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EXPERIMENTAL DETERMINATION OF SHEAR RIGIDITY OF SANDWICH PANELS WITH SOFT CORE

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Abstract. Panels with a polyurethane foam core and thin metal facings are considered. Behaviour of these structures depends strongly on the shear rigidity. Therefore, studies on precise and reliable experimental methods of determination the shear rigidity are still necessary. The recommended in the code EN 14509 experimental determination of the Kirchhoff modulus G_C of the core material is based on bending test of a panel with measurement of its deflection. Using the Timoshenko theory the contributions of bending and shear stiffness coefficients are separated and hence the latter one is determined. The authors observed that this method can lead to disadvantageous size effects. Therefore, other methods are also used in the study, namely double-lap and torsion tests. A new method is proposed, too. It is based on bending test with measurement of the total rotation of cross section and the slope of deflection line. Numerous experiments were carried out and are reported in the paper. The FEM analysis was also performed. The discrepancies in the shear modulus G_C determined in different tests are discussed in the paper.

Keywords: sandwich structures, shear modulus of PU foam, material parameters' identification.

1. Introduction

Sandwich panels with thin steel facings and a flexible polyurethane core are considered in the paper. Panels of this type find wide and still increasing application in civil engineering because of their extraordinary attractive features, namely very good thermal insulation, very small self-weight, relatively good bearing capacity and small cost of production. Note that small weight of panels strongly reduces cost of transport and erection, too. Ongoing improvements of technology of production and corrosion protection motivate the tendency to reduce the thickness and the depth of profiling of metal cover sheets. Simultaneously, there is strong tendency to apply these panels for increasing span lengths and to use them also as bracing of purlins or frames. These two tendencies are in conflict. Therefore a number of papers is devoted to optimisation of sandwich structures (Icardi and Ferrero 2009; Studziński *et al.* 2009; Valdevit *et al.* 2004). There is also good motivation for further research with the aim to develop the methods of design and testing. In this respect important is proper identification of mechanical parameters of materials of the cover sheets and the core The latter one is even more crucial because material parameters of the core usually exhibit greater deviations than the parameters of the cover plates. Moreover, these parameters strongly influence the displacements of the plate and play decisive role in local stability (wrinkling) of the compressed cover plate.

The main aim of this study is developing the methods of identification the mechanical parameters of the material of the core in sandwich plates. Many papers have appeared recently which take up various problems of identification the parameters of in multiplayer structures (Harders *et al.* 2004; Mills 2007; Ramsteiner *et al.* 2001; Saha *et al.* 2005). In this paper the attention is focussed on the soft core made of PU, however the authors carried out also tests on panels with the core of mineral wool. It can be expected that some observations and conclusions related to PU can be useful in considerations of the panels with other materials of the soft core.

In the code EN 14509 various experimental methods of determination of the Kirchhoff modulus G_C of the core are recommended. Characteristic is that in all these methods the tests are carried out not on the plain material of the core but the specimens compose of the core and two cover plates. This is reasonable because such specimens properly illustrate the behaviour of the sandwich panel where different constituent materials contribute to the total response of the structure. The numerous experiments carried out by the authors demonstrated that the recommended laboratory methods provide the results with rather unacceptable scatter. This has been discussed in (Chuda-Kowalska *et al.* 2008) and induced authors to further develop the study.

This paper briefly describes the applied methods of experimental determination of G_C and presents the results obtained from these methods. The 3D numerical model has also been created, where the material constants have been calibrated basing on experimental tests. Chapters 4 and 5 contain the analysis and discussion of the results obtained from different experimental methods with comparison to results of numerical simulations. Chapter 6 provides conclusions with respect to the usefulness of various tests.

2. Methods of determination of soft core parameters

2.1 Assumptions

Plantema (1966) and Allen (1969) were the first authors who generalized the sandwich panel theories. Classical approaches to the problem are presented in works of Zenkert (1995) and Wang (*et al.* 2000). In the present paper the theoretical model of the three-layer structure with soft core is applied, where it is assumed that the materials of steel facings and polyurethane core are isotropic, homogeneous and linearly elastic. The facings are parallel. In the analysed sandwich panels the Young modulus of the core is much smaller compared than the Young modulus of facings. Therefore, normal stress in the foam core is negligible and the shear stresses are constant in transverse direction ($E_C / E_F \approx 2.0 \cdot 10^{-5} \Rightarrow \sigma_{xC} \approx 0$, $\tau_{xzC} = \tau_{zxC} = \text{const.}$). The considerations are limited to small strains and displacements (linear geometric relations). Contribution of the shear stress and strain in the facings to the displacement of the panel is neglected because of small thickness of the facings compared to the core. Hence, the Bernoulli hypothesis can be applied independently for both facings. The shear deformation of the core makes that normal element 1-4 before deformation becomes piecewise linear 1'-2'-3'-4' after deformation (cf. Figs. 1 and 2)

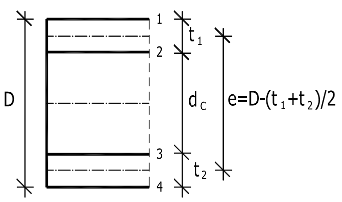


Fig 1. Cross-section of a panel before deformation

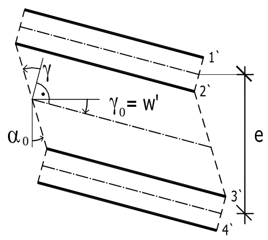


Fig 2. Cross-section of a panel after deformation

2.2 Bending tests by EN 14509

The methods, proposed by the code EN 14509 are based on bending and shear tests of panels with measurement of the transverse displacement *w*. These experiments are carried out on the samples of different length of the span (short panel, long panel).

