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NUMERICAL MODELING OF INNOVATIVE CAVITY INSULATED LSF PANELS WITH DIFFERENT WALLBOARDS

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ABSTRACT

Light steel framed (LSF) panels are increasingly being used as loadbearing and non-loadbearing elements as an alternative to traditional masonry and concrete structures. They are widely used in the U.S., Australia and Japan, while their use is increasing in Europe. Some advantages offered by LSF panels compared to masonry and concrete elements are low weight, high mechanical strength, higher construction speed, possibility of recycling and reuse, high architectural flexibility, easy prefabrication that allows modular construction, precise tolerances, etc. However, among the major disadvantages is the high thermal conductivity of steel elements, which can lead to significant thermal bridging and somewhat lower thermal mass. Based on the numerous potential advantages and considering the disadvantages, a new innovative LSF panel is proposed within the research project KLIK PANEL. The innovative panel consists of sheathing boards, steel studs and tracks while the cavity is completely filled with polymer foam (PUR), which structurally connects the components into a single coherent product. To further prevent cold bridges, thermal breaks in form of spacers are used. Since the polymer foam insulation is highly flammable, the fire performance of such panel is questionable. The main objective of this preliminary study is to determine the appropriate sheathing to prevent the temperature leading to ignition of the polymer foam. Currently, there are a variety of sheathing options that provide high fire resistance. To determine the best option, 2D numerical models were created using different sheathing boards (gypsum plasterboards, magnesium oxide boards, magnesium sulphate boards, calcium silicate boards, fiber cement boards, perlite boards) to study the temperature development through the structure and determine the temperature that leads to ignition of the polymer foam.

Keywords: LSF panels; Fire resistance; Finite-element modelling; Fire-resistant wallboards.

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1. INTRODUCTION

The basic composition of LSF panels consists of three components, each of which has its own function that benefits the whole assembly. The three components are: thin lipped steel channels, sheathing boards, and insulation. The cold-formed, thin-walled steel sections are responsible for load-bearing capacity, while the sheathing provides the necessary aesthetic finish while protecting the steel elements. The insulation provides the necessary thermal comfort and acoustic damping. Most LSF wall and floor systems consist of cold-formed, thin-walled steel sections and gypsum plasterboards (GP), with insulation placed in the cavity or outside the cavity [1], [2]. The most commonly used insulation material is mineral wool (MW), which is used mainly because of its non-combustibility, acoustic dampening, and ease of installation. While MW is non-combustible, other insulation materials, mostly polymer materials, have lower thermal conductivity, lower water permeability, stability over time [3]. In addition, cold bridging often occurs when MW is used in the cavity. Fig. 1. shows a typical LSF construction.

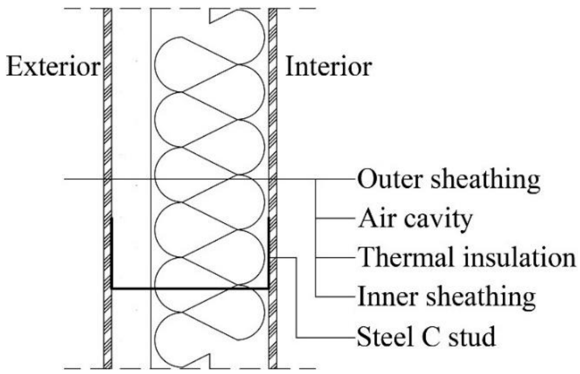

Fig. 1. Standard LSF construction

When LSF wall panels are used in buildings, they must meet the seven basic requirements for construction work, of which fire safety is extremely important. One method of determining the fire resistance of such panels is fire tests based on a standard temperature-time curve specified in the standard ISO 834 [4].The fire resistance rating is then determined based on the failure time in three categories: mechanical resistance (R), insulation (I), and integrity (E). When LSF panels are exposed to fire, the thin steel, lipped channels, and joists tend to heat up rapidly, leading to loss of their loadbearing capacity [5] and eventual collapse, endangering potential occupants. It is believed that the critical temperature at which the steel deforms is about 600-650 °C. Failure based on the insulation criteria is determined when the average temperature rises above the initial average temperature on the unexposed surface by more than 140 °C, or when at any point on the unexposed side the recorded temperature rises above the initial average temperature by more than 180 °C. In this case, the insulation of the panel is extremely important as it prevents the rapid temperature rise. The integrity criterion specifies that there must be no spread of fire and smoke on the unexposed side.

