

## **EFFECT OF FOAM'S HETEROGENEITY ON THE BEHAVIOUR OF SANDWICH PANELS**

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### **Abstract**

This study aimed to develop a knowledge about material parameters identification of the foam core and numerical modelling of the sandwich panels to accurately predict the behaviour of this kind of structures. The polyisocyanurate foam (PIR) with low density used in sandwich panels dedicated to civil engineering is examined in the paper. A series of experiments (tensile, compression and bending tests) were carried out to identify its mechanical parameters. To determine the heterogeneity of analysed foam a Digital Image Correlation (DIC) technique, named Aramis, is applied in the paper. The results obtained from FE analyses are compared with the experimental results on full-size plates carried out by the author and proper conclusions are drawn.

Keywords: sandwich panels, material parameters, PU-PIR foam, heterogeneous core, DIC technique

### **1. INTRODUCTION**

Sandwich panels made up of two external thin and stiff metal facings separated by a thick, lightweight core are considered in the paper. As a core material the different kind of foams, usually made from polymers, metals, ceramics, glass, etc. are widely used in various branches of civil engineering since 80s. In the literature, it is possible to find many papers focused on sandwich structures, their

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applications, designing and testing procedures which take into account the influence of the soft core on the behaviour of the layered structure [6,15].

The simplest structure of cellular material is two-dimensional cellular solid called honeycomb often found as a sandwich shell in aircraft and offshore engineering. In the civil engineering, however, more common are three-dimensional cellular materials, which cells are polyhedrons. In general the 3D structure of a foam can have open or closed-cells. The first one has the solid material only in cell edges. The second one has the solid material in edges and faces of cells. All closed cells may contain gas, which is produced through physical and biochemical processes during the production. For the engineering purposes, cellular solids as foams contain an attractive set of features compared to solids. One of the most important is its low density leading to the most common application, which is thermal insulation. A large capacity of compressive strains make the foams very attractive as an energy-absorption structures [14].

The low densities of the foam used in a sandwich panels allows to design light and relatively stiff structures. In this case the design process is connected to an optimization because the structural modelling of the sandwich panels is a complex task and depends on the various factors [1, 16].

The most common, especially for building applications, are polyurethane/polyisocyanurate (PUR/PIR) foams. Since their role in a construction nowadays is not only to act as a thermal barrier but also to take some of the loads, therefore, the engineers and scientists need to know also their mechanical properties. The vast majority of them assumed that the foam core is isotropic, linear-elastic and homogeneous material [9, 17]. Then, only two independent material parameters are needed to describe the material. Usually, they are the Young's modulus  $E$  and the shear modulus  $G$ . These parameters play significant role in a sandwich panels response. In fact, when the material has porous structure, like a polyisocyanurate foam, the identification of mechanical properties is an intricate task [8]. Therefore, establishing of reliable experimental methods for determining these parameters are important and still under consideration. These parameters usually are determined in a macro scale approach [11] but micro mechanical methods have also been used [10,18]. Unfortunately, foams can exhibit highly anisotropic properties depending on the direction of measurement [4]. Additionally, very short elastic range and the fact that the same material may exhibit brittle, perfect plastic or hardened responses, depending on the direction along which the load is applied, complicate the determination of mechanical response of analysed material. Therefore, using porous materials in the structural applications (e.g. as a core in three-layered panels), a knowledge about their mechanical behaviour on both a micro- and a macroscopic scale is necessary [13] and more advanced analyses and tests are needed [2, 12, 19]. In that case, the set of parameters required by material model reflect the need for

numerous experimental tests. Thus, simplifying the material model of foam to be elastic and isotropic is very attractive and useful for engineers and designers as well as for scientists. Nevertheless, the degree of anisotropy of analysed foam should be always controlled and taken into account if it is needed.

Additionally, the next problem is in their non-homogeneity. The manufacturing process of sandwich panels produced for civil engineering can have vast influence on the microstructure and behaviour of the core material because steel facings limit the growth of foam in the thickness direction. In the author's opinion this is the reason of the anisotropy of the core material and its heterogeneity.

