EXPERIMENTAL AND NUMERICAL ANALYSES OF ANISOTROPIC BEHAVIOUR OF PU FOAM

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Keywords: Polyurethane foam, Anisotropy, Sandwich panels, Material model.

Abstract
Polyurethane foam with low density used in sandwich panels is examined in the paper. A series of experiments was carried out to identify required mechanical parameters of this foam. For determining shear modulus different test methods were used, namely a four and three point bending test (the most common), a double-lap shear test and a torsion test was discovered. Further experimental revealed evident anisotropy of the foam. The influence of the anisotropy on the behavior of sandwich panels and proper material models are discussed.

1. Introduction

Sandwich panels with porous materials as a core are widely and still increasingly applied in civil engineering because of their extraordinary attractive features, namely good thermal insulation, very small self-weight, good bearing capacity and small cost of production. There is strong tendency to apply these panels for increasing span lengths and to use them also as bracing of purlins or frames. Therefore, a number of papers are devoted to optimization of sandwich structures [1, 2, 3]. It is also a good motivation for further research with the aim to develop the methods of design and testing [4, 5, 6]. Using soft core in the layers of structural elements requires good knowledge of its mechanical parameters. Usually they are determined in a macro scale approach [7, 8] but micro mechanical methods can also be used [9, 10].
In this paper the PU foam with a closed-cell structure and approximately 40 kg/m^3 density used in sandwich plates is analyzed. This specific application generates the microstructure of the foam core, its behavior and implies research and computational methods. In the analyzed case the assumption about isotropy and elastic range of weak core material is common and very useful from the engineering point of view [11]. Then the Kirchhoff modulus of the core material plays a crucial role in functional response of sandwich panels such as load-bearing capacity, maximum permissible span and deflection. Therefore, development of a suitable experimental method of the determining shear modulus and its application is very important [12, 13, 14]. The authors carried out a series of experiments with the aim to determine shear modulus of the PU foam produced in the manufacturing process of sandwich structures. Typically, modulus G_C of the soft core is determined in a bending test of the panel. The dimensions of the plate and the loading in this test allow to analyze the results in frame of the Timoshenko beam theory [15]. Since the dimensions and elasticity moduli of the thin facings

are known the measured deflection of the plate provides sufficient information for evaluation of G_C. The authors identified this parameter also in a torsion test and in a double-lap shear test. The latter one had two options with and without constraint of the lateral displacements. It was observed that each type of test provided different values of G_C, although similar results were obtained within each test.

Manufacturing process of sandwich panels used in civil engineering has vast influence on microstructure and behavior of core material and the whole panel. In the analyzed case, steel facings limited the growth of foam in the thickness direction and forced it partially in length direction, which increases the degree of anisotropy. Therefore, this phenomenon should be taken into account in analyses of mechanical response of considered plates.

The main aim of this study is to develop methods, which could be used to identify mechanical parameters of the core material in sandwich plates. Therefore, a series of tests was conducted to examine the possibility of the mentioned above anisotropy of the foam.

2. Isotropic model

For the examined sandwich panels with PU foam core the standard experimental methods used to estimate material parameters of the core (E_C, G_C) are described in the code [16]. They are based on the assumption that the materials of steel facings and he core are isotropic, homogeneous and linearly elastic. The Young modulus E_S of the steel is evaluated in typical tension tests. The Kirchhoff modulus G_C of the core is identified in various tests. The authors used tests illustrated in Figure 1.