Numerous full-scale and small-scale fire tests have been conducted on loadbearing and non-loadbearing panels to increase the knowledge of fire safety and fire performance of such panels sheathed with different boards and different insulation. Feng et al. [6] conducted 8 small-scale fire tests on cavity insulated and non-insulated panels with different numbers of sheathing boards to determine the effects on fire behaviour. The authors concluded that the thermal performance of cold-formed thin-walled steel channel panels is not significantly affected by the type of internal insulation and the shape of the cold-formed thin-walled steel cross-section, and that the temperatures of the steel cross-section of a steel stud framing system depend primarily on the insulation panels on the side exposed to fire. In another study by Ariyanayagam and Mahendran [7], a series of two cavity-insulated and non-insulated loadbearing and non-loadbearing panels were tested and it was found that the fire resistance of cavity insulated LSF panels decreased compared to non-insulated panels. It was concluded that the cavity insulation limits the heat transfer through the panel, which increases the temperature at the hot flange of the steel lipped channel and causes the stud to deform and lose its mechanical resistance. On the other hand, the limited heat transfer through the panel benefits the non-load bearing panels and increases the fire resistance rating based on the insulation criteria. Further research has been conducted on innovative LSF panel design such as externally insulated panels.

Kesawan and Mahendran [8] conducted small and full scale fire tests on cavity and externally insulated panels and found that the externally insulated panels had significantly higher fire resistance than the cavity insulated panels. On the other hand, they also concluded that such panels are difficult to fabricate because the insulation is flexible and compressed differently in different places when the outer plasterboard layer is applied, making it difficult to maintain the vertical alignment of the outer plasterboard layer. This also increases the manufacturing time and cost. Further research and fire tests were conducted to evaluate the influence of different sheathing options such as magnesium oxide boards, calcium silicate boards and PCM plasterboards on the fire performance of LSF panels. Chen et al. [9] conducted five full scale fire tests on LSF panels sheathed with magnesium oxide boards, calcium silicate boards and gypsum plasterboards. The researchers concluded that explosive spalling occurred with the calcium silicate board, raising questions about the overall safety of the assembly, while the magnesium oxide boards exhibited better fire resistance than gypsum plasterboard. On the other hand, tests conducted by Gnanachelvam et al. [10] revealed lower fire resistance of magnesium oxide boards because of rapid loss of mass leading to severe cracking, which means higher heat transfer in case of fire and pre mature integrity failures.

In summary, the research to date on LSF panels and their fire resistance provides somewhat conflicting results regarding the best sheathing option and configuration details. When it comes to the type of thermal insulation, most of the research mentioned above focuses on glass wool, rock wool and cellulose fibers, as they are all non-combustible. On the other hand, polymer materials have better insulating properties at ambient temperatures, allowing thinner walls that also provide the necessary thermal comfort. Because they are flammable in the event of a fire, they can pose a safety hazard. To date, no significant research has been conducted on LSF panels with combustible cavity insulation materials. Full scale and small scale fire tests are often expensive, so a numerical approach is used instead to predict the fire resistance of LSF panels [4], [5], [11], [12].

In the framework of research project, KLIK PANEL, research is being conducted at the Faculty of Civil Engineering at the University of Zagreb to develop an LSF panel with improved thermal performance. The panel consists of thin, lipped channel sections that are cavity insulated with expanding polymer foam (PUR) to achieve a complete composite structure. Due to the flammability of the foam, the project is researching a suitable sheathing board to prevent the foam from reaching the ignition temperature. 2D numerical models are developed using the commercial Abaqus CAE software to investigate heat transfer through the whole panel to determine the preliminary best available option.

2. NUMERICAL MODELING

2.1. Model description

The numerical model of the panel was created using FEA in Abaqus CAE to simulate the temperature distribution during fire exposure. One side of the panel is considered exposed and the other unexposed. Prior to the simulation, a temperature field was defined to simulate the ambient temperatures on both sides of the panel before it is exposed to the furnace temperatures.

