study a case which considered the connected element between the two parts (inner and outer walls) of the concrete to investigate the influence of heat transfer on the steel tie connectors between the two walls. As shown in Figure 10, on the unexposed surface, the temperatures given by the ties model (dashed black line) are generally higher than the ones obtained for the simple model (red line). Also, in Figure 9, the influence of concrete spalling on recorded temperatures can be seen clearly.

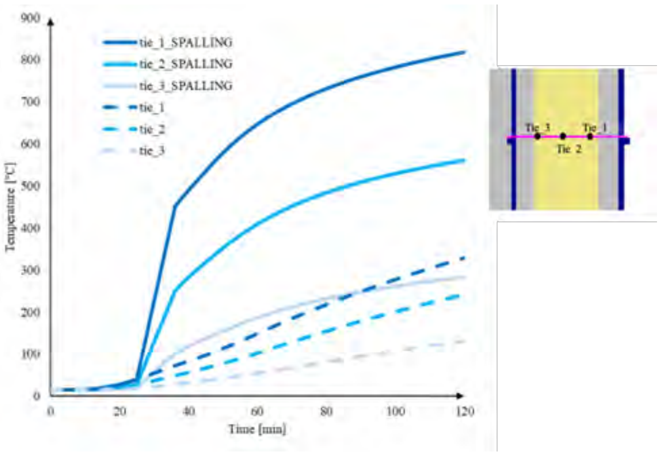


Figure 9. Steel Ties influenced by the concrete spalling

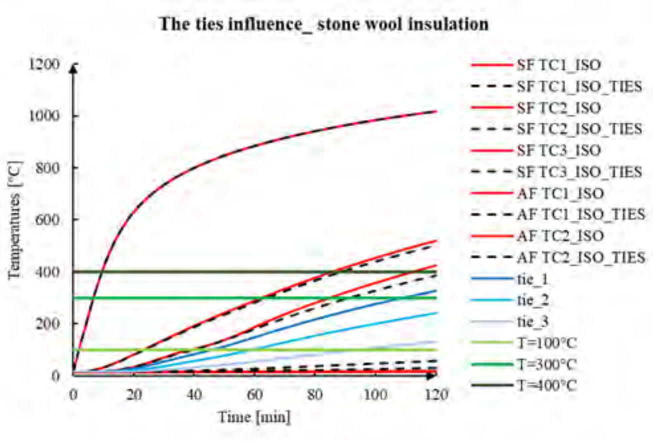


Figure 10. Maximum temperature recorded at steel ties is between 160^{0}C- 330^{0}C for 2 hours fire resistance ISO834

Eurocodes, BS EN 1993-1-2: 2005 [9], propose the reduction factors at elevated temperatures related to strength and stiff as presented in Table 1. This if compared to the FE analysis results where the temperatures in the steel ties was around 300°C or less, it can be concluded that the stiffness and strength are almost at its full capacity, 88% and 73% as evident from Table 1 below.

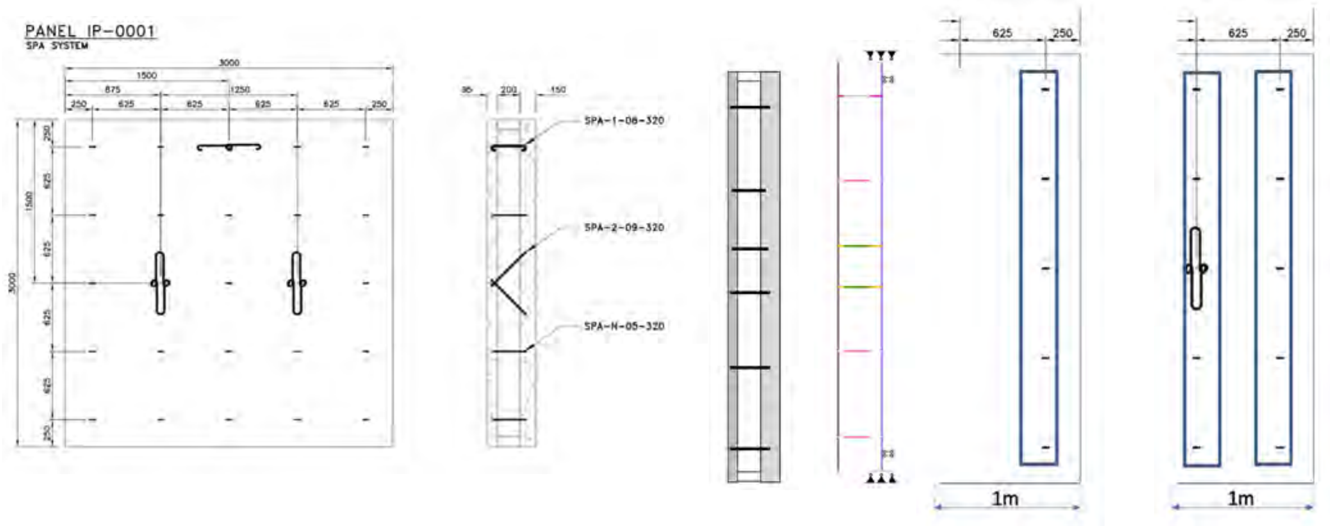
Table 1. Factors for determination of stain and stiffness steel at elevated temperatures

