EXPERIMENTAL AND NUMERICAL EVALUATION OF COMPOSITE STRUCTURAL INSULATED WALL PANELS

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Abstract
Experimental and numerical results are given for composite structural insulated wall panels. The panels 1.0×2.5 m^2 were composed of two external stiff facesheets of glass fibre-magnesium-cement boards glued with a central thick soft core of expanded polystyrene. Comprehensive investigations were carried out to optimize their mechanical, acoustic and thermal properties. Advantages and disadvantages of panels were outlined.

1 Introduction
The structural design in housing can be improved through the development and application of composite materials that capitalize on multifunctional components. Light structural insulated panels (SIPs), developed nearly 75 years, are high-performance composite building panels used in floors, walls, and roofs for residential and light commercial buildings. These panels are fabricated in a factory and shipped to a construction site, where they can be quickly assembled to form a tight, energy-efficient building envelope. SIPs are simple composite sandwich panels formed as three layered constructions by bonding a thin layer (facing) to each side of a thick layer (core). The facesheets carry the bending stresses while core resists the shear loads and stabilizes the faces against buckling or wrinkling. Core also increases the stiffness of the structure by holding the facesheets apart. In general, core materials have lower mechanical properties compared to those of facesheets. The final product has enhanced and more desirable properties than its constituents.

We investigated SIPs 1.0×2.5 m^2 composed of two external stiff faces of glass fibre-magnesium-cement boards (2×11 mm) glued by adhesives to a central thick, lightweight and soft core of expanded polystyrene (15 cm). The main intention of our experimental and theoretical investigations was to optimize and eventually to improve their mechanical, sound and hygrothermal properties for structural applications in modern residential buildings.

2. Mechanical properties of SIPs
The mechanical properties were investigated on large SIP specimens. Different large-scale tests were carried out, e.g.: bending tests with free supported and fixed single and three connected panels under vertical loads, buckling tests with free supported single panels under central and eccentric loading, impact resistance tests using a hard and soft body, thermal resistance tests and strength tests against fixed objects [1].

Experimental investigations of the bearing capacity of a single wall panel and three wall panels connected with each other by the oriented strand board OSB under bending were performed with panels loaded by four uniform vertical loads under displacement control (Fig.1).

The experimental vertical force-deflection curves are show in Fig.2. The maximum vertical force was 20-21 kN at the deflection of 19 mm (vertical normal stress ≈8 kN/m^2) for a single wall panel and 45 kN at the deflection of 23 mm for three connected wall panels. Failure was fast and brittle through the appearance of a discrete macro-crack at the bottom of the skin board (Fig.3).

The buckling investigations were carried out with a wall panel with hinges at ends. Steel C-profiles were put at panel ends to approximately simulate a joint connection with a slab panel. The wall panel was put in a horizontal position due to its large size (Fig.4). The maximum experimental vertical compressive force was 140 kN under concentric loading. The panel did not fail in buckling but through damage of the skin board in a steel profile (Fig.5).

