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# Numerical and Experimental Study on Loading Behavior of Facade Sandwich Panels

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**Abstract:** This paper focuses on the study of the strength of facade sandwich panels used in building construction. The paper describes the results of experimental and numerical research on the behavior of sandwich panels made of polyisocyanurate core (PIR) and their structural connections when exposed to tensile and compressive loads. In the initial phase of this study, laboratory tests were performed to determine the physical and mechanical characteristics of the material from which the sandwich panels are made. Laboratory tensile and compression tests were performed on small samples of sandwich facade panels. In order to verify the obtained results, they were compared with the numerical analysis performed in the ANSYS software. The numerical model was found to accurately predict the results of the laboratory tests, suggesting that the model can be used to predict the behavior of these panels under different loads in service. The study showed that the foam core sandwich panel exhibits excellent mechanical properties. The results indicate the suitability of foam-based composite structures in the construction industry for various applications, such as roof and wall structures. The findings of this study may help in the development of lightweight and durable construction materials for the industry.

**Keywords:** walls sandwich panels; PIR core; experimental tests; finite element modeling



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## 1. Introduction

The daily needs of modern construction are placing increasingly complex demands on designers and architects, both in the application of new materials and in the optimal use of existing materials. This includes the application of new technologies in the production process and technical innovations in the construction process, as well as the realization of optimal requirements in terms of rationality, durability, and aesthetics. Sandwich panels as facade elements are widely used in modern construction. In addition to aesthetic benefits, they also fulfill requirements for thermal insulation, fire resistance, and durability.

The structure of sandwich panels comprises two facings that are relatively thin and of high strength and a core of high thickness and low density [1]. The facings can be made of steel, aluminum, wood, fiber-reinforced plastic, or even concrete. The core can be made of cork, balsa wood, rubber, solid plastic material (polyethylene), rigid foam material (polyurethane, polystyrene, phenolic foam), mineral wool slabs, or from honeycombs of metal or even paper [2]. The sandwich structure is widely used in the automotive, aerospace, and marine industries due to its light weight, high strength, and excellent structural properties. It offers significant advantages in these domains [3–5].

Nowadays, the structure of the wall sandwich panel that is used in building construction is two metal facings that enclose a rigid core (polyisocyanurate foam or mineral wool). The metal facings are very thin. Steel sheets have a minimum thickness of approximately

0.5 mm and aluminum of approximately 0.7 mm. The metal surface can be lightly profiled, also known as "micro-profiled", or deep-profiled. Therefore, the flat faces carry bending moments, such as tensile and compressive stresses, and the core carries shear force. If the faces are deep-profiled, they convey additional bending moments and shear force related to their bending and shear stiffness [6].

The core is usually made of a rigid plastic foam material or mineral wool. The characteristic properties of rigid foam (PIR), especially fire resistance, were discussed in paper [7]. The behavior of mineral wool sandwich panels under bending load at room and elevated temperatures was studied by Ashjan Shoushtarian Mofrad et al. [8].The core material must have enough strength and stiffness to contribute to the composite action and to enable the structural sandwich to carry the design loads [9]. The adhesive bond between the facing and the core must carry a shear stress equal to the shear in the core. Prevention of the relative slipping of facings requires a core with a sufficiently high shear modulus, as well as adequate shear strength [10]. Valean et al. investigated the mechanical behavior of a polyurethane-foam-based sandwich panel under tensile and bending tests [11]. They found that in the transverse tensile test, the foam-based composite structure showed a brittle behavior until its final failure, the fracture taking place in the core and not at the core–face interface.

The production of sandwich panels typically involves the following steps:

- Sheet placement: two flat or slightly profiled galvanized sheets, usually with a thickness of 0.5 to 0.6 mm, are inserted into the machine, for example, PUMA-KROWN. The sheets are positioned horizontally and placed at a distance from each other that corresponds to the desired thickness of the panel.
- Injection of PIR Foam: the polyisocyanurate (PIR) foam is injected between the two sheets. PIR foam is a type of rigid foam insulation known for its excellent thermal properties. The foam is injected as a liquid mixture, and it expands to fill the volume between the sheets. During this expansion, the foam adheres securely to the sheets.
- Foam Expansion and Adhesion: as the PIR foam expands, it forms a strong bond with the sheets. The foam contains various components, including adhesion-promoting agents, that ensure a secure adhesion between the foam and the sheets. This adhesion is important to prevent fractures or separation at the junction between the sheet and the foam when the panel is subjected to tensile stress. Therefore, during tensile stress, the fracture does not occur at the junction of the sheet and the PIR but within the structure itself, as the experiments we performed showed.
- Cooling: After the foam injection, the panels are allowed to cool down. The cooling process allows the foam to harden and set, ensuring structural integrity.
- Cutting and Processing: Once the foam has cooled and hardened, the sandwich panels are cut into the desired dimensions. The sides of the panels may also be processed or trimmed as needed to achieve the desired finish or fit.
- Finishing: The outer surfaces of the panels, typically the sheet surfaces, can be plasticized or coated with a layer of plastic material. This plasticization process serves to enhance the panel's appearance and protect it from environmental factors. The color of the plasticized surface is customized according to the customer's requirements.
- Storage: Finally, the finished sandwich panels are stored before they are shipped or used in various applications such as construction, insulation, or industrial purposes.