In previous works the anisotropy of the foam core and limitations of application of its isotropic model in engineering practice is discussed [3]. Therefore, the aim of the present work is to extend this knowledge by studying the changeability of Young's modulus on the thickness of the sample and its impact on the structural response. In Chapter 3 the results of various types of laboratory tests are presented and discussed. Moreover, the tests on full-size plates have also been carried out and shown in detail. FE model and numerical simulations are presented in Chapter 4 and compared with experiment. The results are summarized in Conclusions.

## **2. PROBLEM FORMULATION**

In this work the concept of non-homogenization identification and layered modelling of the sandwich panel core are proposed. In order to estimate the variability of the deformation field at the foam's core height, an optical system called Aramis was used. Next, the impact of this variability on the load-bearing capacity of the sandwich panel is studied using finite element analysis. To validate the numerical model correctly, laboratory experiments on full-scaled sandwich panels were carried out.

## **3. EXPERIMENTAL APPROACH**

### **3.1. Material parameters of the polyisocyanurate foam (PIR)**

In order to accurately identify the behaviour of the foam, a series of tests (tensile, compression and bending) were carried out using standard procedures and a Digital Image Correlation (DIC) technique, named Aramis. Methods and samples were presented in detail by Chuda-Kowalska and Urbaniak [4]. For analysed foam used as a core material in sandwich panels the standard experimental methods adopted to estimate material parameters of the core are described in code EN 14509 [7]. They are based on the assumption that the materials of steel facings and the core are isotropic, homogeneous and linearly elastic. For the foam only two parameters are mentioned:  $G_C$  and  $E_C$  - because the

relation (3.1) must be obligatory held in this classical model. Therefore, the attention in this work has been focused on the determination of these two parameters.

$$G = \frac{E}{2(1 + \nu)} \quad (3.1)$$

### 3.1.1. Shear modulus $G_C$

According to code EN 14509 [7], the shear modulus of the core  $G_C$  should be identified from the four-point bending test based on the Sandwich Beam Theory (Fig.1). The total displacement  $w$  of the mid-point of the span of the panel ( $L_0 = 0.9$  m), which is reduced by crushing the foam's core on supports, can be decomposed into a flexural component  $w_B$  due to the bending moment and shear component  $w_S$  due to the shear force. The second one can be assessed and used to estimate the desired parameter  $G_C$ . This parameter plays significant role in structural response of sandwich panels and should be identified in reliable way. Obtained values are summarized in Table 1.

Table 1. Shear parameters of the foam

		1	2	3	4	MEAN
$G_C$	[MPa]	3.30	3.22	3.23	3.37	<b>3.28</b>
$f_{Cv}^*$	[MPa]	0.112	0.108	0.110	0.120	<b>0.112</b>

\* shear strength



Fig. 1. The scheme of four-point bending test

### 3.1.2. Young's modulus $E_C$

The next material parameter of the core mentioned in [7] is Young's modulus. It can be determined in tensile/compression tests on cubic samples containing the

core material and facings. Therefore, the height and cross-section of the sample depend on the thickness of the plate.

In the present case, the PIR foam has a density of  $38 \text{ kg/m}^3$ . The thickness of tested plates is about 100 mm, therefore, dimensions of the samples had about  $100 \times 100 \times 100 \text{ mm}$ . The exact dimensions of each sample were measured and inventoried prior to testing.