Steel Temperature θ_a	Reduction factor (relative to E_a) for the slope of the linear elastic range $k_{E,\theta} = E_{a,\theta}/E_a$	Reduction factor (relative to f_y) for proof strength $k_{0.2p,\theta} = f_{0.2p,\theta}/f_y$	Reduction factor (relative to f_u) for tensile strength $k_{u,\theta} = f_{u,\theta}/f_u$	Factor for determination of the yield strength $f_{y,\theta}$ $k_{2\%,\theta}$
Grade 1.4301				
20	1,00	1,00	1,00	0,26
100	0,96	0,82	0,87	0,24
200	0,92	0,68	0,77	0,19
300	0,88	0,64	0,73	0,19
400	0,84	0,60	0,72	0,19
500	0,80	0,54	0,67	0,19
600	0,76	0,49	0,58	0,22
700	0,71	0,40	0,43	0,26
800	0,63	0,27	0,27	0,35
900	0,45	0,14	0,15	0,38
1000	0,20	0,06	0,07	0,40
1100	0,10	0,03	0,03	0,40
1200	0,00	0,00	0,00	0,40

4 ANALYSIS OF FULL-SCALE PRECAST SANDWICH PANEL FAÇADE

With the full satisfaction with the validation, the computational study was extended to model a real scale PCSPF system (see Figure 11) with the external panel subjected to gravity loading which facilitated a possibility of vertical deflection. In a situation where the PCSPF is exposed to fire, the insulation layer should first ensure the thermal protection of the load-bearing layer, stay firm during the fire, and not contribute to fire spread. Further, the effectiveness of shear transfer during fire provided by the insulation and connectors should be assessed, especially for sandwich walls, since these are one of the core elements of PSPF system and contribute to their functionality as a construction element.

The thickness of the insulation between the concrete walls is one of the key aspects in the design of PCSPF systems as it influences the temperature development along their cross-section, therefore, different mechanical performances. Additionally, since the concrete precast walls in any PCSPF system have different thickness, the side of the wall being exposed to fire could potentially impact the behaviour of connectors. In case of higher thickness of insulation, longer length of the connector will be outside concrete and may expose to fire which may result in achieving higher temperatures. As the mechanical properties deteriorate at higher temperatures, longer connectors can lead to more severe damage to the shear connection between the precast concrete walls of a PCSPF system as compared to the case with short connectors. To study the response of a critical PCSPF system, the worst scenario was considered during this study with assumptions discussed before.