It is worth noting that the specific production process may vary depending on the equipment, materials, and technologies used by different manufacturers. The description provided above outlines a general process for producing sandwich panels with galvanized sheets and PIR foam.

In this study, the initial objective is to verify the numerical results with the experimental results for the maximum tension sandwich panel with thin steel faces and PIR foam core. The finite element method represents an efficient and reliable method for the structural analysis of complex structures [12,13].

Sandwich panels can be subjected to a combination of tension and compression loads, which can cause the panel to deform or fail if the stress is not distributed properly throughout the panel. When sandwich panels are subjected to both tension and compression loads, the load is distributed throughout the panel in a complex manner. The stresses in each layer of the panel are influenced by the load, the geometry of the panel, and the properties of the materials used in the panel. Generally, the facings of a sandwich panel are designed to withstand the majority of the tension and compression loads, while the core material provides additional support and stability. The core material can be chosen based on its ability to withstand the compression loads and transfer the load to the facings.

During the design phase, static analysis is typically carried out for the facility while in operation, without taking into account the construction phases. This is precisely where the contractor's biggest responsibility lies—planning the order for panel installation to avoid creating conditions for significantly less favorable wind action than what was designed (Figure 1).

**Figure 1.** Cladding failure; Source: Photo taken by company Frigomex, in September 2017, Sremska Mitrovica, Serbia.

The goal of this study is to provide contractors with reliable data related to the panels themselves, including the choice of colors and dimensions, as well as the number and type of mechanical fasteners required to withstand all potential impacts that may occur during both the construction and exploitation phases of the facility. It was observed that in most cases of damage, the fracture occurs exactly at the points where the mechanical joints of the panels are located, where the bolt head, together with the supporting plate, breaks through the panel itself, while the connecting means remain undamaged (Figures 2 and 3).

**Figure 2.** Panel failure: Delaminated metal facing; Source: Photo taken by company Frigomex, in September 2017, Sremska Mitrovica, Serbia.

For this reason, special attention in this study is devoted to the analysis of the bearing capacity of these joints, with the application of different diameters of screws and washers as a part of the experimental research. It is also known that in practice, local surface deformations of the cladding occur on the rendered facade panels due to temperature changes, especially during the summer period. These changes are mostly influenced by the chosen color of the exterior cladding and the dimensions of the element (length). In addition to local deformation, the chosen color can also affect the reactions on the beams near the columns and, therefore, the required number of connecting means. This will also be the subject of further research in order to offer optimal solutions to designers and contractors.

**Figure 3.** Pull-through failure of fastenings; Source: Photo taken by company Frigomex, in September 2017, Sremska Mitrovica, Serbia.

The wind can exert significant forces on the building envelope, including the facade sandwich panels, and these forces can cause the panels to bend, buckle, or even detach from the building. This can lead to structural damage, water infiltration, or other issues. One of the most common types of damage that can occur in sandwich panels under wind action is deflection, where the panel bends or bows due to the wind force. Deflection can be caused by a variety of factors, such as insufficient panel thickness, inadequate support, or incorrect installation.

Another type of damage that can occur in sandwich panels under wind action is fatigue, which is caused by the repeated loading and unloading of the panel due to wind gusts. This can cause small cracks or fractures to form in the panel, which can grow over time and weaken the panel, leading to potential failure.

To prevent damage to sandwich panels under wind action, it is essential to ensure proper design, installation, and maintenance. Panels should be designed to withstand the wind forces in the area where the building is located. This may involve increasing the panel's thickness, providing additional support, or installing the panel with specific clips or fasteners. Regular inspection and maintenance can also help detect and prevent potential issues before they become significant problems.