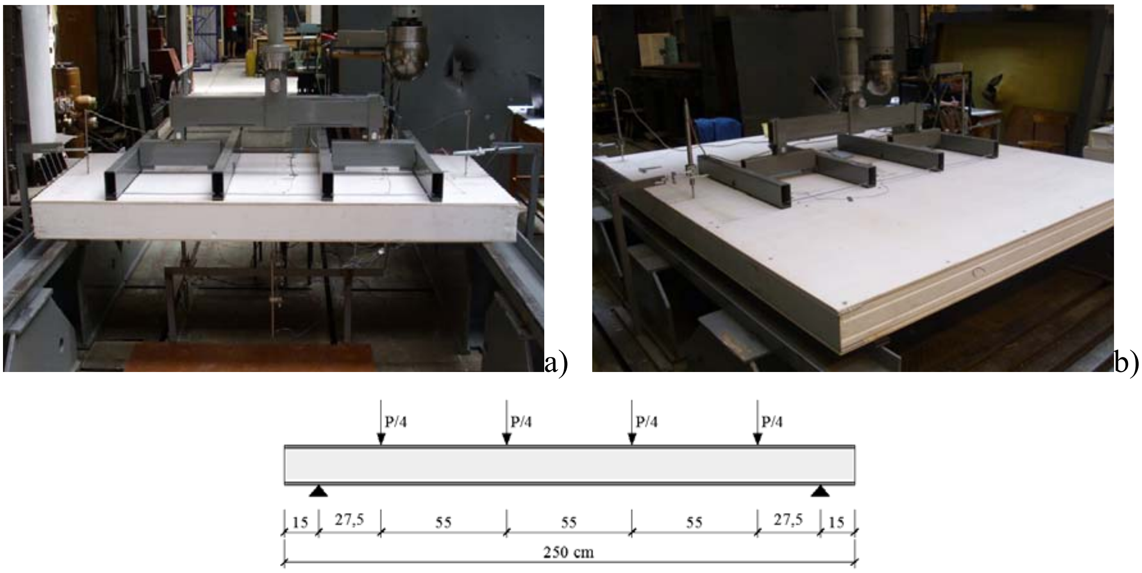

Figure 1. Experimental set-up for investigations of bearing capacity of wall panels under bending:
a) single panel, b) triple panel.

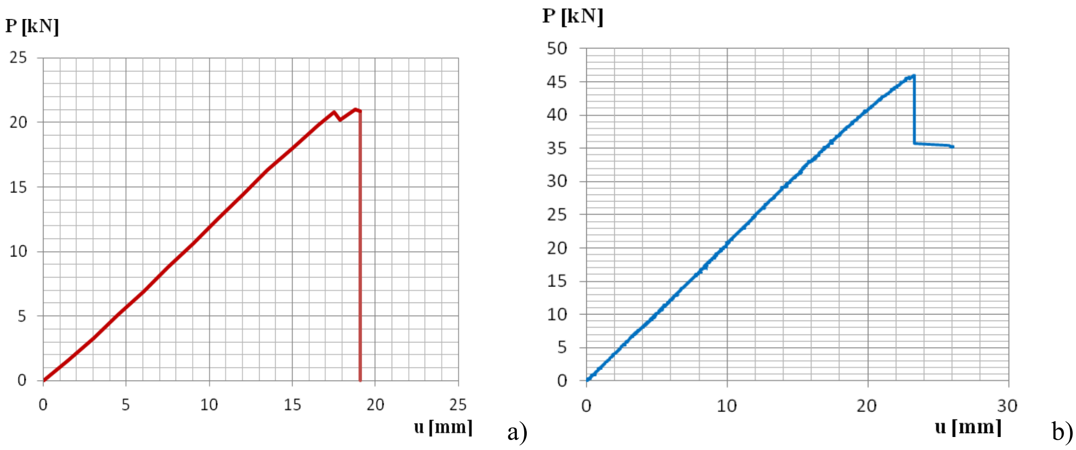

Figure 2. Experimental vertical force-deflection curve for wall panels under bending:
a) single panel, b) triple panel.