The real LSF construction of the panel will consist of steel lipped channel sections, at least two sheathing boards and the cavity insulation. Two sheathing panels are proposed due to the high flammability of the polymer foam. The panel consists of thin, lipped steel channels (89 x 42 x 10 x 0.95 mm) spaced 551.6 mm apart. The studs are additionally stiffened by horizontal tracks and diagonal steel channels connecting the studs and tracks. After the sheathing is in place, the polymer foam is injected into the cavity. As the foam expands, it combines all the components into a compact product and fills the entire cavity. The density of the polymer foam at ambient temperatures is 45 kg/m3. The selected steel grade is galvanized steel S550 GD. The sheathing boards that are part of the numerical analysis include gypsum plasterboards, magnesium oxide and magnesium sulfate boards, perlite boards, calcium silicate boards and fiber cement boards. A 2D model was created to represent the panel and observe the heat transfer through the entire assembly, which is shown in Fig. 2.

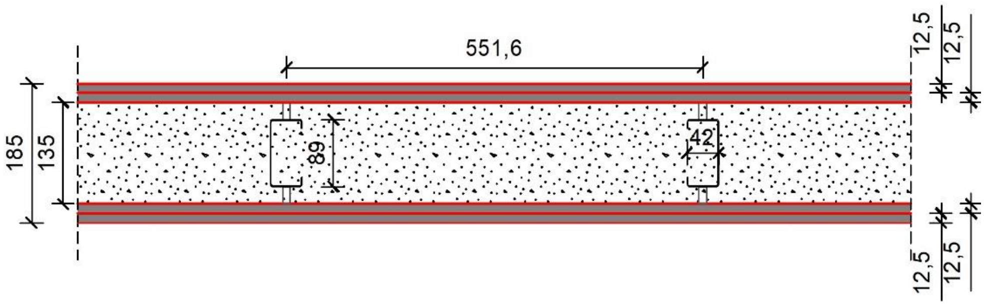

Fig. 2. CAD sketch of the panel

The finite element analysis (FEA) was performed under transient conditions to simulate a full-scale fire test. This means that the heat transfer through the panel is not constant in time, but changes depending on the fire exposure according to the ISO 834 curve and due to the changing material properties.

The overall size of the model is determined by the real LSF construction, which has a size of 2995 x 2800 mm. The model in Fig. 2 is a top view of the structure. The model consists of independent parts, steel profiles, sheathing boards and polymer insulation, created in the Part module and assembled in the Assembly module of Abaqus CAE. In order to bond the individual parts together, "Tie constraints" were defined on the contact surfaces of each part to ensure heat transfer between the parts. Once the parts were created, they were individually meshed. For all parts, the Quad mesh was used with different mesh sizes for precision. Typically, a finer mesh produces more precise results. Therefore, the steel parts were meshed with a mesh size of 0.95 x 0.95 mm, and the polymer foam and sheathing were meshed with a mesh size of 5 x 5 mm. The mesh size for the steel sections was influenced by the thickness of the section and the mesh size of 5 x 5 mm for the insulation and sheathing is considered sufficient.

2.2. Material properties

The necessary data for the boards, i.e., temperature-dependent specific heat capacity, density, and thermal conductivity, for the numerical models were obtained from the literature [13], [14]. All the chosen fire-resistant boards have a significant amount of free and bound water in their structure, which affects the fire behaviour of LSF assemblies. These changes in the amount of water and the endothermic reactions that occur during the evaporation process are clearly reflected in the changes in thermal properties. In particular, the changes in the amount of water and the endothermic reactions are best observed in the changes in specific heat capacity as a function of temperature. As the chemically bound and free water evaporates from the board and its molecules, the energy required for this process increases dramatically and is shown as peak values in Fig. 4. Gypsum plasterboards go through two endothermic reactions due to the changing water content at temperatures around 150 °C and 180 °C. At higher temperatures, some changes in the chemical composition of the board are studied by [13]. As with gypsum plasterboards, similar reactions occur in calcium silicate board at temperatures around 160 °C and 180 °C. In magnesium oxide boards, five endothermic reactions occur due to the changing water content. These reactions are observed at temperatures around 180 °C, 230 °C, 426, 470 °C and 620 °C [13]. Since magnesium oxide and magnesium sulphate boards have similar chemical composition [14], the observed reactions are observed at similar temperatures. Perlite boards showed two reactions at temperatures around 270 °C and 320 °C [13]. For fibre cement boards, reactions were observed at temperatures around 160 °C, 700 °C, and 870 °C.

Figures 4, 5, and 6 show the temperature-dependent thermal properties of the chosen fire-resistant wallboards. Fig. 4. shows the temperature-dependent changes in specific heat capacity, Fig. 5. the temperature-dependent changes in density, and Fig. 6. the temperature-dependent changes in thermal conductivity.