According to the appropriate procedure described in code the quasi-static loading velocity is controlled by the strain rate (1-3 % of the thickness of the plate). In the analysed case 2.4 mm/min was used. The tests were carried out in the Instron testing machine with a 10 kN load cell and class 0.5. From the Instron machine (classical procedure) we can estimate Young's modulus of the tested material based on the displacement of the machine piston. In this way we obtain only a simplified value. Additionally, the procedure does not allow for more advanced analysis like a heterogeneity of the tested sample. Therefore, the Aramis system, which allows to observe the field of strain (deformation) for the whole sample, was used. In favour of this article and analyses of the core heterogeneity it was decided to divide the sample into 5 layers according to Fig. 2a. In order to recognize the surface of the specimen by 3D cameras it was covered with stochastic pattern what is shown in Fig. 2b. All moduli values have been determined for the 40 to 60 kPa range.

(a) Theoretical division into 5 layers      (b) Sample pasted between special composite handles

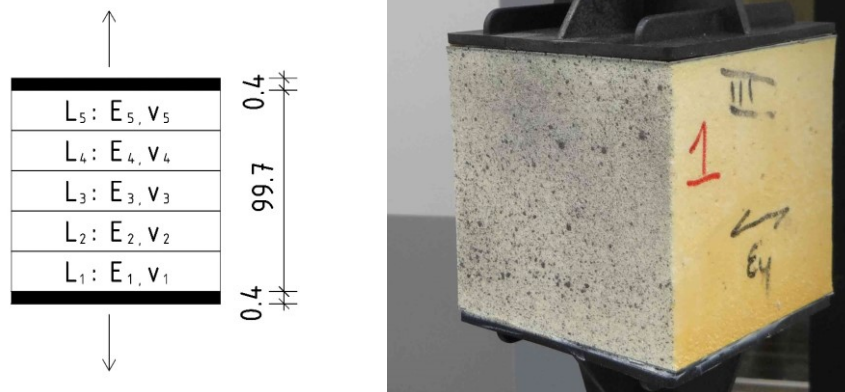


Fig. 2. Samples

### Tensile test

At the beginning, cubic samples had to be pasted between special composite handles. The test was carried out until the ultimate load was reached and the failure of the sample was occurred as shown in Fig. 3.

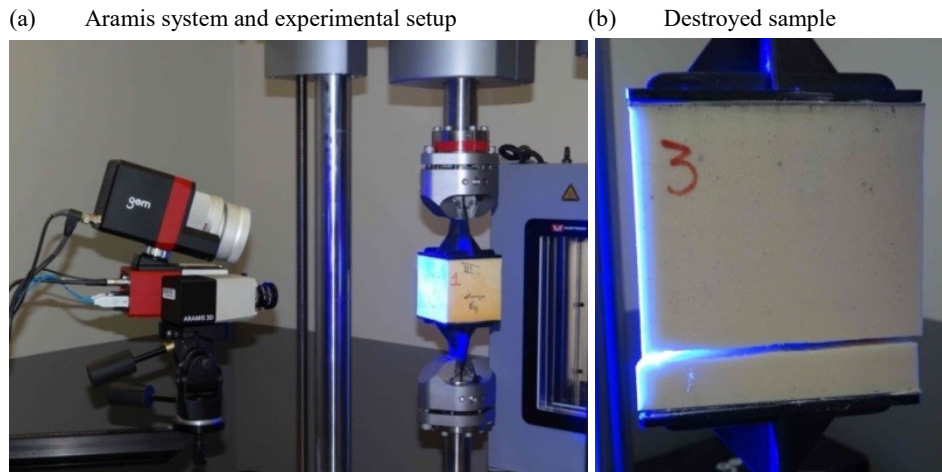


Fig. 3. Tensile test

During these tests the analysed PIR foam presents quasi - brittle response. Samples are destroyed by overall rupture of the structure for a various range of forces, what is presented in Fig. 4. This kind of failure is usually initiated at the weakest point of the microstructure of the foam and therefore, large differences in ultimate load for various samples appeared.