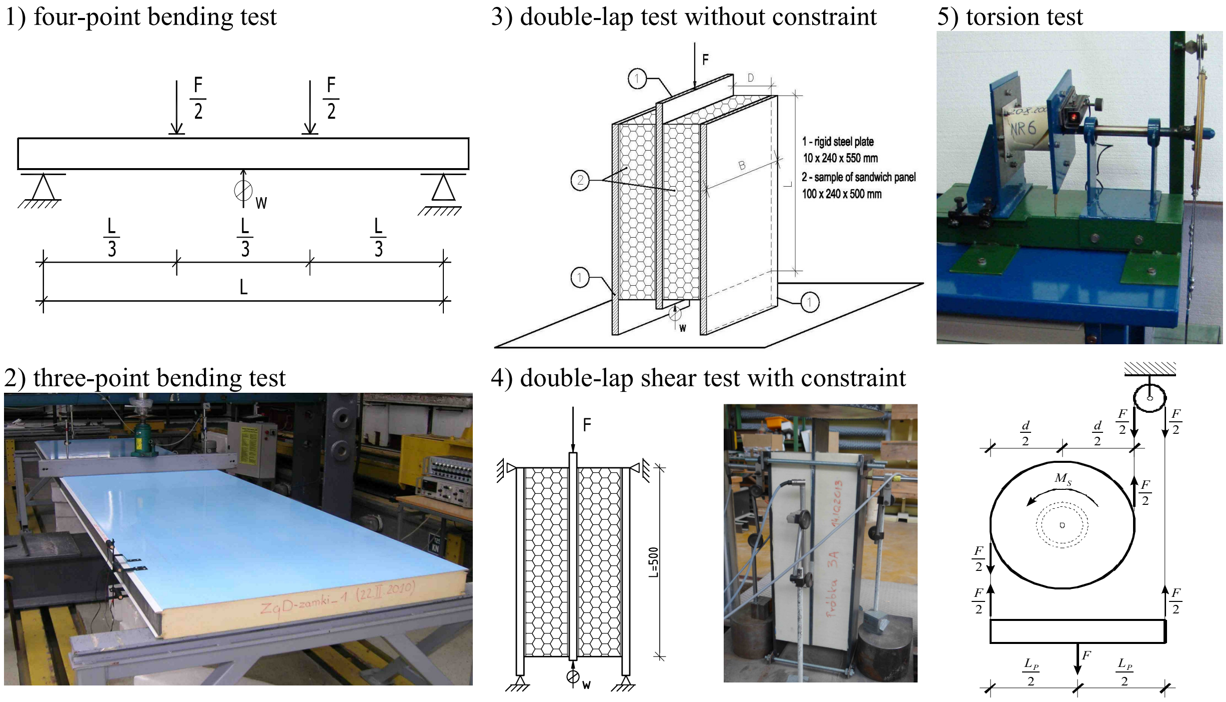

Figure 1. Set up for various shear test 1) four-point bending test, 2) three-point bending test, 3) double-lap shear test without constraint, 4) double-lap shear test with constraint, 5) torsion test

The idea of determination of the shear modulus G_C from a bending test is based on hypothesis of the simplified sandwich beam deflection model, where the total transverse deflection of the beam can be decomposed into a flexural component w_b due to the bending moment and a shear component w_s due to the shear force. The total transverse deflection is written as (1)

$$w = w_b + w_s. \tag{1}$$

The bending deflection is evaluated from a closed-form approximate formula, where the known thickness and Young modulus of facings are introduced. Thus the second component assigned to the shear can be assessed and used in identification of the modulus G_C.
Four-point bending test was carried out on two different samples: beam like strips with the width 100 mm (test **1a**) and panels of the actual width (test **1b**). The Kirchhoff modulus is determined according to the equation (2):

$$G_C = \frac{\Delta F \cdot L}{6 \cdot B \cdot d_C \cdot \Delta w_S} \tag{2}$$

where B, L and d_C denote width, height and core depth of one specimen, respectively.
In both cases the span L should be sufficiently small to expose shear of the core. Usually $L \leq 1.0$ m is used. In these tests compression of the core material at the supports is visible and should be taken into account [17].
Three-point bending test was carried out on long panels with actual width (test **2** in Figure 1). In this case the shear force is much smaller than in tests on short panels. Therefore, compression at the support has not occurred. On the other hand, bending part w_b is bigger than w_s and it has to be determined with a sufficient accuracy. Otherwise the error in w_b results in errors in w_s assessed from (1) and finally in errors in G_C. Next shortcomings of this method are: large samples, which generates higher research costs and the influence of longitudinal edges profiling on the estimated parameter w_b [18]. The Kirchhoff modulus is determined from the equation (3):

$$G_C = \frac{\Delta F \cdot L}{4 \cdot B \cdot d_C \cdot \Delta w_S} \tag{3}$$

In double-lap shear tests (test **3** and **4** in Figure 1) the shear modulus is determined according to the equation (4):