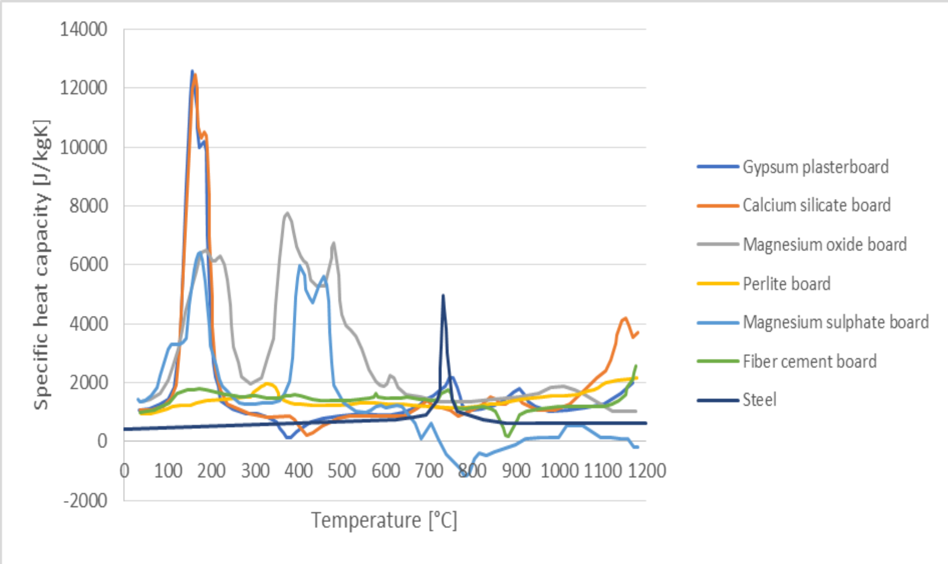

Fig. 4. Temperature dependent specific heat capacity of the chosen boards [13], [14], [15]

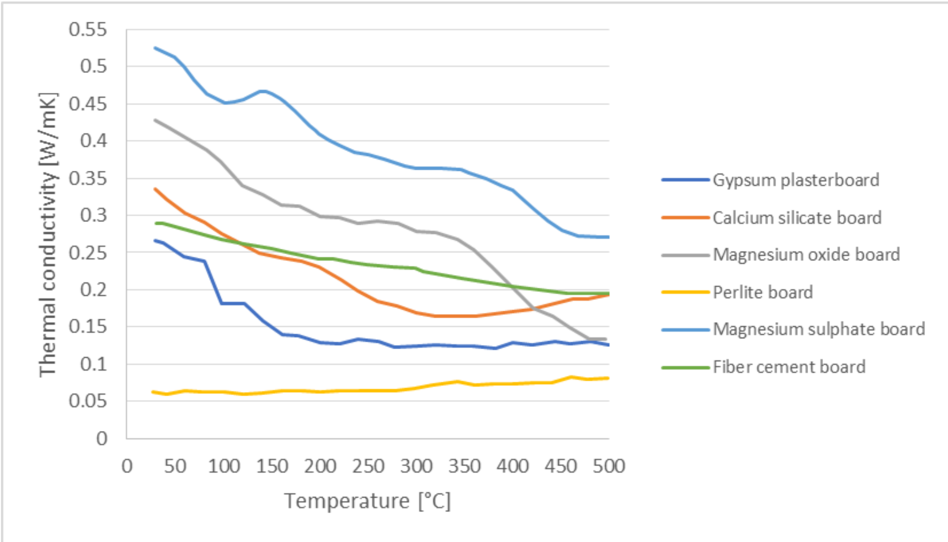

Fig. 5. Temperature dependent thermal conductivity of the chosen boards [13], [14]