Standard practical use of PCSPF

Frame Analogy Model

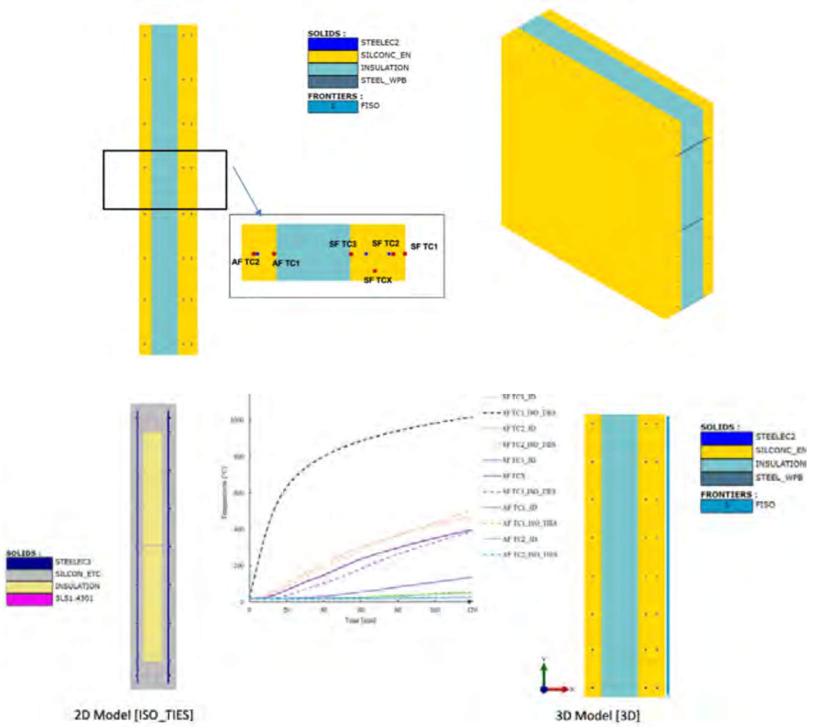
Case 1: one column of SPA-N-05

Case 2: two columns of SPA-N-05 is considered.

Figure 11. Detailing of PCSPF and model used with two scenarios using minimum steel tie reinforcement

4.1 SAFIR 2D and 3D computational models

Before proceeding with further studies, a benchmark study was conducted usign 2D and 3D moddelling approaches. The pupose of this benchmark study was to find the most economical modelling approach in terms of comoputational time. Figure 12 demonstrates the temperatures distribution in the PCSPF system by comparing the the 2D and 3D modelling reults. It can be seen that the 2D modelling resutls are in a good agreement with the 3D results, hence, the 2D modelling apprioach will be used to sutdy furhter cases of PCSPF systems.



(a)

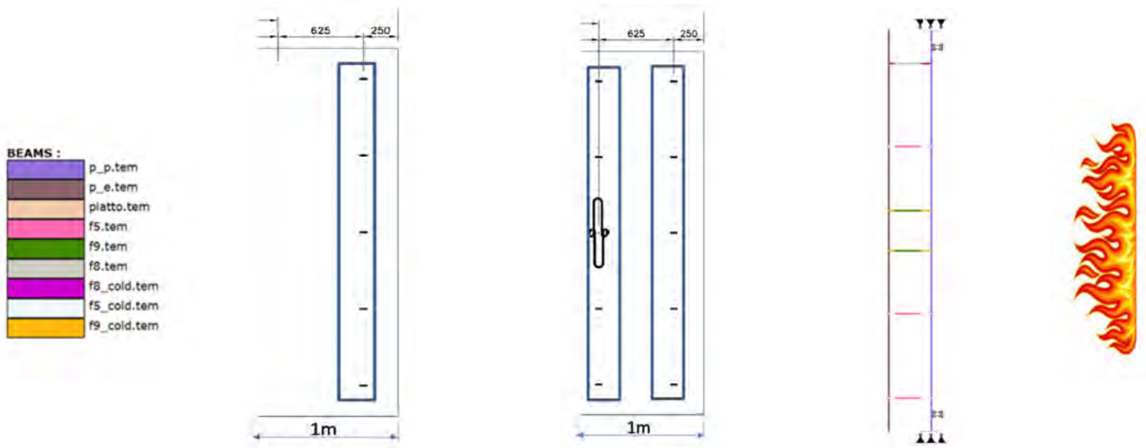
(b)

Figure 12. Comparison 2-D with 3-D modelling results, (a) 3D, (b) 2D

4.2 SAFIR Model for a possible worst-case scenario

4.2.1 FE Modelling Approach

The FE modelling was conducted for a worst-case scenario (the critical case) by modelling a 1m band with minimum steel reinforcement of one column of reinforcement considering only the SPA-N-05-320. In particular, the SAFIR thermo-mechanical analyses were performed by considering each part of the wall (e.g. external wall and structural wall) as beam elements, connected by the ties (see Figure 13), developed by Nadjai [6]. The software SAFIR works in a decoupled way, by means thermal analyses of all the structural section in the first step and the thermo-mechanical analyses in the second step. Therefore, in the next sections the results of both thermal (STEP 1) and thermo-mechanical (STEP 2) analyses are reported, by including all the assumptions and thermal conditions.