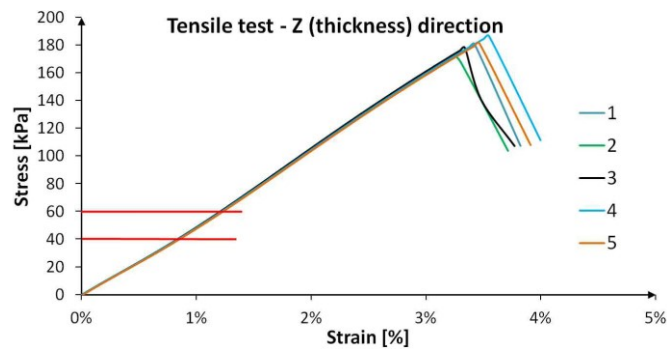


Fig. 4. The slope of tensile tests

Young's moduli obtained from the tensile test are summarized in Table 2 where the following notation is used:  $E_{Ct}^{1-5}$  (columns 2 to 6) – Young's modulus obtained from optical system named Aramis for a particular layer numbered in Fig. 2(a), respectively,  $E_{Ct}^{Aramis}$  (column 7) – the value obtained from optical system for the whole component (sample) and  $E_{Ct}^{Instron}$  (column 8) – the value obtained from instron machine. The tensile strength  $f_{Ct}^{max}$  and corresponding strain  $\epsilon_{max}$  obtained from these tests are presented in columns number 9 and 10, respectively.

In the last two lines, mean values  $\bar{k}$  and standard deviations  $\delta$  from all five tests are presented.

Table 2. Characteristic values obtained from tensile test in thickness direction

	$E_{Ct}^1$	$E_{Ct}^2$	$E_{Ct}^3$	$E_{Ct}^4$	$E_{Ct}^5$	$E_{Ct}^{Aramis}$	$E_{Ct}^{Instron}$	$f_{Ct}^{max}$	$\varepsilon^{max}$
1	2	3	4	5	6	7	8	9	10
[MPa]									[%]
1	5.89	9.58	9.72	8.94	5.54	7.93	5.35	0.181	3.42
2	6.05	9.85	9.93	9.28	5.52	8.13	5.33	0.172	3.26
3	6.23	9.61	9.98	9.08	5.41	8.06	5.36	0.178	3.34
4	5.92	9.72	9.79	9.03	5.24	7.94	5.31	0.187	3.55
5	5.93	9.52	9.87	8.97	5.31	7.92	5.27	0.181	3.46
$\bar{k}$	6.00	9.66	9.86	9.06	5.40	8.00	5.32	0.180	3.41
$\delta$	0.14	0.13	0.10	0.13	0.13	0.09	0.04	0.005	0.11

The obtained values show considerable heterogeneity of the foam core on the sample thickness. The layers located in vicinity of the metal sheets (numbers 1 and 5) demonstrate much larger deformations than another one, which is reflected in much lower values of Young's moduli. This phenomenon is most probably related to the production process of this kind of panels. Low values of standard deviation indicate small spreads between the tested samples.

### Compression test

In this case, no additional handles are needed. Stress-strain relations for compression are shown in Fig. 4b. The PIR foam is a compressible material and does not exhibit a well-defined ultimate load. Therefore, compressive strength of the core material is calculated for specific strain levels:  $\varepsilon = 2\% \rightarrow f_{Cc}^{0.02}$  and  $\varepsilon = 10\% \rightarrow f_{Cc}^{0.1}$ .