$$G_C = \frac{F \cdot d_C}{2 \cdot w \cdot B \cdot L} \tag{4}$$

where B, L and d_C denote width, height and core depth of one specimen, respectively.
A double-lap shear test seems to have the best theoretical grounds, but the edge effects are still present, which means that the assumption about the pure shear is false and the obtained value of G_C is not precise. The next disadvantage of this test is connected with the time needed to prepare the sample. Therefore, the authors tested only three samples.
Scheme of force excitation in the torsion test is illustrated in Figure 1 (test **5**). The cylinder specimen has two steel rigid head plates. One of them is rigidly fixed and the second can rotate. The angle of rotation of a specimen is measured using laser pointer attached to the rotating plate and it is pointing at the leveling staff standing in front of the pointer. The sample is loaded by the torque. Shear modulus is calculated using the following relation between torque M_S and the angle of specimen rotation φ

$$\varphi = \frac{M_S \cdot L}{G_C \cdot I_0} \tag{5}$$

where L and I_0 denote length of the sample and the central second order moment of the area of the cylinder cross-section respectively.
The values of each series of tests are summarized in Table 1

	Type of test (Figure 1)					
	1a	**1b**	**2**	**3**	**4**	**5**
	3.41	4.73	4.61	2.95	2.98	2.61
	3.48	4.80	4.83	2.93	3.04	2.59
G_C [MPa]	3.15	4.64	4.74	2.91	3.02	2.75
	3.32	-	-	-	-	2.63
	3.29	-	-	-	-	2.76
Average value	**3.33**	**4.72**	**4.73**	**2.93**	**3.01**	**2.67**
Standard deviation	0.11	0.07	0.09	0.02	0.02	0.07

Table 1. Experimental results of G_C.

Tests number 1a, 3, 4 and 5 were carried out on samples which were cut out from the panel but included all layers. Samples in tests 1b and 2 have real width. In order to examine the influence of edge profiling on the estimated value of G_C, the samples without these endings were prepared and tested, too. Obtained results are presented in Table 2.

	1b	**2**
G_C [MPa] – with edge profiling	4.72	4.73
G_C [MPa] – without edge profiling	3.81	3.85

Table 2. The influence of longitudinal edge profiling.

The results demonstrate large influence of edge profiling on estimated value of G_C. Received difference is more than 20%. Therefore, it has to be taken into account in experimental test methods used for determining shear modulus.
The next identified parameter is Young's modulus E_C. It is determined on cubic samples containing the core material and facings according to the appropriate code procedure recommended in [16]. Obtained results from tension and compression tests are presented in Table 3.

	Young modulus E_C [MPa]	**Standard deviation**
Tension	3.59	0.17
Compression	3.82	0.44

Table 3. Experimental results of E_C.

The simplest and most commonly used material model is linear elastic, isotropic. This model is very attractive and useful for designers. However, it appears that the relation (6) between the engineering constants E_C , G_C and Poisson's ratio ν existing in this model does not hold in case of PU foam examined in the paper.

$$G = \frac{E}{2(1+\nu)}. \tag{6}$$

For the analyzed polyurethane foam obtained values of E_C and G_C are similar. In this case the Poisson's ratio should achieve an unreal value of nearly -1.5. During the compression test even for large strain the transverse deformation has not occurred. It can be observed in Figure 2a. It suggested that Poisson's ratio is equal to zero. The compression tests with constraints

(Figure 2b) were carried out and confirmed this assumption (curve of the relationship between σ-ε with and without constraints in elastic regime were the same - Figure 2c)

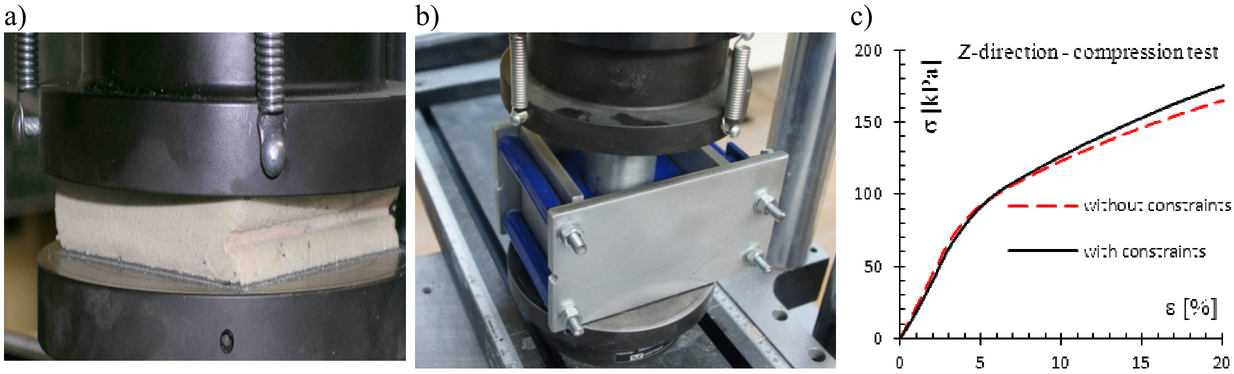

Figure 2. Compression test a) without constraints, b) with constraints, c) σ-ε relationship

This observation may indicate that the assumption about isotropy is not correct.
The second problem, which is observed in this kind of plates, is heterogeneity of the core material over the width. Next series of tests were carried out in order to examine the variation of material parameters of the foam in the width direction of the plate.