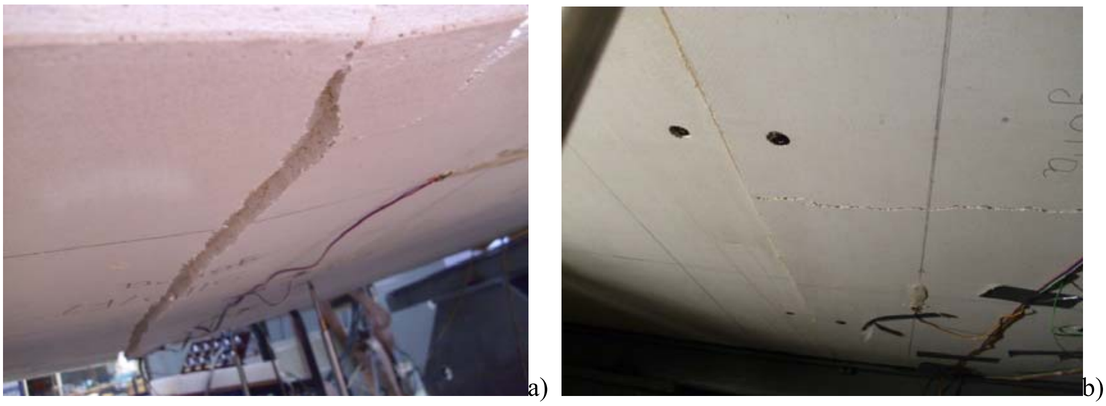

Figure 3. Failure of SIPs by cracking under bending (view from bottom): a) single panel, b) triple panel.

Figurę 4. Buckling tests of SIPs: a) experimental set-up, b) support

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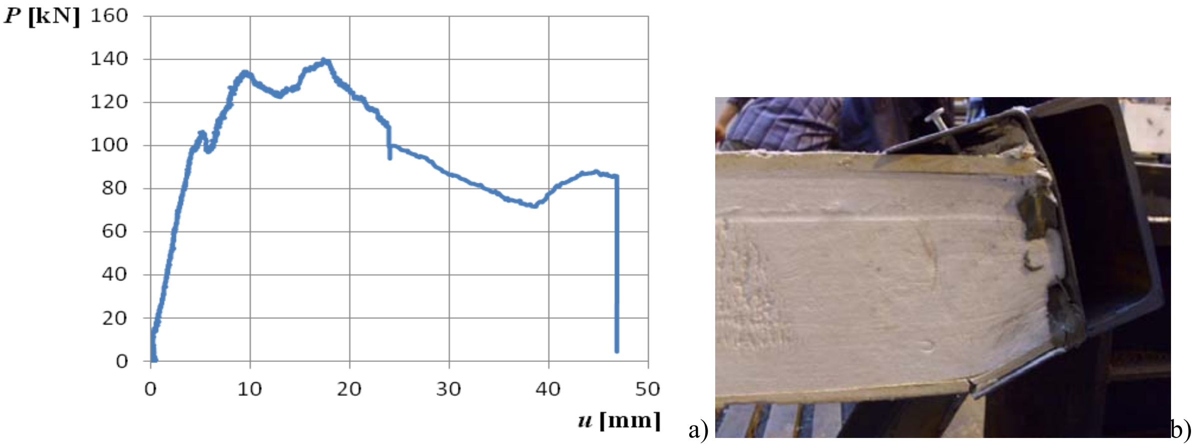


Figure 5. Experiments with SIPs under uniaxial compression: a) horizontal force against horizontal displacement and b) support failure**.**

The bending experiment of Figs.1 and 2 was numerically simulated using the FEM [2]. In the first step, a simple linear elastic theory was used. A fixed connection between skin and core was assumed. The material constants were determined with separate laboratory bending tests on glass fibre-magnesium-cement boards (E=4900 MPa, ν=0.18) and internal EP core (E=6.4 MPa, ν=0.25). A satisfactory agreement was achieved between calculations and experiments with respect to the composite stiffness (Fig.6). In addition, stresses in were numerically studied [2] in the connection between one slab and two walls under standard uniform loads (Fig.7). At present, the FE calculations are performed using a cohesive crack model for concrete and EP core by assuming cracking in the panel and slip and delamination of external layers.