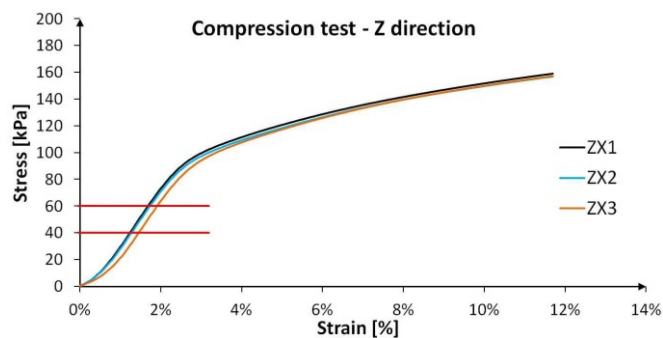


Fig. 5. The slope of compression tests

Table 3. Characteristic values obtained from compression test

	$E_{Cc}^1$	$E_{Cc}^2$	$E_{Cc}^3$	$E_{Cc}^4$	$E_{Cc}^5$	$E_{Cc}^{Aramis}$	$E_{Cc}^{Instron}$	$f_{Cc}^{0.02}$	$f_{Cc}^{0.1}$
1	2	3	4	5	6	7	8	9	10
[MPa]									
1	5.73	7.73	8.04	7.81	5.71	7.00	4.50	0.073	0.152
2	5.85	7.92	8.21	7.94	5.98	7.18	4.41	0.071	0.150
3	5.51	7.68	7.96	7.65	5.52	6.86	4.38	0.064	0.150
$\bar{k}$	5.70	7.78	8.07	7.80	5.74	7.02	4.43	0.069	0.151
$\delta$	0.17	0.13	0.13	0.15	0.23	0.16	0.06	0.049	0.001

We can say that values of Young's moduli for external layers (numbers 1 and 5) are comparable to the tensile test. Contrariwise, in compression test the middle layers exhibit higher deformation. Therefore, in this case, the moduli have much lower values.

### 3.2. Full-scale tests

In order to verify numerical results, experimental studies on full-size plates have been carried out. Two plates with a length of 5 m and a thickness of about 100 mm were analysed. To avoid the influence of additional factors related to profiling of the facings, panels with flat, metal faces were selected. The bottom plate shown in Fig. 6 is a full-width plate. However, in the case of the upper panel, longitudinal edge profiling have been cut. Therefore, in the first case the width  $B$  was equal to 1.1 m, while in the second plate  $B = 1.0$  m. The removal of these edges had two purposes. Firstly, to analyse the impact of the edges on the load-bearing capacity of the sandwich panel. Secondly and more importantly, the results obtained from the panel prepared in such a way could be compared with the numerical results where these edges were not modelled.



Fig. 6. Full-scaled samples – experiment in vacuum box



In Fig.7 the graph force-displacement and calculated wrinkling stresses for both plates are shown.

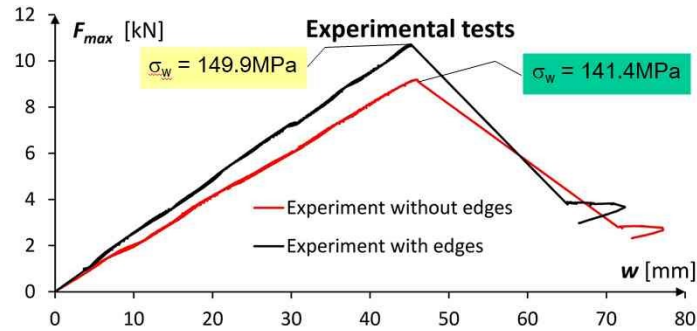


Fig. 7. The results of bending test on full-scaled samples

To analyse the obtained results we can say that for the tested panels the influence of edge profiling on load-bearing capacity of sandwich panel is rather small and it is about 6%. On the other hand, these edges change the stiffness of the panel, which is reflected in another inclination of the force-displacement curves.

## 4. NUMERICAL AND EXPERIMENTAL ANALYSIS

### 4.1. FE model

The Finite element model is created in Abaqus simulation software package [5]. The geometrically nonlinear static analysis is used. The problem is solved using Newton-Raphson procedures. Numerical instability is used as a failure criterion. Geometric imperfections are introduced as a combination of five buckling modes with the multiplier equal to 0.5 mm.

The geometric parameters of the modelled plate are: width  $B = 1.0$  m, total length  $L = 5.0$  m, length of the span  $L_0 = 5.9$  m, thickness of the core  $d_C = 99.7$  mm, and the thickness of steel facings  $t = 0.40$  mm.