## 2. Materials and Methods

### *2.1. Experimental Test Arrangement*

The study used Kingspan wall horizontal sandwich panels KS1000 TF/NF with a polyisocyanurate (PIR) core [14]. The panels had a thickness of 100 mm and were mostly used as horizontal elements connected by mechanical means to the building's columns. The panels were selected from a range of positions with lightly profiled faces. The faces of the panels were made of steel with a modulus of elasticity of $2.1 \times 10^5$ N/mm$^2$, and the core had a density of 40 kg/m$^3$. The specimens had a cross-sectional shape as depicted in Figure 4. The purpose of the test was to determine the strength of the panels when they were subjected to bending loads, tensile loads, and compressive loads, depending on the effects of wind or temperature. The connecting means themselves were subjected to tensile loads or combined loads of tension and bending.

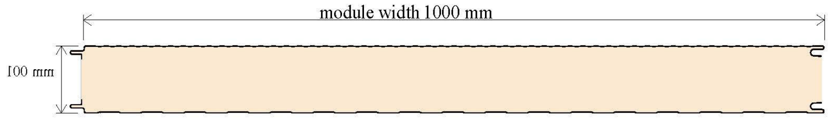
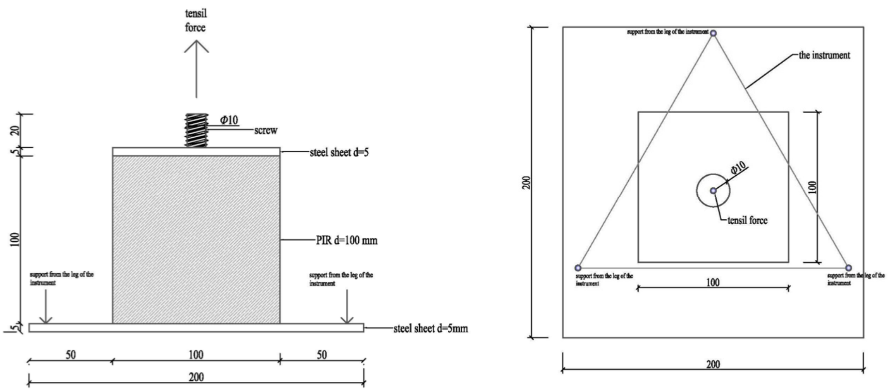



**Figure 4.** Cross section of panel PIR core 100 mm.

The testing of the specimens was conducted in accordance with the EN 14509:2013 [15] Standard, which states that the tensile and compressive samples should have square cross-sections with side dimensions between 100 mm and 300 mm. The specimens for the tensile test had a width of 100 mm and length of 100 mm and were connected using the glue SikaDur 52, on both sides, for metal sheets with a thickness of 5 mm and with the dimensions of the sheets required by the testing devices. In order to accurately determine the maximum load capacity of the panel, the specimens were tied with a screw, and a tension test was performed over the screw (as shown in Figure 5). The instrument used to measure the maximum load capacity of the panel was the "Dynatest" (Figure 6) testing instrument, which has a maximum tensile strength capacity of up to 16 kN. The setup for the tensile test is shown in Figure 7.




(**a**) (**b**)

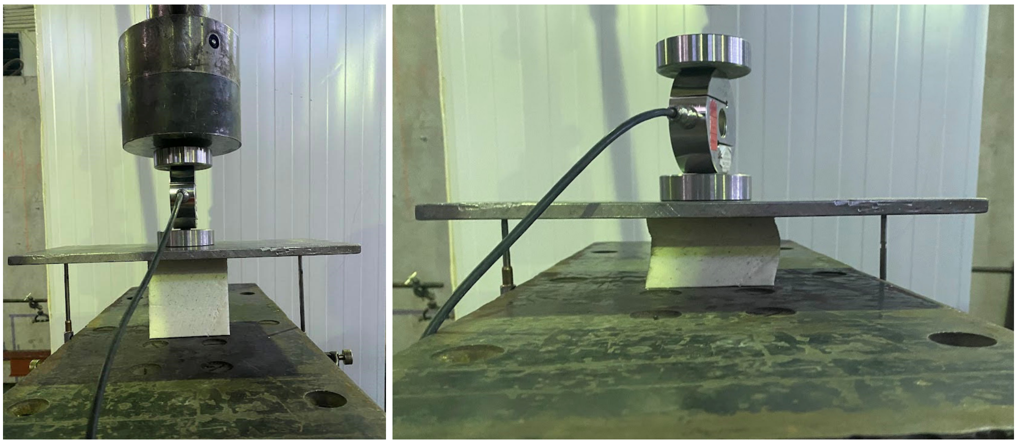
**Figure 5.** Tensile test: (**a**) cross section; (**b**) background of the specimen.