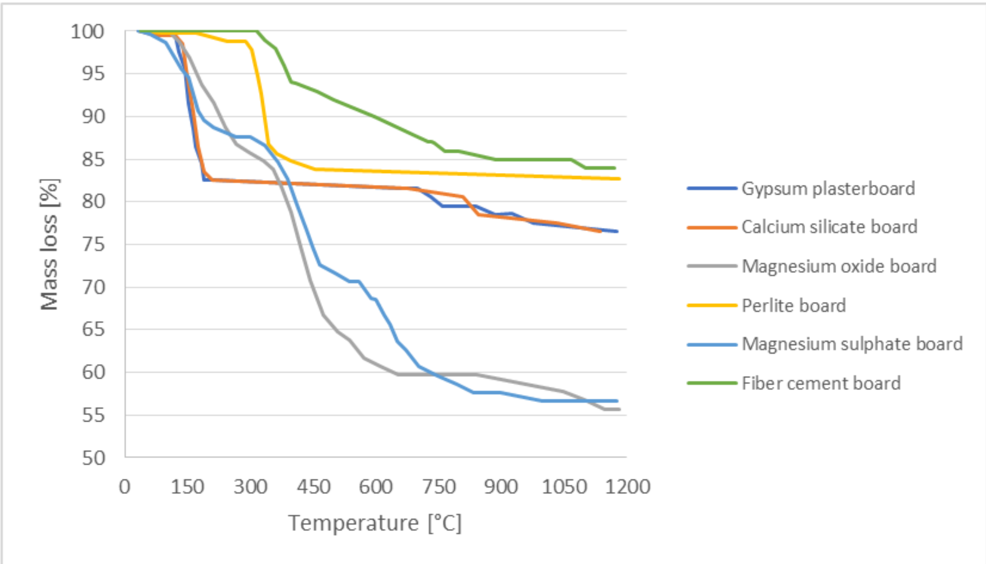

Fig. 6. Temperature dependent mass loss of the chosen boards [13], [14]

As with the various fire-resistant boards, the thermal properties of steel change with the increase in temperature, as shown in Fig. 4 and Fig. 7. The thermal properties of steel are also taken from the literature [15] and are primarily the result of changes that occur in the crystal structure of the steel at elevated temperatures. Fig. 4. clearly shows that the specific heat capacity increases at a temperature of about 650 °C as a result of the above-mentioned changes in the crystal structure. This temperature is also considered critical, since at this temperature the load-bearing capacity of the steel decreases drastically due to the deformation of the thin steel elements.

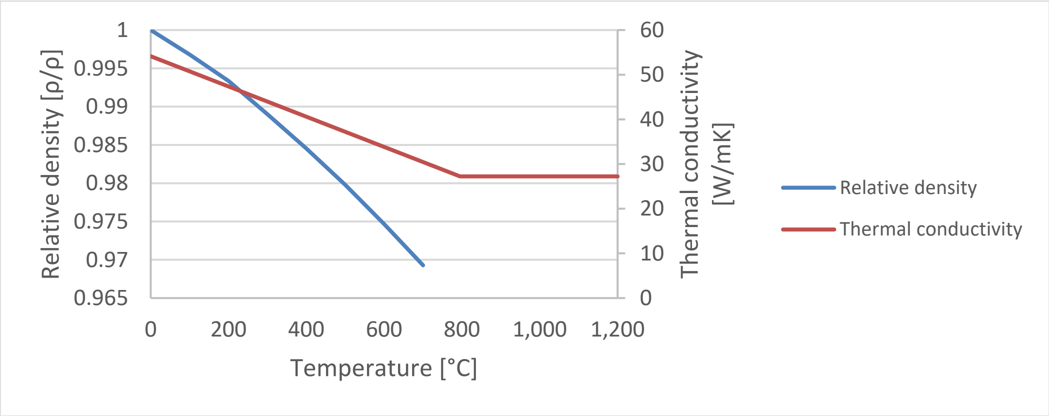

Fig. 7. Temperature dependent density and thermal conductivity of steel [15]

The thermal properties of the foam for the purpose of numerical analysis are taken from the literature [3], [16]. The relative density and specific heat are assumed to be constant values, i.e. the density is 45 kg/m^3, while the specific heat is 1400 J/kgK. Since the main focus of the numerical analysis is on the temperature on the connection of the sheathing and the foam, it is assumed that the specific heat will not drastically affect the results. The thermal conductivity of the foam is shown in Fig. 9. and is taken from the literature [16].