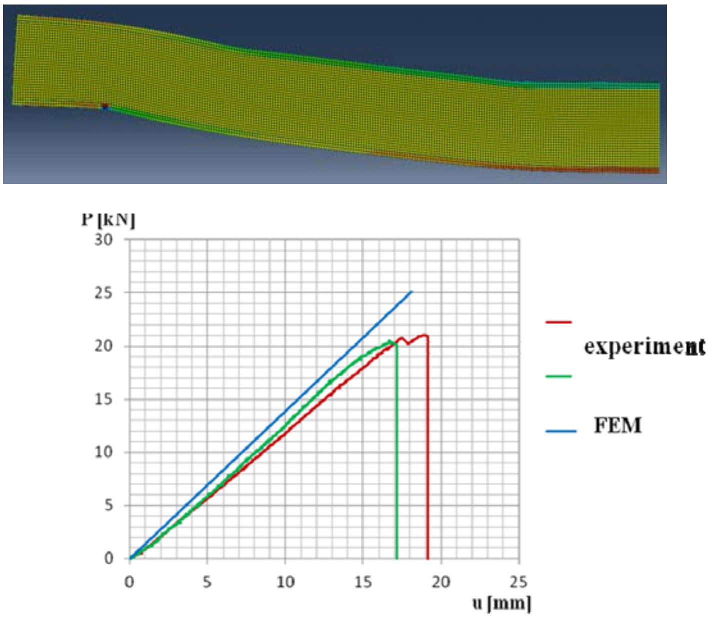
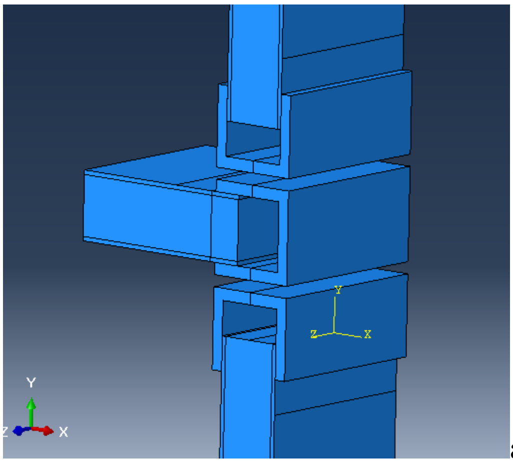


Figure 6. FE mesh and calculated force-deflection curve from FEM against two experimental curves for single wall panel of Figs.1a and 2a using linear elastic theory.



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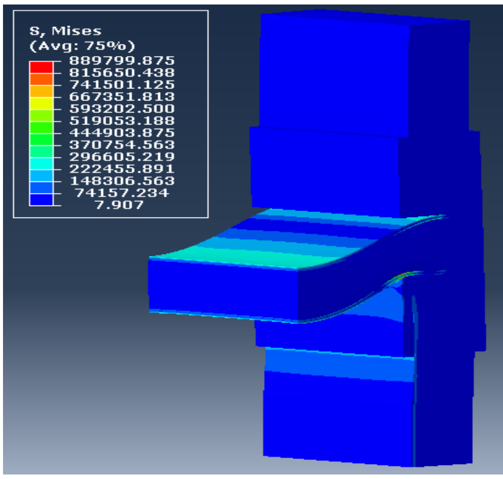


b)

Figure 7. Panel bond under standard uniform loads: a) FE model, b) calculated von Mises stresses from FE calculations (maximum stress 0.9 MPa).

3 Acoustic properties of SIPs

The acoustic properties were measured experimentally in an acoustic standard reverberation chamber composed of 2 rooms (transmission room 212 m^3 and receiving room 190 m^3, SIP specimen area 3170×3160 mm^2) and simulated next numerically using the FEM (based on the equation of a compressible, inviscid and linear fluid and simplified interface in fluid-structure interaction [2]). Figure 8 shows the experimental sound reduction index in the frequency range of the wall panel based on experiments as compared to the standard reference curve for buildings in Poland. The wall sound reduction index is too small for walls by 5-10 dB due to a resonance effect in the EP core at the frequency of 400-600 Hz. In 2D FE simulations using the implicit approach, 109500 finite elements were applied. Figure 9 indicates that the calculated reduction index is slightly displaced in direction of small frequencies probably due to the fact that a cellular structure of the expanded polystyrene was not taken into account. Based on experiments, SIP has to be improved to increase the sound reduction index. Therefore, the FE calculations were carried out next with an improved layered structure of the wall panel (Figs.10 and 11). The results show that a wall panel with an internal damping layer (wool) (Fig.10) or a panel including air voids or air voids containing wool (Fig.11) may satisfy the standard reference curve.

