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New generation composite panels for military and civil applications: mechanical, thermal, fire, and acoustic properties

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Abstract

The article presents selected results from a research programme on innovative composite panels featuring an insulating core and magnesium cement facings, optionally reinforced with additional steel facings. The scope of the research programme includes the assessment of the panels themselves, as well as the partitions constructed from them and entire buildings, including portable structures built in accordance with the requirements of the United States Army (UFC – Unified Facilities Criteria). Issues relating to structural performance, thermal efficiency, fire resistance, and acoustics were analysed.

Keywords: sandwich panel, insulation, acoustic, thermal, fire performance

1 Introduction

The aim of the research programme was to determine the properties of the new generation of sandwich panels, as well as to design partitions and relocatable buildings made from them, meeting the requirements of the United States Army (UFC). Standardized testing methods were used under both laboratory and field conditions. Advanced numerical models were created and validated by the results of tests conducted under laboratory and field conditions. The area of analysis included structural, thermal, fire, and acoustic issues. Additionally, installation issues in field conditions had to be considered.

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2 Sandwich panels

2.1 The new generation of sandwich panels

The design of building structures can be enhanced by using innovative composite products. Structural Insulated Panels (SIPs) developed in the first half of the 20th century are high-performance, three-layer construction panels used as floor, wall, and roof elements, attached to steel or wooden structures. The panels are manufactured as three-layer units by bonding the outer facings on both sides of a thicker insulating layer, known as the core, with an adhesive (Figure 1). The facings bear the bending stresses, while the core resists shear forces and stabilizes the facings, protecting them from buckling and wrinkling. The core, which has lower mechanical properties compared to the facings, increases the rigidity of the structure by maintaining a constant distance between the facings. The final product is lightweight and has better properties than its individual components (Smakosz et al., 2012).

SIP panels are manufactured in factories and transported to construction sites, where they can be quickly assembled to create a tight, energy-efficient building envelope. Their primary use is in residential buildings and lightweight commercial structures (The Federation of American Scientist, 2009). Due to their high strength-to-weight ratio, they have the potential for military applications in the construction of Relocatable Buildings (RLB) in accordance with the American UFC requirements (UFC 1-201-01).

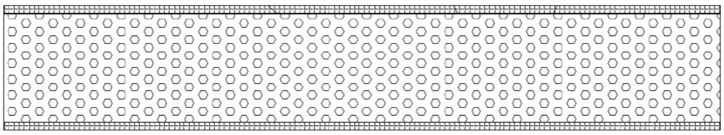


Figure 1. *Cross-section of a typical SIP sandwich panel constructed from rigid, thin facings and a lightweight insulating core*

2.2 SIP sandwich panels with OSB facings

The most commonly used material for facings in SIPs is oriented strand board (OSB), an engineered wood product made from cross-laminated layers of thin, rectangular wood strips that are pressed and bonded with wax and resin adhesives (The Federation of American Scientist, 2009). Since it is a wood-based material, it requires proper impregnation to prevent water infiltration, resistance to windborne debris, and biological degradation (e.g., mould growth, termite attacks). The flexibility, strength, and thermal properties of SIPs have made them an important 21st-century building material, used in structures with high-performance requirements, despite certain disadvantages of the panels themselves (The Federation of American Scientist, 2009).

2.3 SIP sandwich panels with cement facings

An advancement of typical SIP panels is the development of panels with magnesium cement facings. These facings themselves form an advanced composite of special (magnesium) cement, reinforced with fiberglass mesh (one or multiple layers), fibres, fillers, and other components that enhance its properties. Due to the advanced nature of these facings, as well as the sandwich panels made from them, the term Composite Structural Insulated Panels (CSIP) has been adopted in the literature. The CSIP panels in question consist of thin, magnesium cement facings reinforced with fiberglass, and a thick polystyrene (EPS) insulation core, bonded with a thin layer of adhesive (Fig. 2).