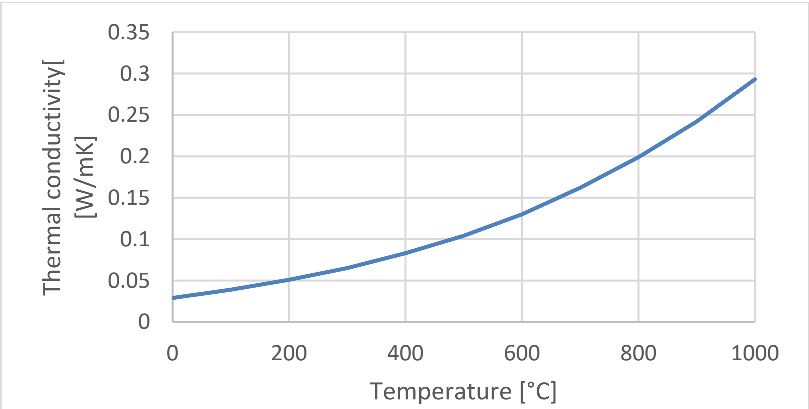

Fig. 8. Temperature dependent thermal conductivity of polymer foam

2.3. Boundary conditions

The heat flux at the boundary will be calculated from the temperature of the ISO 834 curve and the temperature on the surface according to Eq. 2.

$$q = h(T_g - T_s) + \sigma\varepsilon(T_g^4 - T_s^4) \quad (2)$$

where q is the total heat flux, ε is the relative emissivity, σ is the Stefan–Boltzmann constant (5.67x10−8 W/m^2/C^4), Tg is the gas temperature following the ISO 834 fire curve, and Ts is the surface temperature. According to literature [17], the convective heat transfer coefficient (h) is 25 W/m^{2}K on the side exposed to fire and 10 W/m^{2}K on the unexposed side. The emissivity for gypsum plasterboard is 0.9 [17] , for fibre cement board 0.93 [18], while for magnesium oxide and magnesium sulfate board it is 0.73 [18] . Since no value is given in the literature for perlite boards, 0.9 is also assumed here.

3. RESULTS OF THE NUMERICAL ANALYSIS

According to Giunta d'Albani et al. [19],since the polymer foam is highly flammable, it is assumed that flash ignition of PUR takes place in the temperature range of 350-450 °C depending on the use of flame retardants. In addition to the temperature at the connection between the foam and sheathing board the temperatures between the two sheets, on the steel section and on the unexposed side are also shown. Figs. 10.-13. show the results of the numerical analysis.