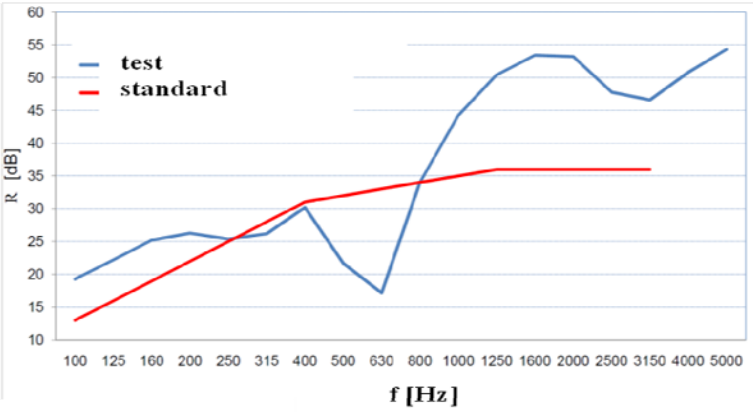


Figure 8. Measured sound reduction index of SIP as compared to standard reference curve.

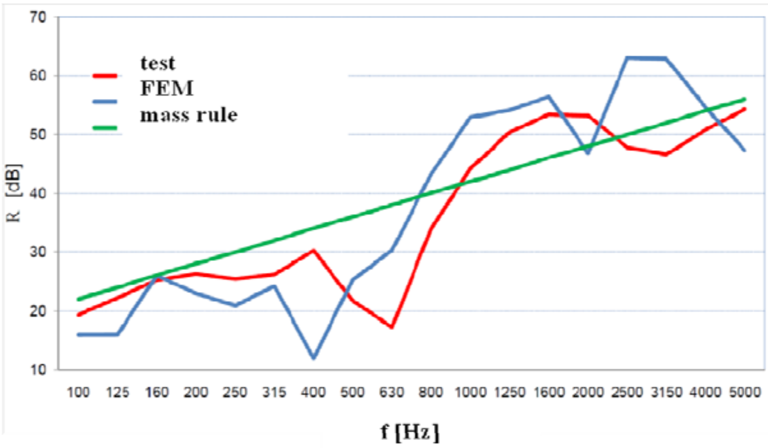


Figure 9. Measured and calculated sound reduction index for SIP versus frequency.

4 Thermal properties

Based on laboratory tests, the heat conduction coefficient was 0.152 [W/(m K)] (glass fibre-magnesium-cement board) and 0.036 [W/(m K)] (expanded polystyrene), and the coefficient of the diffusive resistance was 579.6 [-] (glass fibre-magnesium-cement board) and 31.47 [-] (expanded polystyrene). The requirements with respect to the overall heat transfer coefficient for external walls [4] were fulfilled (U=0.22 W/m^{2}K < U_{max}=0.30 W/m^{2}K) [4]. The risk of the water vapour condensation in the wall panel did not take place (f_{Rsi}=0.963 W/m^{2}K > $f_{Rsi,max}$=0.775 W/m^{2}K) [4].