Case 1 Case 2 ISO834 Curve

Figure 13. Minimum reinforcement used the 1m band with wall constraints are hinged

4.2.2 *STEP1: Sectional thermal analyses*

The temperature distribution in each part of the PCSPF system were calculated starting from the results of the detailed thermal analyses explained before which yielded a good agreement between the experimental and numerical results. The details of thermal analyses for each component of the PCSPF section are given in the following.

External wall: The F20 frontier has been imposed to the unexposed architectural face, to permit the heat exchange with the external ambient. While, on the other face, the temperature distribution called "myfire.fct" (see Figure 14), which is the temperatures curve reached in the nondimensional analysis (as seen before in Figure 8), to better reproduce the real thermal field reached during the experimental test was assigned. This frontier is assigned to the face on the insulation side.

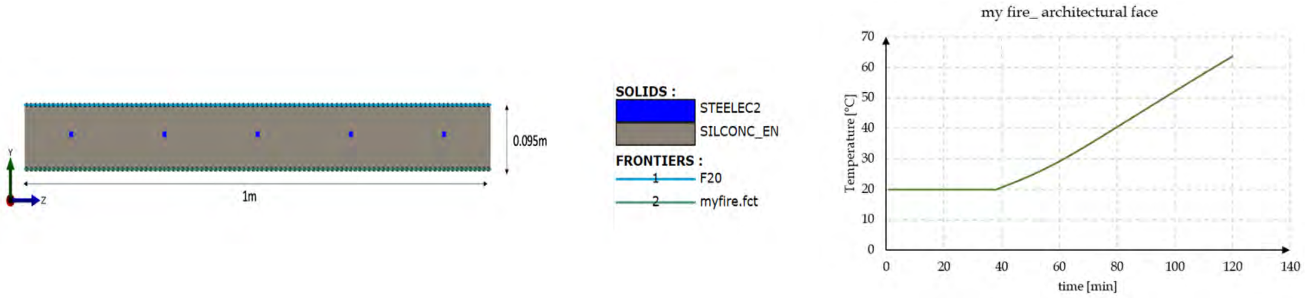


Figure 14. The external wall and temperature curve used

Structural Wall: The structural wall is exposed to the standard fire curve, ISO-834.

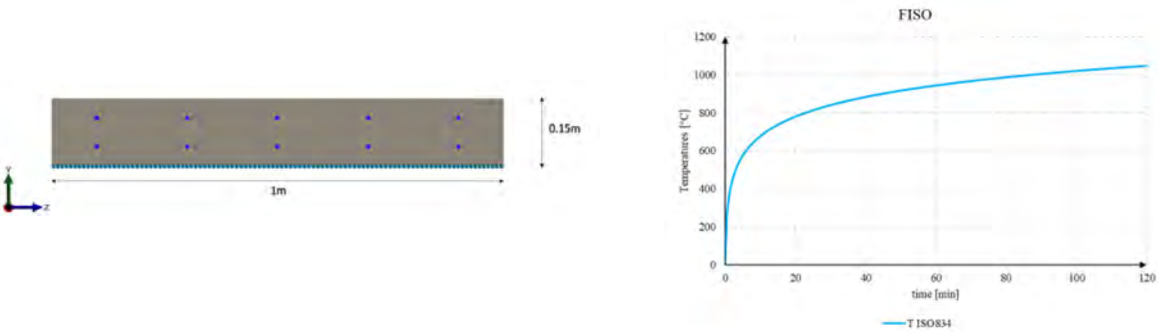


Figure 15. Bearing wall exposed of ISO fire curve

Ties Temperatures: For better reproduce the real condition, the temperature frontier for the ties sections was directly taken from the 3D thermal model, as shown in the following Figure 16.