**Figure 6.** Dynatest—testing instrument.

(a) (b)

**Figure 7.** Tensile specimens: (**a**) before the test; (**b**) after the test (failure of panel core).

The specimens for the compressive test had dimensions of 100 mm (height) × 100 mm (width) × 100 mm (thickness). The compression tests were performed using the hydraulic machine "Amsel", which had a maximum load capacity of 100 kN, as shown in Figure 8. The displacement due to the action of the tensile and compression force was also measured using the instrument "Compac".



(a) (b)

**Figure 8.** Compression specimens, (**a**) before the test, (**b**) after the test (failure of panel core).

*2.2. Finite Element Modeling*

The finite element method (FEM) is the numerical technique that is used to perform finite element analysis. When the finite element method originated, it held exciting potential for the modeling of various mechanical applications related to civil and aerospace engineering. However, the possible uses of the FEM can extend far beyond this to use in coupled problems including biomechanics and biomedical engineering, fluid–structure interaction, and electromagnetics. Finite element analysis (FEA) is the use of calculations, models, and simulations to predict and understand how an object might behave under various physical conditions. Using finite element analysis can reduce the number of physical prototypes created and experiments performed while also optimizing all components during the design phase. Finite element analysis software emerged in the 1970s with programs such as Abaqus, Adina and Ansys. Now, it is common to find virtual testing and design optimization integrated into the product development cycle to improve the product quality and reduce the time it takes to enter the market. The objective of this work is to develop a modeling approach to predict response of sandwich panels under static bending conditions. In this work, the finite element method was used to verify the obtained results within the analysis carried out in this research. For that purpose, isoparametric three-dimensional 8-node solid finite elements were used. The glue material between steel faces was modeled using solid finite elements as well.

This section presents the results of the numerical simulation of the tensile test specimen shown in Figure 5. The structural analysis was performed using the finite element method. ANSYS software was used for this purpose. ANSYS software is an essential tool for modern engineering, providing the ability to model, simulate, and analyze complex structures and systems and helping engineers design structures that are efficient, safe and sustainable [16].

Figure 9 shows the finite element model of the specimen.

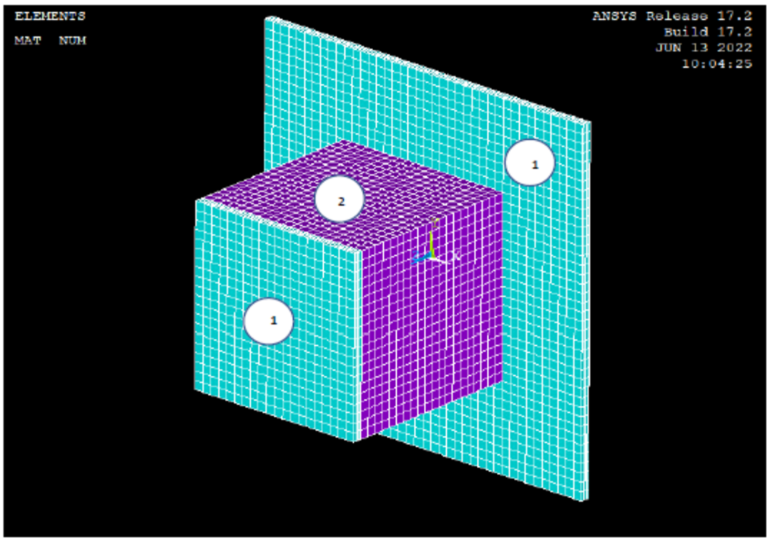



**Figure 9.** Finite element model of the tensile specimen: (1) steel sheets, (2) polyisocyanurate foam.

Figures 10 and 11 show the corresponding stresses states in the tensile test specimen itself for the corresponding force, F, with which the test specimen is loaded as shown in Figure 5.