The process of the heat exchange in different joints of SIPs was simulated by the FEM [3] (Fig.12). The 2D results show that there exists the risk of the water vapour condensation on the internal surfaces of angle joints from steel profiles since the smallest temperature was 9^o-10^oC only (Figs.13a and 13c). This risk does not occur for wall panels with pultrusion profiles since the temperature is about 15^o-17^o (Figs.13b and 13d).
Finally, the FEM analysis of the transient heat transfer based on the Laplace heat transfer equation [2] was performed for a simple residential house composed of concrete frames and SIPs. The 3D results of the temperature distribution (Fig.14) show that thermal bridges are created in connections between panels and concrete columns.

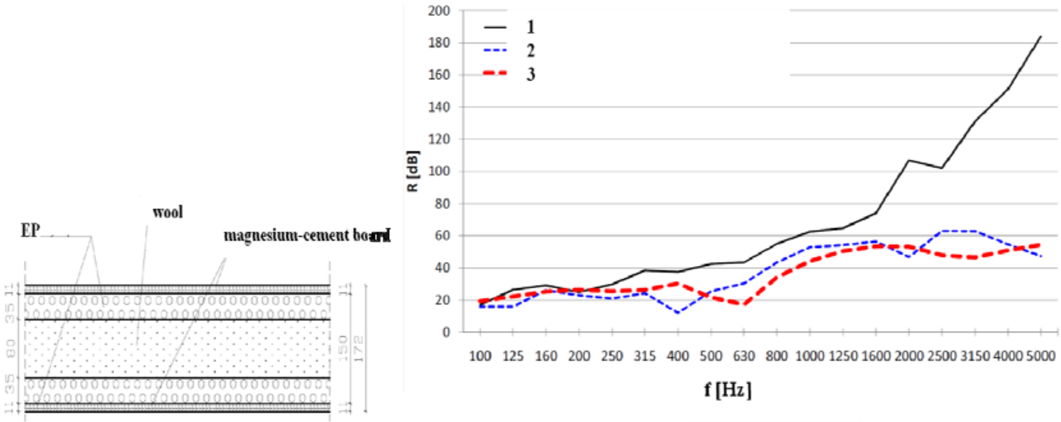


Figure 10. Numerical results versus experiment for sound reduction index versus frequency: 1) FEM – improved SIP panel with wool or 2) FEM – original SIP panel, 3) experiment – original SIP panel.

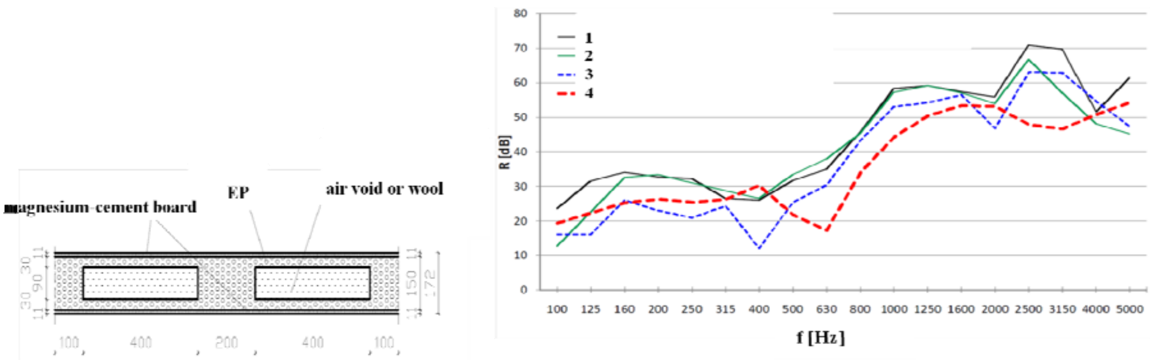


Figure 11. Numerical results versus experiment for sound reduction index versus frequency: 1) FEM – improved SIP with wool, 2) FEM – improved SIP with air voids, 3) FEM – original SIP. 4) experiment – original SIP.