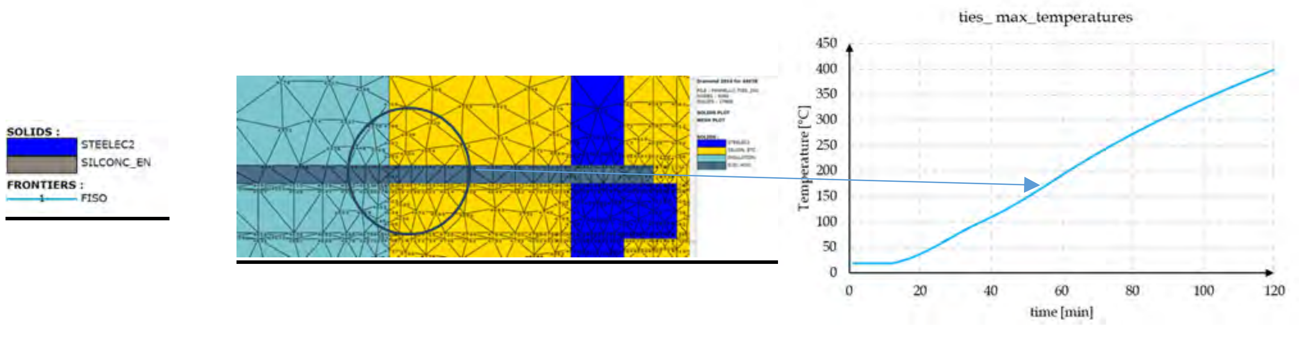


Figure 16: The temperatures given by the mono-dimensional analysis (Node 4545) were assigned as frontier (1) to the tie's boundary

4.2.3 Thermo-mechanical Analyses Results

In this section the results of the performed thermo-mechanical analyses were reported. The loading applied on the structural internal wall is 50 kN/m on a strip of 1m band of walls considering the self-weight of both internal and external walls. Considering the same boundary conditions as in practice where the top and bottom parts are restrained by the side walls and slabs above and below at the level of each intermediate floor. The deflection of the external cladding between each level should not exceed the practical gap of 15mm. It can be seen from Figure 17 that the deflections of the external wall in both case is not exceeding the 15 mm. Therefore, the stainless-steel ties integrity of the external wall cladding is well satisfied for both cases.