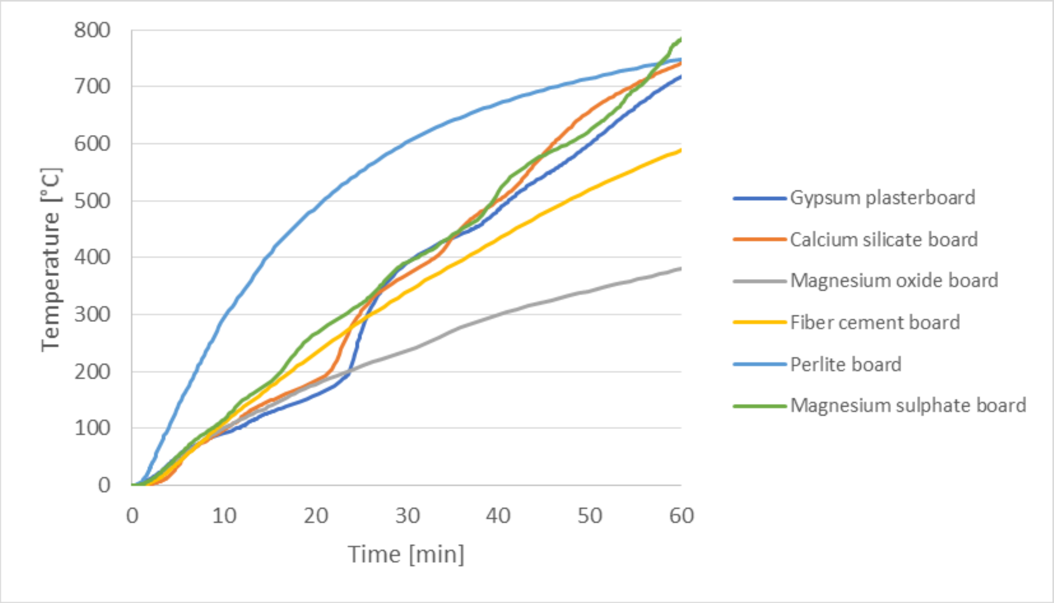

Fig. 9. Temperature profile on the connection point of the two sheathing boards

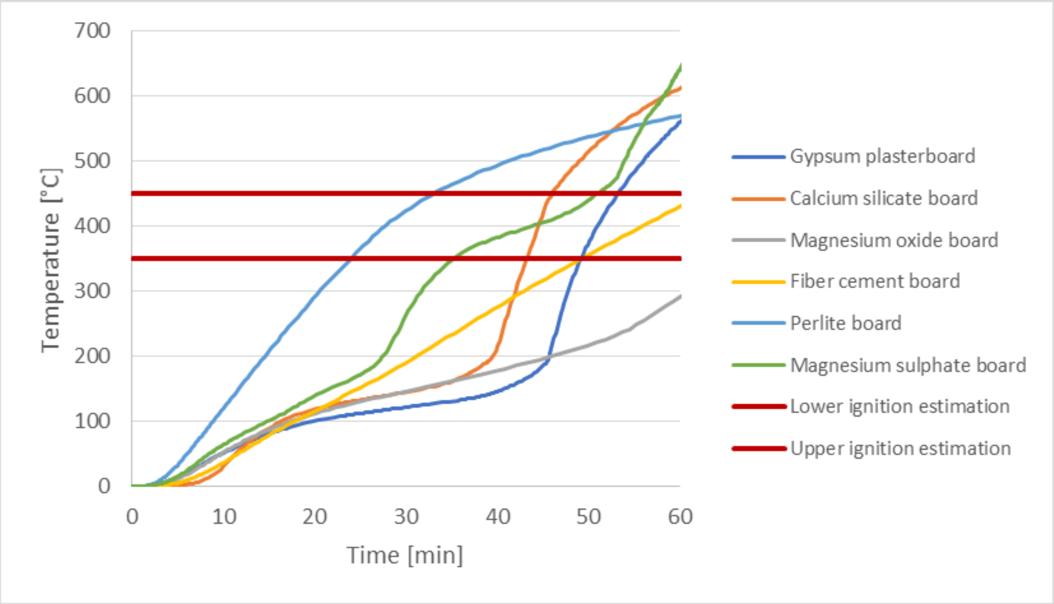

Fig. 10. Temperature profile on the connection point of the sheathing and polymer foam