In this paper, steel faces are modelled using four node thin shell nonlinear finite elements, referred as S4, with the size of  $2 \times 2$  cm. The core is modelled using eight node linear brick elements C3D8 (3D element) with the size of  $2 \times 2 \times 2$  cm. S4 and C3D8 elements with full integration in stiffness computation are used in order to avoid non-physical phenomenon like hourglassing. Additionally, these elements give more accurate results in stress field for deformed elements, especially, when wrinkling phenomenon occurs. The "tie" interaction has been used between the layers facing-core-facing, what correspond to constrained degrees of freedom of corresponding sheet and core nodes. The core is divided into the parallel regions to enable the possibility of assigning various materials to

core's layers. Each region corresponds to the particular layer of finite elements on the core's thickness.

The panel is supported by two basing plates ( $b = 100 \text{ mm} \rightarrow \text{Fig. 8b}$ ) modelled as rigid bodies. The right supporting basing plate is free to rotate with respect to  $Y$  axis, whereas the left basing plate differs only in that, it has the possibility to move in the  $X$  direction. The contact interaction between supports and sandwich panel (lower sheet) is used, with the friction coefficient equal to 0.3 and no penetration allowed. The panel is loaded by uniform pressure  $q$ , which is applying to the lower face as shown in Fig. 8a.

It was assumed that the facings are flat and made of steel with Young's modulus  $E_F = 210 \text{ GPa}$  and Poisson's ratio  $\nu_F = 0.3$ . Moreover, the actual relationship obtained from laboratory test between stress and strain is introduced. In the tensile test the obtained yield strength was equal to 360 MPa and the tensile strength reached 436 MPa. These parameters are used for modelling of the elastic and plastic behaviour of sheets.

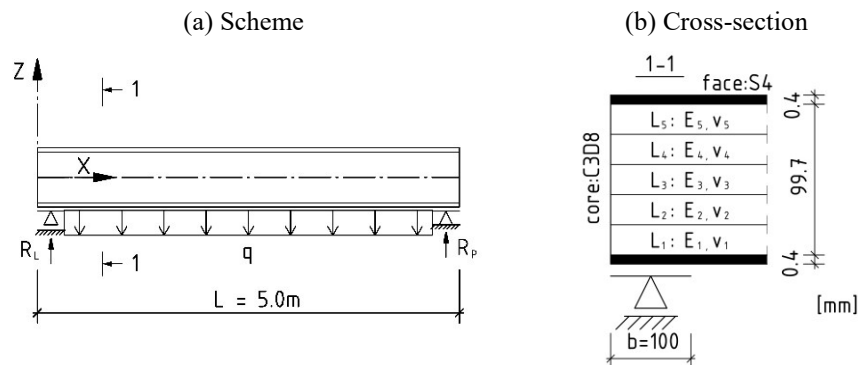


Fig. 8. Geometry

In this paper, the PIR foam with a closed-cell structure and approximately  $38 \text{ kg/m}^3$  density is used as a core material of analysed sandwich panels. The main goal of this paper is to study the non-homogeneous strength material characterization of foam core and its impact on the structural response of the whole panel. The assumption of the foam isotropy was accepted at this work, taking into account the limitations connected with this simplified assumption discussed by Chuda-Kowalska and Malendowski [3].

#### 4.2. Numerical simulations

Based on experimental data described in Chapter 3, three examples were subjected to numerical analysis and summarized in Table 4.

Table 4. Numerical examples

	$E_{C1}^1$	$E_{C1}^2$	$E_{C1}^3$	$E_{C1}^4$	$E_{C1}^5$	$E_{C1}^{one\ layer}$	$G_C$
	[MPa]						
	2	3	4	5	6	7	8
Example 1	-	-	-	-	-	8.00	3.28
Example 2	6.00	9.66	9.86	9.06	5.40	-	
Example 3	6.00	9.66	9.86	9.06	5.40	-	4.00

The first example reflects the case of a homogeneous, single-layer core with material parameters:  $E_C = 8$  MPa and  $G_C = 3.28$  MPa. Example 2 introduces a layered core and allows to investigate the effect of the core heterogeneity on the structure response. In the third example also a plate with a laminar core was analysed, however in this case the  $G_C$  value was increased from 3.28 to 4.0 MPa. In this case, the sensitivity of the model to the change of this parameter was analysed. Obtained relations between applied force  $F = R_L + R_P$  and displacement  $w$  measured in the middle of the span are presented in Fig. 9.