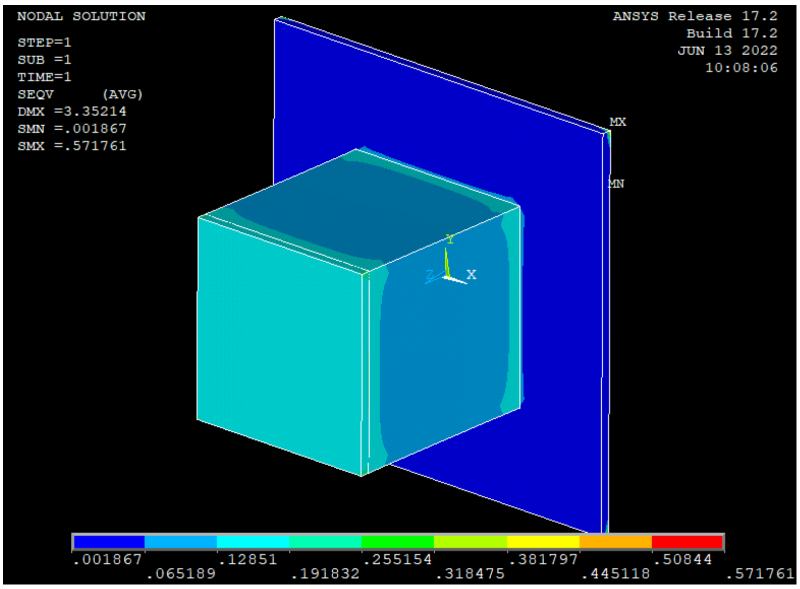



**Figure 10.** Von Mises stresses in nodes, $S_{max}$ = 571 kN/mm$^2$ subject to force F = 1.279 kN.

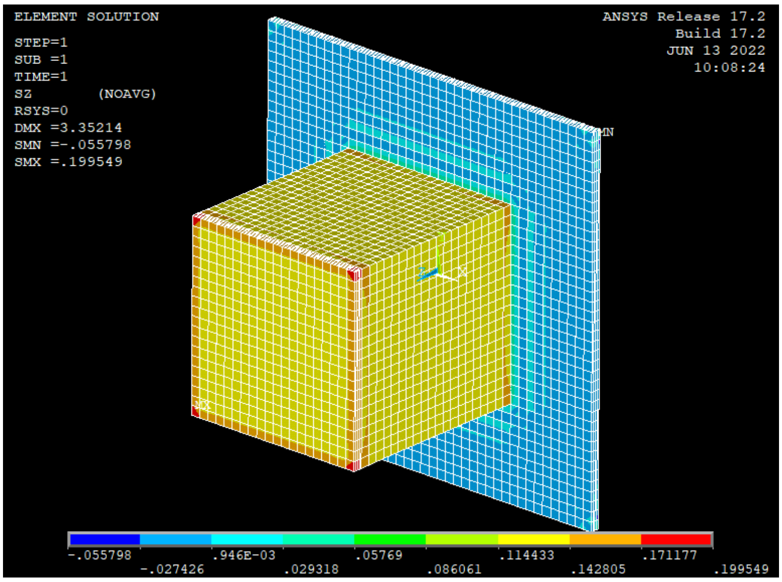



**Figure 11.** Stresses in the axial direction in the finite elements, $S_{max}$ = 199 kN/mm$^2$ subject to force F = 1.279 kN.

Figure 12 shows the displacement in the axial direction, i.e., in the direction of the load. Figure 12 graphically illustrates in color the displacement values obtained by structural analysis using FEM under load force F = 1.279 kN. The blue color represents the minimum displacement value and the red color represents the maximum displacement value; in this case, it is 3.35 mm, marked in the figure as DXX + 3.35 mm.

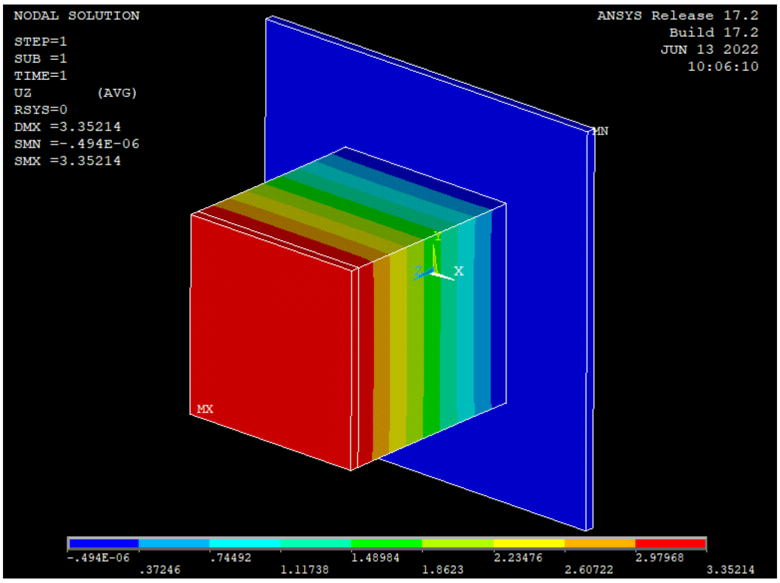



**Figure 12.** Displacement in the axial direction, δmax = 3.35 mm for a force of F = 1.279 kN.

Figure 13 shows the axial stresses on the outer edge of the filling (material 2) for the force F = 1.050 kN.