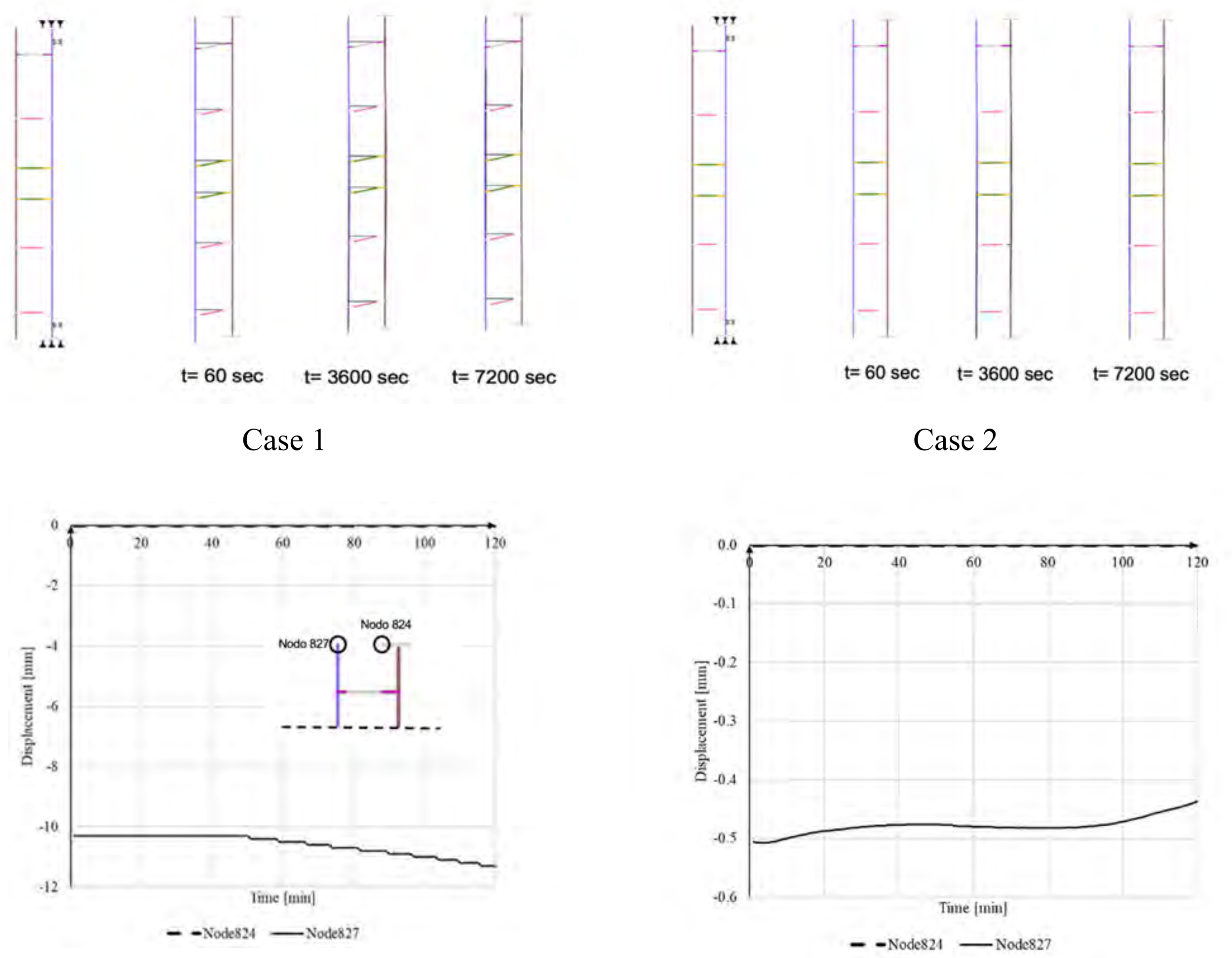


Figure 17: deflection of the external wall for both cases are less than 15mm provided in the gap between walls of each floor level

5 DISCUSSION ON RESULTS

Following the frame analogy model process and the obtained results by considering the worst-case scenarios in the absence of real fire full scale, and with the assumption discussed in the core it can be summarised that: The model provided an excellent validation with the experimental conducted by FireSERT at Ulster University, the thermal and structural performance of the insulation and connectors under high temperatures were analysed. Following the BS EN 1993-1-2: 2005, it can be concluded that the stiffness and strength are almost at its full capacity. The displacement of the unsupported facing wall is very small for case 1 and negligible for case 2 using the minimum reinforcement as the critical benchmark.

- In case 1, the deflection of the external wall is already 10.2 mm at the early stage and next increase beyond 50min and achieve 11.3 mm in 120min. This case can represent a PCSPF left with minimum tie connectors reinforcement in actions.
- In case 2, with the increase of the tie connectors reinforcement area the deflection of the external wall is reduced at 0.5mm at early stage but next moved upwards to 0.45mm for a duration of 120min. This indicates that the displacement of the edge resulting from the rotation caused by the heat induced bowing that the potential sagging of the wall under its weight supported by the core layer.

6 CONCLUSIONS

It can be concluded that with the minimum reinforcement connectors maintain their mechanical properties throughout the fire resistance of 120 minutes and are able to maintain a constant distance between the concrete precast walls, coupling them together for a typical external wall 95mm, insulation 200mm and internal wall 150mm. Increasing the thickness of the internal wall over 150mm will increase the fire resistance of the system and with the additional connectors as designed in the system will maintain their mechanical properties throughout the fire resistance of 120 minutes even with the increase of the insulation thickness over 200mm, and the deflection of the external will be very small by moving upward and behave like case 2 as discussed above. On the other hand, if the internal wall thickness is reduced than 150mm, for example 130mm with less insulation thickness as 100mm, the PCSPF system can achieve 120min fire resistance as the assumptions used are the most critical. Further experimental tests of the PCSPF system are under consideration to be conducted in the near future in FireSERT at Ulster University.

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