Alternatively, polyurethane insulation boards can be used as the core. Mass production of polyurethane insulation boards, used as the core of sandwich panels, is more expensive; however, it enables a significantly lower thermal conductivity coefficient for the mass-produced insulation (core), around 0.022 W/(mK) (Wawrzynowicz, and Florczuk, 2023). The mechanical properties, reaction to fire class, and fire resistance of partitions made from sandwich panels with a polyurethane core are also superior.

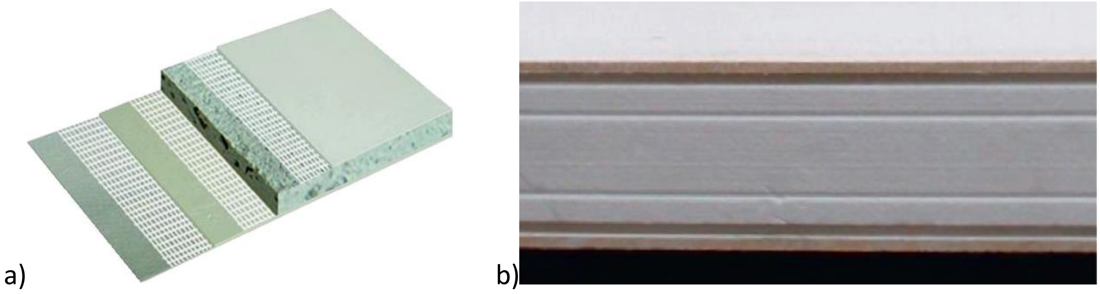


Figure 2. *Cross-section of the magnesium cement facing a) and the composite CSIP sandwich panel with a polystyrene core b)*

2.4 Modified CSIP sandwich panels

Every material has its advantages and disadvantages. The use of magnesium cement boards instead of OSB boards for the production of SIP panels has improved many characteristics, including reaction to fire, fire resistance classification, and resistance to microbiological growth such as fungi and mould. However, compared to OSB boards, a drawback of cement-based materials is their greater brittleness. While this may not be a significant issue for installations in civilian structures, it becomes important in military applications according to the American UFC guidelines (UFC 1-201-01). Relocatable buildings (RLBs) are generally required to be assembled and disassembled several times. Meeting this requirement in field conditions with facings that exhibit increased brittleness may be unfeasible.

To address this issue, it is proposed to reinforce the CSIP sandwich panel with thin steel facings, approximately 0.5 mm thick, attached to the magnesium cement facings using adhesive. A prototype panel with additional reinforcement from steel sheet layers is shown in Fig. 3.

SIP or CSIP panels are typically used as cladding elements, with the structural framework optionally hidden within the joints between panels. The solution of embedding a timber frame within the core of the panels (in the joint between them) is a well-known practice in residential construction. CSIP panels can be further reinforced with profiles embedded around the perimeter. This results in a panel that is strengthened both at the edges (with profiles) and across the surface (with steel sheet layers). Such a panel is resistant to impacts during assembly or disassembly in field conditions and has enhanced mechanical properties, allowing it to serve as a load-bearing element independently.

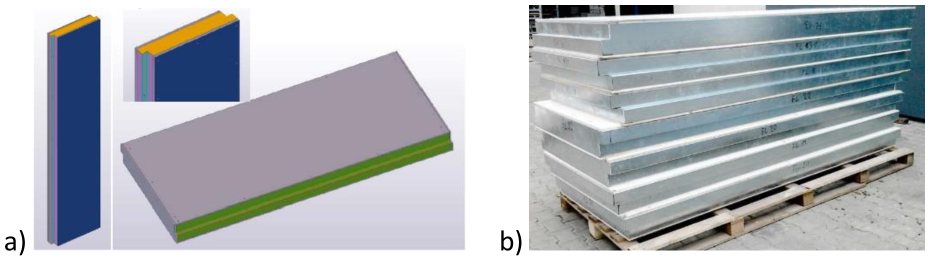


Figure 3. *Modified CSIP composite panel reinforced with steel sheet claddings and edge profiles: a) computer model, b) prototype*

3 Results

Unique results were obtained from laboratory and field tests, as well as numerical simulations in the mechanical, thermal, fire, and acoustic domains. A prototype of the sandwich panels and the relocatable building was produced, along with their computer model.