3. Experimental study of homogeneity and anisotropy of the foam in the panel

The three principal directions in the tested sandwich panels are shown in Figure 3.

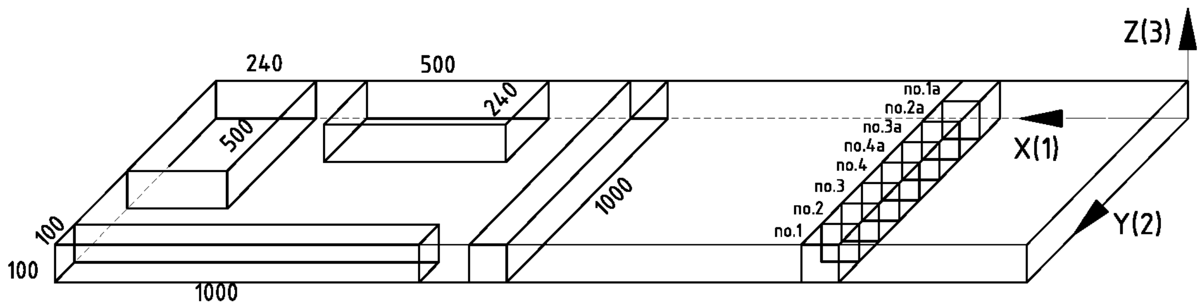

Figure 3. Principal directions in analyzed panel and position of cut out samples.

Previously, the cubic tension and compression tests were carried out on samples consisting of three layers (two faces and the core). At present metal sheets have to be removed in order to permit testing in all principal directions. In this section tested samples come from the same manufacturer but were taken in different time production.
The main aim of the first group of tests was to verify whether the place of cutting samples affects the result of identification the material parameters. This phenomenon is connected with manufacturing process, which can have huge influence on the microstructure of foam and its behavior. Therefore, a series of tests for Z direction were carried out (samples no.1-4 and no.1a-4a in Figure 3). The first group was connected with cubic tension tests. In each case in the same position six tests were done. Obtained results are presented in Table 4. The discrepancies of results, obtained from one cutting positions, is about 4% for no.1 and no.4 and above 6% for no.3 and no.1a. The variance between max and min average value is 5.1%. It shows that the analyzed PU foam is not homogeneous although the tested slabs were made by a producer of high technology level. This fact should be taken into account in the analysis

of local effects e.g. bubbles. In other analyses the material parameters averaged over the width of slab should be used.

	No.Z1	***No.Z1a***	***No.Z3***	***No.Z4***
	3.39	3.56	3.37	3.54
	3.40	3.48	3.48	3.55
E_{Ct} **[MPa]**	3.31	3.60	3.42	3.60
	3.34	3.42	3.28	3.47
	3.36	3.36	3.32	3.49
	3.27	3.37	3.34	3.48
Average value	**3.35**	**3.47**	**3.37**	**3.52**
Standard deviation	0.05	0.09	0.07	0.05

Table 4. Values of E_{Ct} (tension) in Z direction for different sample's positions.

The second group of tests was performed in order to assess experimentally the degree of anisotropy. Nine types of tests were carried out, namely uniaxial compression (E_{Cc}) and tension (E_{Ct}) in three orthogonal directions with two types of boundary conditions in the compression test: lateral displacements in upper and lower faces free or constrained. The values received from these tests are shown in Table 5.

	***X*(1)**	***Y*(2)**	***Z*(3)**
E_{Ct} **[MPa]**	14.33	6.80	3.43
Standard deviation	0.30	0.11	0.11
E_{Cc} **[MPa]**	13.45	4.41	3.65
Standard deviation	0.20	0.21	0.09

Table 5. Experimental results of Young modulus E_C in directions X, Y and Z

The behavior of the tested samples significantly depended on the applied stress direction. Stress-strain relations are shown in Figure 4. Note that in the elasticity region similar E_C is observed but the range of linear relation is different. Different are also the yield limits and the behavior in elasto-plastic region, though the hardening coefficients are similar in all three directions. Averaged results of tension tests are shown in Figure 5.