5 Conclusions

The following conclusions are drawn from our initial experimental and numerical studies on SIPs:

- SIPs can be used as structural elements in residential and light commercial buildings. They show high strength against bending and compression. They do not fail by global buckling or facesheet/core debonding. They are light, fire resistant and can be easily and fast assembled on the building-site.
- SIPs should be improved with respect to the sound insulation performance in residential buildings by introducing e.g. air voids or an internal wool damping layer.

- SIPs can be used as insulation elements; they satisfy requirements with respect to the heat transfer coefficient and the risk of water vapour condensation. The second condition is not fulfilled for panel angle joints with steel profiles (in contrast to pultrusion profiles).

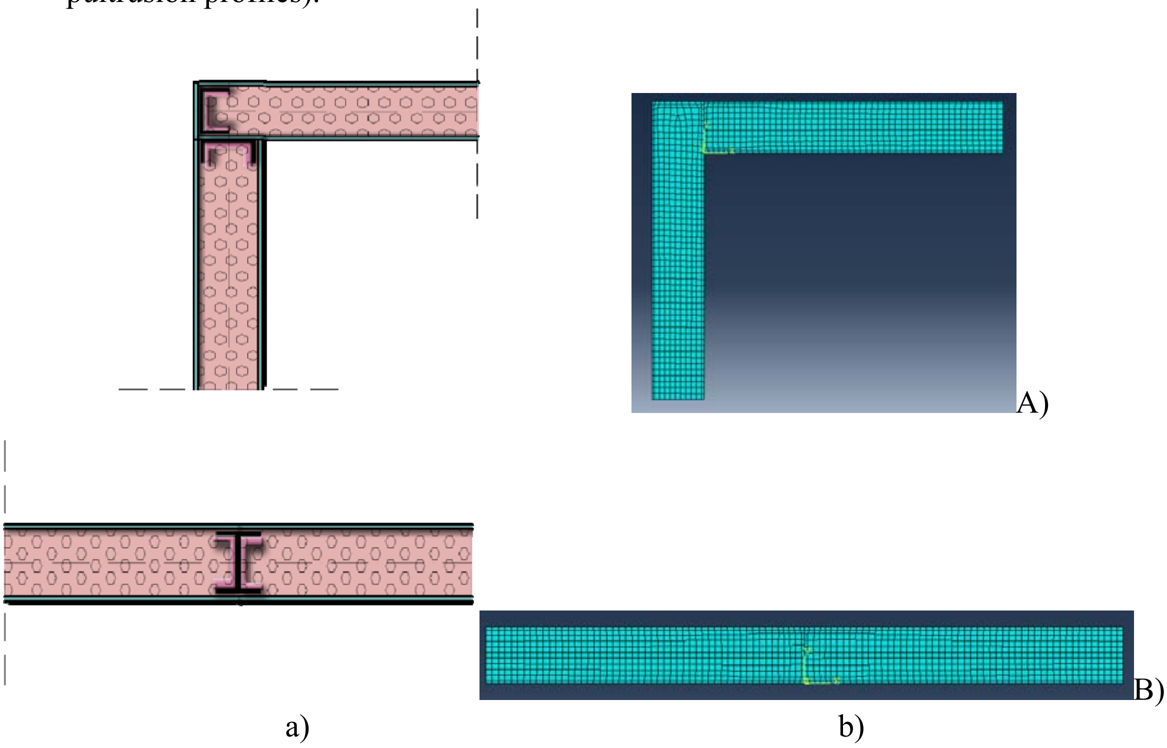


Figure 12. Panel connections: A) external angle joint and B) two external wall panels: a) view, b) FE mesh.