3.1 Mechanical properties

The new generation of CSIP sandwich panels with magnesium cement facings was tested at the Gdańsk University of Technology in a wide range, covering mechanical, thermal, and acoustic properties. Below, key strength properties from the perspective of relocatable buildings are presented.

The SIP or CSIP sandwich panel is not regarded as a structural element in civil construction, but rather as cladding for buildings. However, conducted studies indicate untapped potential in this area. As shown by Smakosz and Tejchman (Smakosz, and Tejchman, 2014), a CSIP panel with a width of 1000 mm, a 150 mm thick expanded polystyrene core, 12 mm thick magnesium-cement facings on both sides, and a height of 2750 mm is capable of bearing vertical compressive loads of 131 kN (e=0), 197 kN (e=d/6), and 163 kN (e=d/3). The eccentricity of the applied force is defined by the ratio e in relation to the total thickness of the tested panel d (172 mm), where e=0 indicates axial force without eccentricity. The panels were tested in a horizontal configuration due to workstation constraints. The setup and failure mechanism are shown in Figure 4.

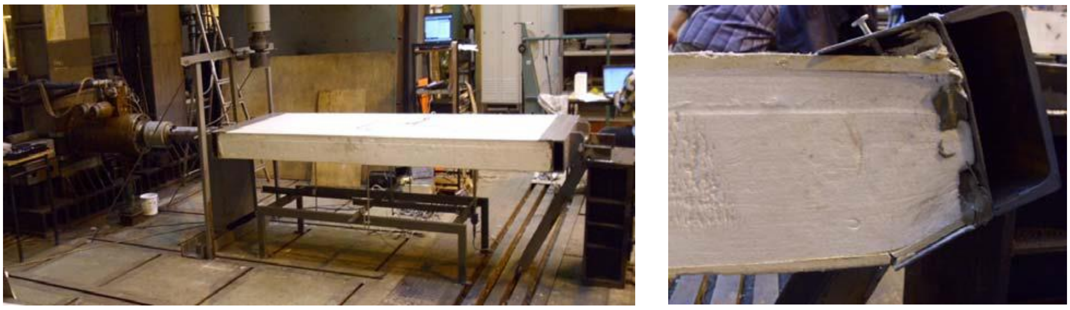


Figure 4. *Strength testing of the CSIP panel under compressive force. Testing setup in horizontal orientation*

3.2 Thermal properties

The thermal transmittance of partitions made from SIP or CSIP sandwich panels depends mainly on the thermal resistance of the panel's core, i.e., its thickness and thermal conductivity coefficient. Thermal bridges have a negligible effect when spline connections are used, but they become significant in modified CSIP panels, where steel edge reinforcements act as conducting elements (see Chapter 1.4). To mitigate this disadvantage while maintaining reinforced edges, perforated edge profiles were proposed (Fig. 5).

The use of perforation has allowed for a 25% reduction in the heat transfer coefficient U of the modified CSIP panel compared to the panel with edge profiles without perforation. Figure 6 illustrates the temperature distribution with an external temperature of -10°C and an internal temperature of +20°C.

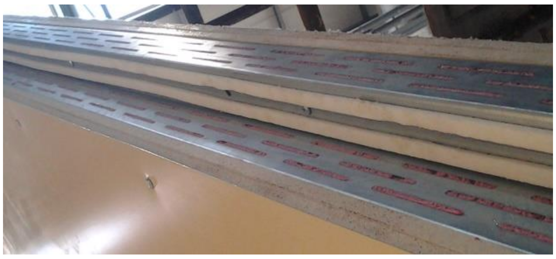


Figure 5. Modified composite sandwich panels: detail of edge reinforcement with perforated steel profiles