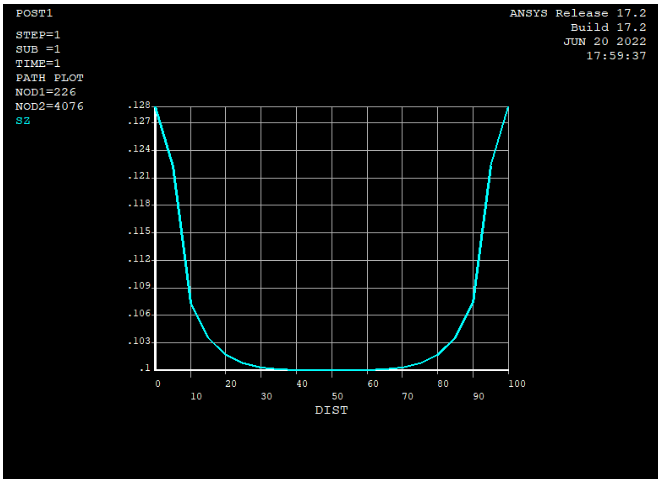



**Figure 13.** Axial normal stresses on the outer edge of the infill (material 2) for force F = 1.050 kN.

## 3. Results

### *3.1. Tensile Test*

The tensile test was performed on nine samples. The results of the tests showed that the fractures occurred in the PIR core near the supports, as seen in Figure 7b. The results of the experimental tests showed that the maximum force was 1.175 kN, the minimum force was 0.50 kN, and the displacements ranged from 3.20 mm to 5.00 mm. On the basis of the derived results, it can be concluded that the flow of diatoms is approximately linear until the break.

It can be seen from the diagram in Figure 14 that the relationship between force and displacement is approximately linear, which means that the material is not plasticized until it breaks. This indicates a material that has no pronounced ductility.

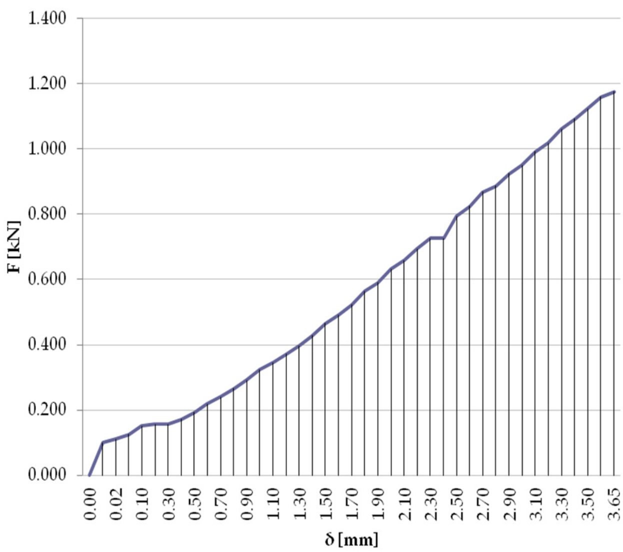



**Figure 14.** Tensile force–displacement curve.

The tensile strength ($f_{ct}$) was calculated based on the results from the experimental test (Figure 14), using Equation (1):

$$f_{ct} = F_u / A, \tag{1}$$

where $F_u$ is the ultimate load, and $A$ is the cross-sectional area of the specimen, determined from the measured dimensions. After replacing the data, the maximum value of $f_{ct}$ $\left(f_{ct,max}\right)$

was 0.1175 MPa. The tensile *E*-modulus for the core material was also calculated using Equation (2):

$$E_{ct} = (F_u \cdot d_c)/(w_u \cdot A) \tag{2}$$

where $d_c$ is the sample thickness and $w_u$ is the ideal displacement at the ultimate load, based on the linear part of the load-displacement curve. The maximum value of *E* was 3.264 MPa.

Comparisons Computation with Experimental Results

In this section, the comparisons of experimental and numerical results of tensile test, based on FEM, which were realized within this work, are given. Table 1 shows the mechanical characteristics that were used in the numerical simulation based on FEM.

**Table 1.** Material properties of sandwich panel.

| **Layers** | **$\gamma$ [kg/m$^3$]** | **E [N/mm$^2$]** | **$\nu$** | **$f_u$ [N/mm$^2$]** |
|---|---|---|---|---|
| Steel sheets | 7850 | 210,000 | 0.3 | 360 |
| Glue | - | 1600 | - | 30 |
| Steel facings | 7850 | 210,000 | 0.3 | 390 |
| PIR core | 40 | 5.7 | 0.05 | - |

In this investigation, material properties from Table 1, denoted as Steel facings and PIR core, are used.