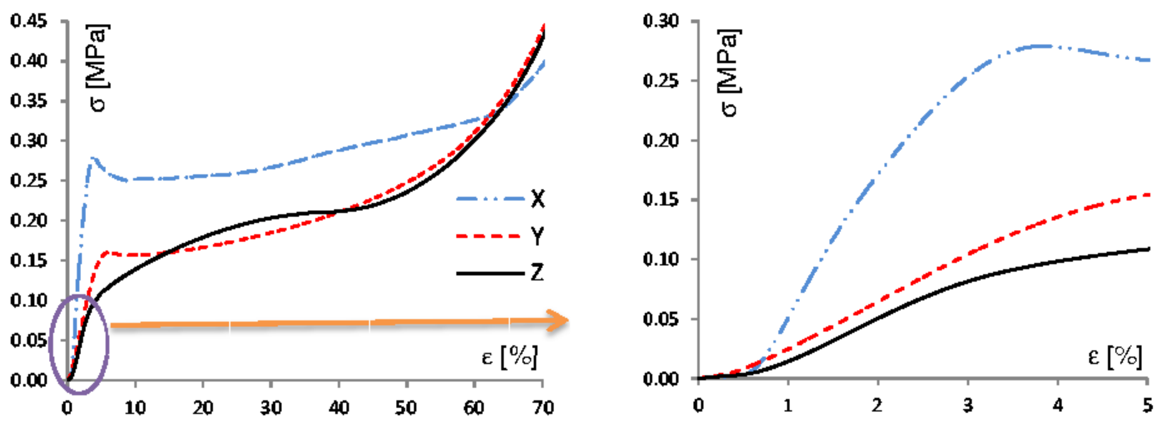

Figure 4. Compression test, σ-ε plots for X, Y and Z directions

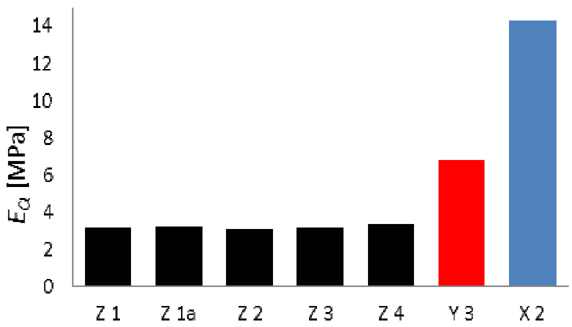

Figure 5. Tension test: E_{Ct} in directions X, Y and Z

Shear tests were carried out using a four-point bending test and a double-lap shear test. The samples were cut out in such way that G_{ZX} and G_{YZ} could be determined (Figure 3). As previously, the results obtained from the double-lap shear test have lower values compared to the bending test.

	G_{ZX} [MPa]	G_{YZ} [MPa]
Double-lap shear test	2.68	2.20
Four-point bending test	3.00	2.30

Table 6. Experimental results of G.

Table 6 demonstrates that both types of the shear tests revealed a pronounced anisotropy of the material.
At present next series of tension and compression tests are carried out on cubic samples cut out at the 45^0 degree to X, Z directions. These tests provide next experimental data which will be used in the formulation of an anisotropic model of the foam, which we will be present at the conference.

4. Conclusions

The foaming processes in PU foam used in production of sandwich panels often result in formation of elongated cells in the foam. In effect the stress-strain relations depend on the direction of the applied stress what has been shown in this paper. The linear elastic response of the foam is observed only at low range of strains less than a few percent. This range also depends on the direction of stress.
Anisotropic material models need a set of parameters and require numerous experimental tests. Therefore, many papers and codes regard cellular foams as elastic and isotropic material. The paper demonstrates that this assumption has to be used with limited confidence. The paper also demonstrated that PU foam is not homogeneous in the direction of slab's width although the tested slabs were made by a producer of high technology level. This fact should be taken into account in the analysis of local effects e.g. bubbles. In other analyses the material parameters averaged over the width of slab should be used.
During the conference the failure modes in different tests, next experimental results and proposed anisotropic model of the PU foam will be presented.

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