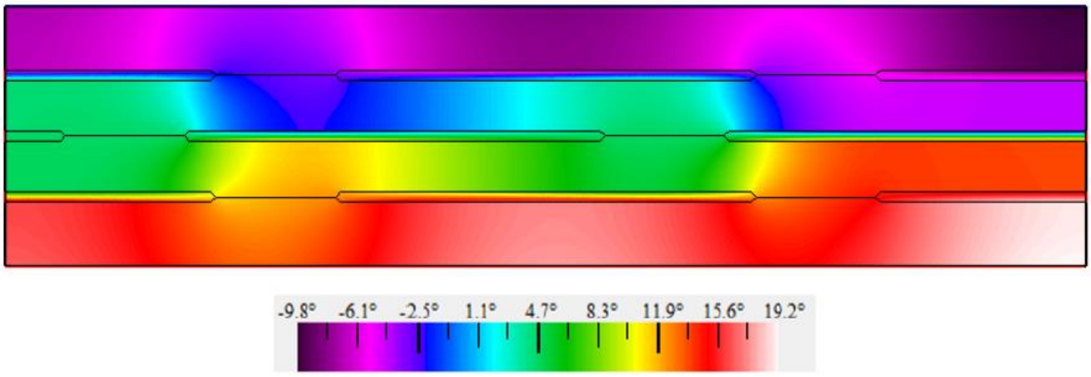


Figure 6. Modified composite sandwich panels with a 120 mm thick PIR core: temperature distribution in the edge profile

3.3 Fire properties

Fire property testing is well known among manufacturers of sandwich panels, particularly those with steel facings produced according to EN 14509. Typical characteristics specified in EN 14509 include fire resistance, reaction to fire, and for roofing panels, the fire spread classification, usually rated as Broof (non-spreading fire). Polish regulations additionally introduce a classification for fire spread from the external side of external walls, known as NRO (PN-B-02867). The aforementioned panels (EN 14509) are not designed as structural elements, meaning they do not carry loads (the dead weight and loads from wind and temperature are transferred to the primary structure), let alone loads during a fire.

Below are the results of tests on modified composite sandwich panels (see Chapter 1.4), which serve a structural function during a fire, including bearing the load of water spray simulating real firefighting conditions. The requirement to withstand water spray loading is mandated for RLB (Relocatable Buildings) in accordance with the Unified Facility Criteria (UFC 1-201-01) developed by the U.S. Department of Defense. The tested partition is made from modified CSP sandwich panels with a 120 mm thick polyurethane core and 11 mm thick magnesium-cement facings on both sides. The facings are reinforced with steel sheets on the outer sides. The edges of the sandwich panel are strengthened with perforated steel profiles (see Fig. 5). The tests were conducted according to ASTM E119-12a. The dimensions of the tested partition were approximately: width 3.5 m, height 2.6 m. The partition was subjected to fire loading in accordance with ASTM E119 for 1 hour. A load of 4.1 kN/m was applied to the upper edge (see Fig. 7a). After 1 hour of fire loading, the panel was removed from the furnace and subjected to water spray loading (see Fig. 7b). The partition achieved a 1-hour fire resistance classification according to American standards (ASTM E119-12a). Horizontal deflections did not exceed 40 mm, and vertical deflections did not exceed 0.3 mm. The maximum temperature on the external surface of the partition (not exposed to fire) did not exceed 100°C during the 60-minute fire loading cycle.

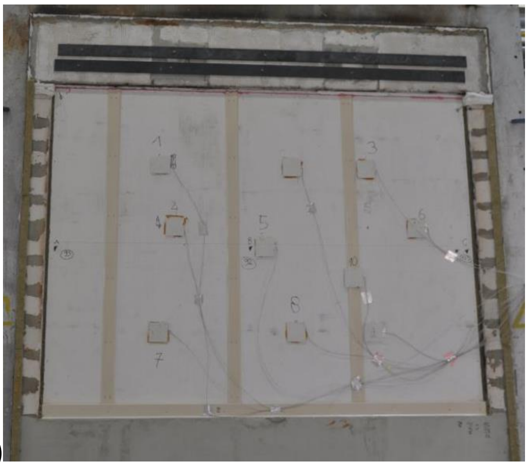
a) 
b) 

Figure 7. Fire resistance tests (ASTM E119-12a). Partition made from modified composite sandwich panels: a) before fire loading, b) after 1 hour of fire loading, during water spray application.