Table 2 gives the comparative values between the experimental results and FEM. In Table 2, a good agreement computation with the experimental results is evident.

**Table 2.** Experimental and numerical results of the tensile test.

| **Item** | **Max F [kN]** | **Max $\delta$ [mm]** | **Type of Failure** | **FEM Max F [kN]** | **FEM Max $\delta$ [mm]** |
|---|---|---|---|---|---|
| 1 | 0.527 | 3.45 | PIR core | | |
| 2 | 0.737 | 3.46 | PIR core | | |
| 3 | 1.143 | 3.20 | PIR core | | |
| 4 | 1.070 | 3.40 | PIR core | | |
| 5 | 1.159 | 3.20 | PIR core | 1.279 | 3.35 |
| 6 | 1.175 | 3.60 | PIR core | | |
| 7 | 0.705 | 2.60 | PIR core | | |
| 8 | 1.164 | 3.20 | PIR core | | |
| 9 | 0.500 | 5.00 | PIR core | | |

The mean value, deviation, and variance according to the Gaussian distribution are determined in Table 3.

**Table 3.** Statistical results from Table 2.

| | **Max F [kN]** | **Max $\delta$ [mm]** | **FEM Max F [kN]** | **FEM Max $\delta$ [mm]** |
|---|---|---|---|---|
| average | 1.09 | 3.40 | 1.279 | 3.35 |
| deviation | 0.70 | 1.91 | | |
| variation | 64.06 | 56.18 | | |

*3.2. Compression Test*

For the compression test, the four samples were examined (Table 4), where F is force, t is time, $\delta_1$ is displacement, and $d_1$ is the thickness after applying the force. It can be concluded based on the obtained experimental results that the thickness of the panels after the completed load test remains approximately the same, regardless of the duration of the force action, which indicates the fact that all samples reach the final compressibility within the same limits.

**Table 4.** Experimental results of compressive test.

| Item | F [kN] | t [s] | $\delta_1$ [mm] | $d_1$ [mm] |
|---|---|---|---|---|
| 1 | 19.810 | 141.9 | 86.98 | 56 |
| 2 | 8.136 | 144.8 | 78.63 | 61 |
| 3 | 7.966 | 195.6 | 80.32 | 56 |
| 4 | 7.060 | 113.6 | 75.39 | 60 |

Based on the results from the experimental test, the compressive strength $f_{cc}$ was calculated using the Equation (3):

$$f_{cc} = F_u / A \tag{3}$$

After replacing the data, an $f_{cc,max}$ value of 0.1175 MPa was obtained. Furthermore, the test report obtained a compressive $E$-modulus for the core material using the Equation (4):

$$E_{cc} = (F_u \cdot d_c) / (w_u \cdot A) \tag{4}$$

The maximal $E$ value was 1.035 MPa.

The flow of the diagram during compression is significantly different from the flow of the diagram during tension, which is understandable considering that there is an increase in the compaction of the fibers when the compressive force increases, until the final failure of the sample. The force ratio during compression and tension ranges from 6 to 8 kN.

In the next phases, which are already underway, attention is focused on the behavior of the facade sandwich panels and their connections in real constructions. In order to fully understand all the factors that influence the behavior of the panels during exploitation, laboratory tests on the behavior of the panels and their connections, as well as measurements on the facades of the constructed buildings, are planned. The future laboratory tests will be focused on facade panels with thermal insulation filling made of polyurethane-PIR, 10 cm and 12 cm thick. For this purpose, panels of the dimensions used in the construction of the building are chosen, joined with self-tapping screws for steel box profiles.