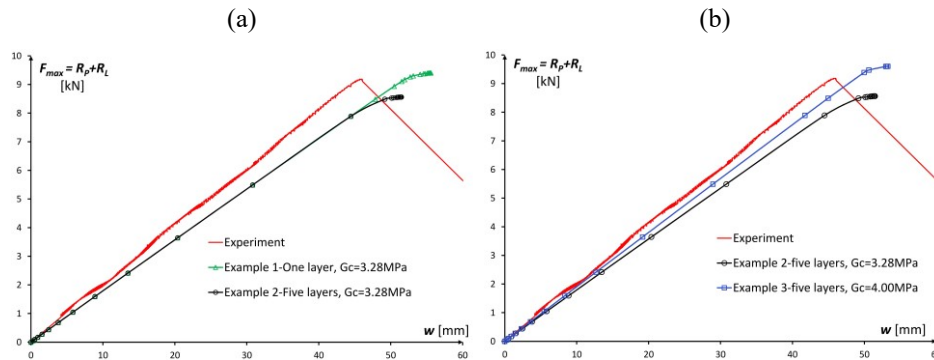


Fig. 9. Numerical and experimental paths

The numerical response of the Example 1 is shown in Figs. 10 and 11. In the first case the normal stresses distribution we can observe. Critical value obtained in this Example is  $\sigma_{wr}^{FE} = 149.3$  MPa, what is shown in Table 5.

Obtained relations between applied force and deflection clearly show that in the case of an isotropic material model, if a constant value of the shear modulus is maintained, the slope of the graphs is the same for both the single-layer and multi-layer model (Fig. 9a). In case of a heterogeneous model, the layer located directly under the compressed metal face plays crucial role for the behaviour of the structure. Conducted analyses showed that lower  $E$  values result in a faster loss of model convergence. As a consequence, we obtain lower critical load values for the layered model where  $E_5 = 5.4$  MPa compared to the homogeneous model for

which  $E_C = 8.0$  MPa. For the analysed cases, the difference was 9.8%. Additionally, paths in Fig. 9a show that results obtained from Examples 1 and 2 do not much properly to the Experiment. In the case of numerical responses we observe too large displacements of the model. So the conclusion is that the shear modulus of the core should be higher. Therefore, in the next example the impact of changing the  $G$  value on the model's responses is analysed. The value  $G_C = 3.28$  MPa was obtained from four-point bending test as presented in subsection 3.1.1 of this paper. While the value of  $G_C = 4.0$  MPa was estimated from the bending test of a full-size panel without edge profiling in vacuum box (red curve in Fig. 9). Increasing the value of  $G$  resulted in a more rigid response of our model (Fig. 9b). We can observe that the inclination of the experimental and numerical curve is similar, however, the load-bearing capacity of the numerical model is slightly higher (3.9 %) than the Experiment would indicate.