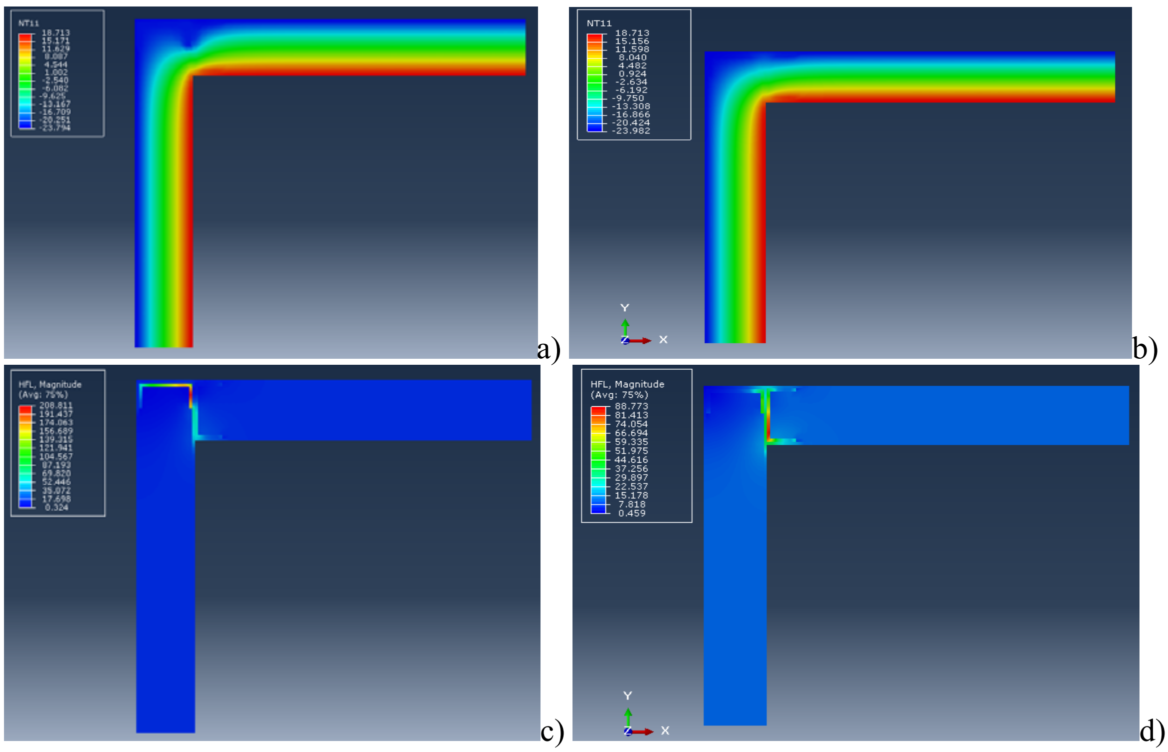
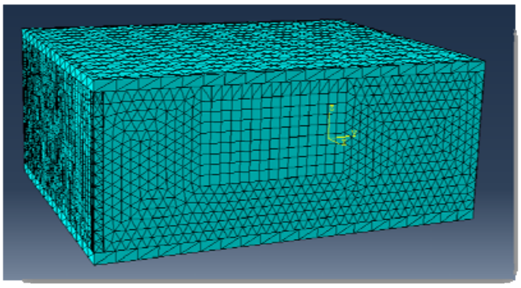
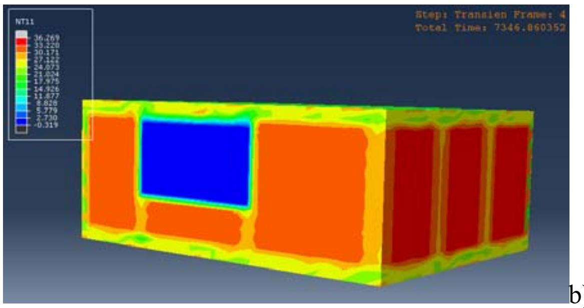


Figure 13. Results of FE simulations for panel angle joint: temperature distribution for steel profiles (a) and pultrusion profiles (b) and heat stream density for steel profiles (c) and pultrusion profiles (d).



a)



b)

Figure 14. FE analysis of residential house composed of concrete frames and SIPs:
a) FE mesh, b) surface temperature distribution.

References

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