It is well known that the wind blowing on the facades of the building, and especially in the corner areas of the building, represents a significant load for the dimensioning of the connection bolts for compression. Within the laboratory tests, it is planned to carry out an analysis of the bearing capacity of the connection bolts with a diameter of 5.5 and 6.3 mm manufactured by E-jot for different diameters of supporting plates from under the screw head [17]. As mentioned earlier, the damage to the buildings that occurred during construction was most often related to the failure of the connection between the sheet metal cladding of the sandwich panel and the screw head, i.e., the supporting plate. As a result of this study, recommendations should be made for application in practice, which would refer to the choice of diameter and number of bolts depending on the drying effect of the wind according to the location of the object and the category of the terrain in accordance with the Eurocode for the analysis of the wind effect [18,19]. The research that would be carried out on the facades of the buildings refers to the measurements of temperature dilatations depending on the temperature change for different colors of the facade. This research is planned in the summer period, when temperature dilatations are most pronounced. For this purpose, it is planned to install measuring instruments on the object itself to monitor the deformations of the metal linings of the sandwich panels. It is foreseen that tests will be carried out on several colors of facades, whereby the property is given to the anthracite color (RAL 7016) and the gray color (RAL 9002), which showed the highest temperature expansions on the performed facades, especially at summer temperatures when the facades are exposed to direct sunlight. The construction of facade panels and their connections must be dimensioned for both of these conditions at the same time, that is, for their most unfavorable combinations, in addition to their own weight. As a result of these investigations, it is planned to make recommendations related to the determination of the maximum panel lengths depending on the chosen color of the facade, as well as the required number of connecting screws for connecting the panels to the steel structure, as well as the optimal choice of screw diameters and washers under the screw heads. The results of these examinations can provide valuable information for the development of energy-efficient and sustainable building materials. The findings can help in the optimization of the design and construction of facade panels with thermal insulation filling, which can improve the energy efficiency of buildings and reduce their environmental impact. The results can also contribute to the development of building codes and standards that promote the use of energy-efficient building materials.

## 4. Conclusions

In conclusion, this study has presented a comprehensive analysis of the stress and strength of foam-based sandwich panels under tearing and compressive loads. The experimental tests and numerical simulations using the finite element method showed good agreement, indicating that FEM is a reliable tool for the structural analysis of complex sandwich structures. The results of this study can be useful for the design and optimization of sandwich panels for various applications.

The results showed:

- The foam-based composite structure exhibited brittle behavior in the tensile test, with failure occurring in the core rather than at the core–face interface. The maximum tensile strength and tensile modulus for the core were 0.1175 and 3.264 MPa, respectively.
- Compressive force–displacement curves (Figure 15) revealed three distinct areas: linear-elastic, plateau, and densification. The compression strength and modulus were 0.8136 MPa and 1.035 MPa, respectively.
- These mechanical properties can be used in the design calculations of sandwich panels for various loads.

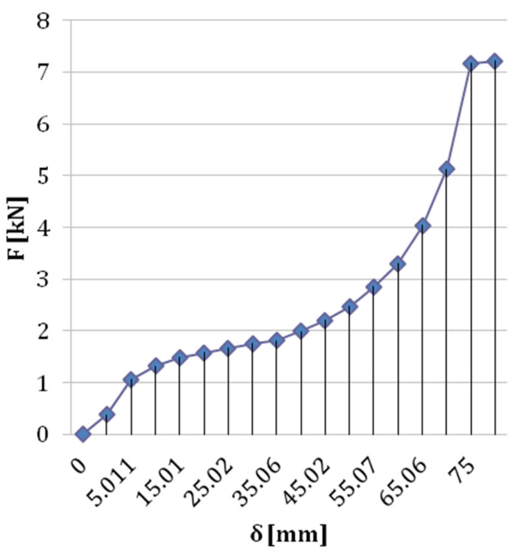



**Figure 15.** Compressive force–displacement curve.

Modern construction methods, utilizing facade sandwich elements, provide contractors and architects with exceptional opportunities to design building facades. These methods involve using different types of facade panels in combination with various colors to meet both aesthetic and functional requirements of the environment, while also facilitating simple and economical construction. Despite the rapid development of technology and innovation in modern construction, facade sandwich panels will undoubtedly continue to be an irreplaceable building material for practical application in facade cladding.

Comprehensive knowledge and consideration of all influential factors that may arise during operation, as well as the creation of calculation models for adequate analysis, including all parameters that may be significant for their behavior in real construction, are essential prerequisites for their rational application in construction.

The first phase of this study involves examining current tendencies in the world, as outlined in the available literature, concerning the analysis of stress states and deformations of these panels and connecting devices in operation. The authors aim to combine these tendencies to provide a comprehensive overview of this complex problem and contribute to modernizing the analysis procedures applied thus far and valid technical regulations in this area.

Part of the study is devoted to numerical analysis based on finite element methods. This method of numerical analysis, involving the discrete element modeling of the continuum, is extremely suitable for precisely analyzing the stress-deformation states of structural elements. The finite element method is the most effective way of controlling experimentally determined parameters relevant for the reliable analysis of structures, and therefore, it is an integral part of all scientific research papers in modern structural analysis.

The results obtained from the experiment were reasonably agreeable to support the finite element analyses results.

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