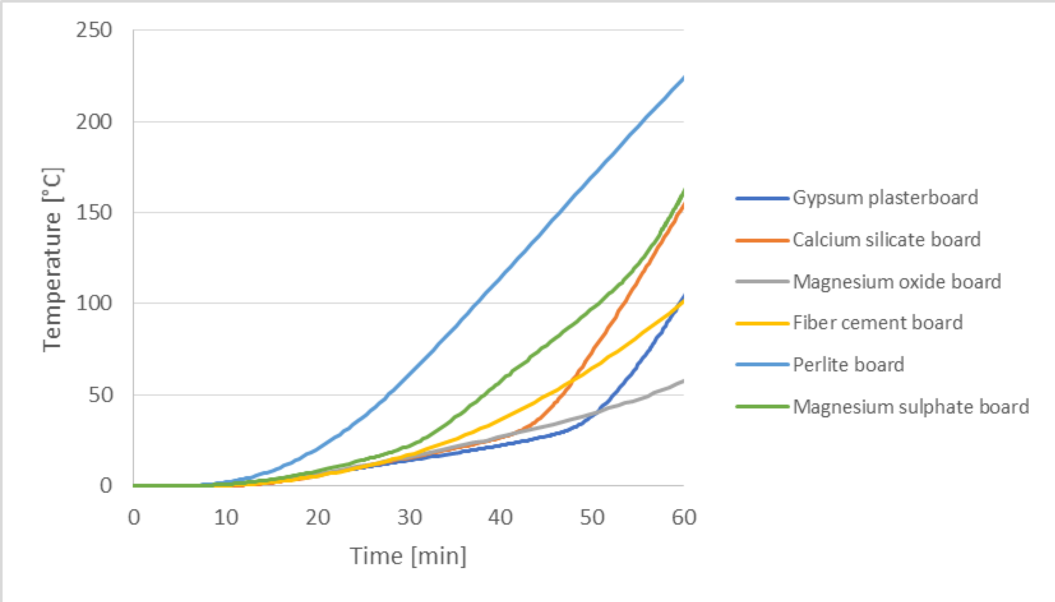

Fig. 11. Temperature profile on the connection point of steel and polymer foam

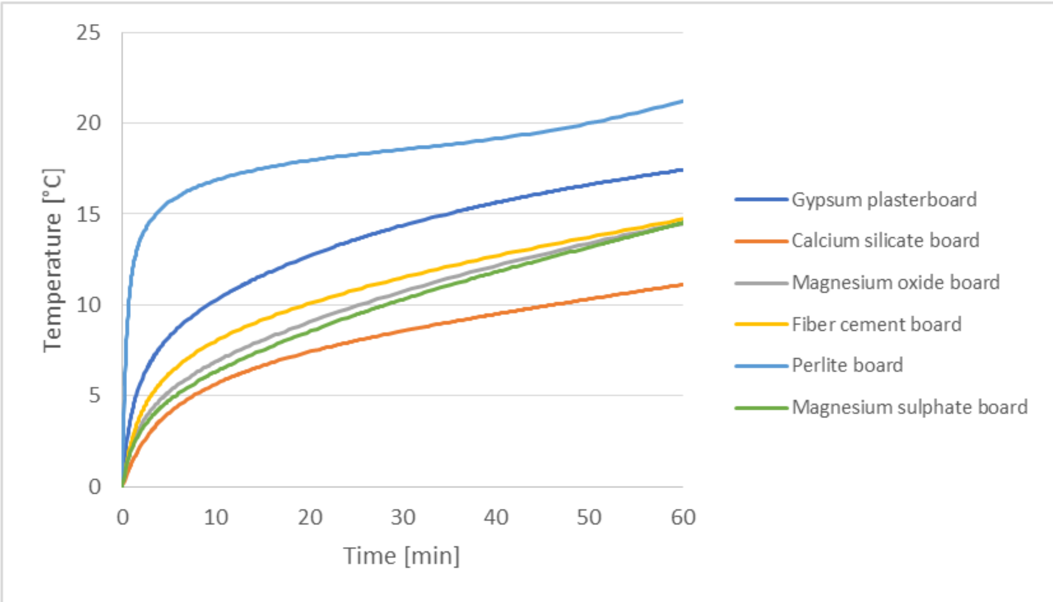

Fig. 12. Temperature profile on the unexposed side

The results show that the best sheathing option for the proposed panel is the magnesium oxide board, since the temperature recorded by the FEM analysis at the connection point of the polymer foam and sheathing is lower than the estimated ignition temperature of 350 °C. In addition to magnesium oxide boards, fibre cement boards could also be a possibility, as shown in Fig. 11., since the temperature at the connection of the foam and sheathing falls within the range of 350 - 450 °C.

Of the modelled boards, perlite boards have the poorest fire resistance, as the temperature of 350 °C at the connection point is reached in less than 30 minutes. Perlite boards are followed by magnesium sulphate boards, calcium silicate boards and gypsum plasterboards. Although magnesium sulphate boards and magnesium oxide boards have quite similar chemical composition [14], their fire behaviour is different according to this FEM analysis. Gypsum plasterboards and calcium silicate boards show similar fire resistance, although the plateau in which the temperature rise is delayed is slightly longer for gypsum plasterboards.

In Fig. 11. a slight plateau can be seen on the time-temperature curve in the time range of 10 - 40 minutes. This plateau is the result of the water evaporation already mentioned. As can be seen in Fig. 12, after 60 minutes the temperature at the connection point of the steel C-sections does not exceed the critical temperature at which the steel deforms. This is due to the excellent insulating properties of the polymer foam introduced into the cavity. The same can be seen in Fig. 13., which shows the time-temperature curve on the unexposed panel side.

4. CONCLUSION

According to the FEM analysis magnesium oxide boards show the best fire resistance for the proposed panel design because the temperature at the connection point of the sheathing and foam is lower than the ignition point of the foam. On the other hand, some researchers have found that the magnesium oxide boards suffer a drastic loss of mass leading to the formation of cracks. Since Abaqus CAE does not directly provide the ability to simulate the formation of cracks, it is modeled only with the increased thermal conductivity and mass loss. Nevertheless, the formation of cracks should be further investigated and tested with experimental tests. As with magnesium oxide boards, the same problem exists with magnesium sulfate boards. As can be seen in Fig. 6. fiber cement boards have the lowest mass loss of all the selected panels. This could be due to the fibers inside the composition. As the water evaporates, the fibers prevent further rapid sinking, falling and cracking. Perhaps the solution to the best sheathing option lies with fire resistant boards with fibers. More research is needed to evaluate sheathing boards. Crack formation also needs to be evaluated and tested, as it greatly affects the fire performance of LSF structures in real life.

The main objective is still to prevent the ignition of the insulating foam. Therefore, further research is needed on the thermal properties and fire behaviour of the polymer insulating foam, as well as conducting experimental tests to verify the modelling results.

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