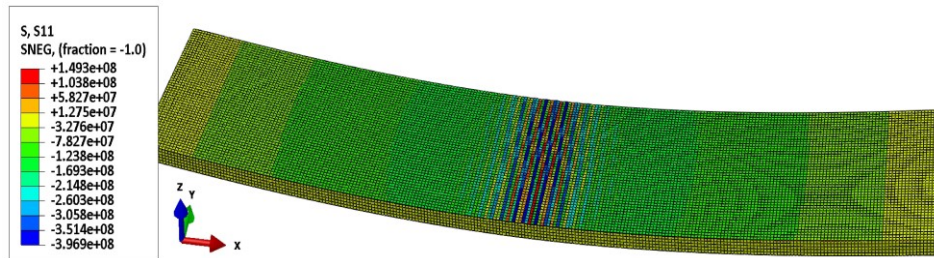


Fig. 10. Wrinkling failure – Example 1

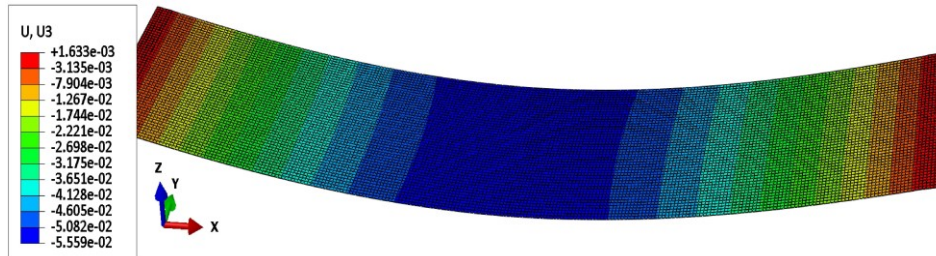


Fig. 11. Displacement of the bottom face – Example 1

Obtained results from FE analysis and theoretical calculations are summarized in Table 5. Column 2 presents the values of deflection in the middle of the span of the plate corresponding to the critical load. Column 3 summarizes the values of the maximum (critical) force obtained from the sum of support reactions shown in Fig. 6a. In column 4, the critical load of the panel is presented.

Between force  $F$  and load  $q$  the relationship  $F = q \cdot L_0 \cdot B$  takes place. For maximum load theoretical results of wrinkling stress (column 5) are calculated according to equation (4.1) and compared with numerical results (column 6) in column 7.

Table 5. Results

	$w_{max}$ [mm]	$F_{max}$ [kN]	$q_{max}$ [kN/m <sup>2</sup> ]	$\sigma_{wr}$ [MPa]	$\sigma_{wr}^{FE}$ [MPa]	$\delta$ [%]
1	2	3	4	5	6	7
Experiment	45.68	9.23	1.88	141.4	-	-
Example 1	55.59	9.40	1.92	143.8	149.3	3.8
Example 2	51.49	8.56	1.75	130.9	134.8	3.0
Example 3	53.26	9.60	1.96	146.9	151.7	3.3

For analysed case:  $L_{eff} = L_0 = 4.9$  m,  $e = 0.1001$  m and  $t_F = 0.40$  mm.

$$\sigma_{wr} = \frac{M}{e \cdot t_F \cdot B} \quad (4.1)$$

$$M = \frac{q \cdot L_{eff}^2}{8} \quad (4.2)$$

## 5. CONCLUSIONS

Different factors have influence on the behaviour and load-bearing capacity of sandwich panels. In this work, the main attention has been focused on analysis of the heterogeneity of the foam core and its impact on the behaviour of the structural response. The foaming processes used in the production of sandwich panels often result in the formation of elongated cells in the foam and different density in thickness direction. As a result, we get a heterogeneous core with quite significant differences in modules at core height, what is shown in the paper.

The isotropic material model could be a good approximation of the PIR foam when the global sandwich panel behaviour is investigated. Then, the most important parameters are shear modulus and Young's modulus what should be taken into account in finite element analysis, where only  $E$  and  $\nu$  can be introduced.

The effect of core heterogeneity on the behaviour of a sandwich panel was taken into account in this work by introducing five layered core. Analysis carried out by the author have shown that the material parameters of the layer located in the immediate vicinity of the compressed metal sheet have a significant influence on the structural behaviour of the model in the critical area.

Future works will be focused on the study of the structural sensitivity of sandwich plates with PIR foam core with respect to heterogeneity and anisotropy

simultaneously and more advanced foam material model will be analysed. In addition, an enhanced failure criterion of the numerical model should be developed.

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