3.4 Acoustic properties

One of the essential characteristics important for ensuring acoustic comfort is the acoustic insulation of partitions against airborne sound. Insulation is determined under laboratory conditions and presented in the form of an acoustic insulation curve as a function of frequency. The standard basic frequency range in Europe is from 100 Hz to 3150 Hz. Based on the insulation curve, single-number ratings Rw (C, Ctr) are established to facilitate the comparison of building products and the partitions made from them in the construction market.

Composite sandwich panels are characterised by a high strength-to-weight ratio compared to traditional materials. Each product has its advantages and disadvantages. In light of this, it can be assumed that the acoustic insulation against airborne sound is a characteristic that can be improved. Typical sandwich panels with a polyurethane core and steel facings (EN 14509) have a single-number rating Rw of around 25 dB. The use of magnesium cement facings allows for an increase in the Rw rating to 32 dB (Wawrzynowicz, 2016). Laboratory test results and advanced numerical simulations (see Fig. 8) of the partition made from composite sandwich panels (see Chapter 1.3) are presented in Table 1. The partition made from modified CSIP panels (see Chapter 1.4) has not been tested, but it is expected that the ratings will not be lower due to the increased weight of the panel (additional steel facing).

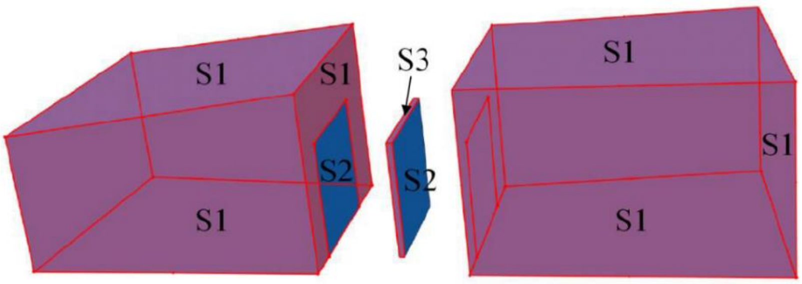


Figure 8. Virtual acoustic laboratory: a set of reverberation chambers. Boundary conditions: S1 – definition of impedance at the surface of the chambers, S2 – structure-acoustic medium interface, S3 – constraint of displacements of the partition.

Rating	Rw [dB]	C [dB]	Ctr [dB]	RA1 [dB]	RA2 [dB]
Simulation 1	29	-3,4	-5,1	26,6	24,9
Simulation 2	30	-4,2	-6,1	25,8	23,9
Measurement	32	-4,5	-6,0	27,5	26,0

Table 1. Single-number acoustic insulation ratings for airborne sound of the partition made from composite sandwich panels (see Fig. 2) were obtained from measurements and numerical simulations (see Fig. 7). Simulation 1 involved a fixed sound source location, while Simulation 2 featured a variable sound source location.

4 Relocatable building

In accordance with the requirements of the Department of Defence (UFC 1-201-01), relocatable buildings (RLBs) should be capable of being assembled and disassembled multiple times at various locations worldwide, from Egypt to Asia and as far as Kazakhstan. Furthermore, the assembly and disassembly should be achievable without the use of heavy machinery, necessitating the design of sandwich panels with a limited weight. A prototype structure has been constructed using modified composite sandwich panels (see Fig. 9). The building requires field tests to demonstrate its ability to maintain the designed properties under challenging conditions.

Figure 9. Prototype portable building constructed using modified composite sandwich panels

5 Conclusions and summary

The obtained results indicate the high potential of the sandwich panels and the structures made from them for civilian protection and military applications (military or civilian relocatable buildings). There is a need for verification in field conditions.

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