In this study different bending tests will be used. For readers' convenience we give the acronyms used henceforth. The acronym has three fields (1 , 2, 3), where (1) specifies a kind of test, namely bending, (2) distinguishes between long and short panels and (3) informs on the measured quantity. Hence, there are the tests:

– BgL-*w*: Bending, Long panel, measured displacement *w*

– BgS-*w*: Bending, Short panel, measured displacement *w*

– BgL-γ: Bending, Long panel, measured angles γ

Tests on short panels (BgS-*w*).

In the code it is recommended the 4-point bending test of a panel (Fig.3). The span *L* should be sufficiently small to induce failure mechanism by shear of the core. Usually $L \leq 1.0$m is used. Two types of samples are used: beam like strips with the width 100 mm and panels of the actual width. The loads are step-wise increased and the deflection *w* in the middle point of the span is recorded till the failure occurs. It is assumed, that the deflection can be decomposed $w = w_B + w_S$ in such a way, that w_B and w_S represent the deflections due to bending and shear, respectively.

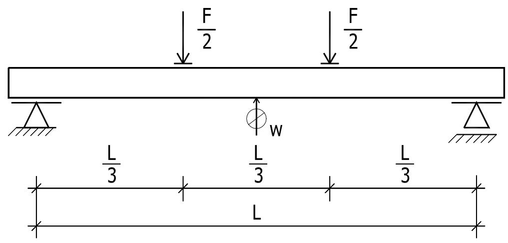
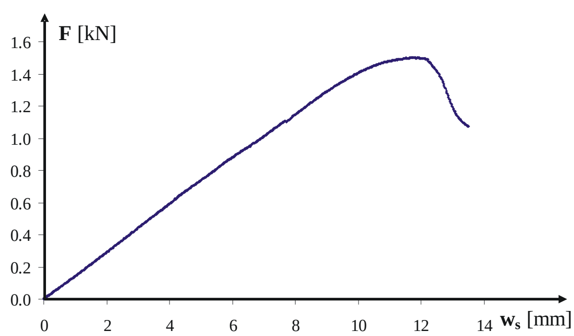


Fig 3. 4-point bending test

Fig 4 shows a typical $F - w_S$ relation obtained in experiments carried out by the authors. The linear part of the function $F(w_S)$ was used for the assessment of the modulus G_C .



Fi g 4. Typical load – displacement relation ($F - w_S$)

According to assumptions presented in 2.1, the following formulae follow from the Timoshenko theory generalized to sandwich beams:

$$\Delta w_B = \frac{23 \cdot \Delta F \cdot L^3}{1296 \cdot B_S}\,, \tag{1}$$

$$B_S = \frac{E_{F1} \cdot A_{F1} \cdot E_{F2} \cdot A_{F2}}{E_{F1} \cdot A_{F1} + E_{F2} \cdot A_{F2}} \cdot e^2\,, \tag{2}$$

$$G_C = \frac{\Delta F \cdot L}{6 \cdot B \cdot d_C \cdot \Delta w_S}\,, \tag{3}$$

$$d_C = D - (t_1 + t_2)\,. \tag{4}$$

where:
B_S – the flexural rigidity,
A_{F1}, A_{F2} – the area of facings,
E_{F1}, E_{F2} – the Young modulus of facings,
e – the distance between centres of facings,
d_C – the depth of the core
B – the width of the specimen.

Tests on long panels (BgL-*w*).

Experiments are carried out on the panels, in which the span L is relatively large. It must guarantee that the failure in bending occurs starting from local buckling of the compressed facing. The code EN 14509 recommends different loading systems shown in Fig 5

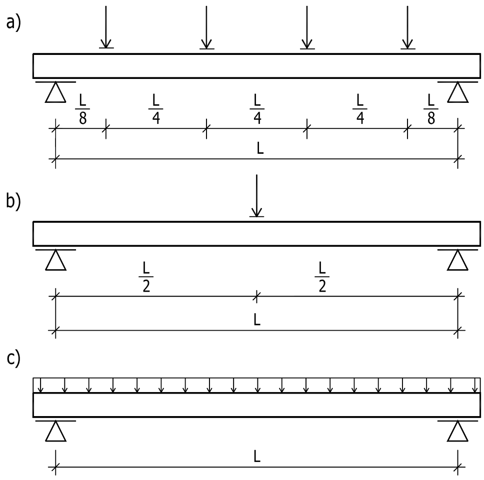


Fig 5. Loading systems used in bending tests

The Authors used the loading system, which is presented in Fig 5b. The displacement was always measured in the middle point of the span. The idea of determination of shear modulus G_C is similar as in the test on short panel. In this case, the respective formulas are:

$$\Delta w_B = \frac{\Delta F \cdot L^3}{48 \cdot B_S}\,, \tag{5}$$

$$G_C = \frac{\Delta F \cdot L}{4 \cdot B \cdot d_C \cdot \Delta w_S}\,. \tag{6}$$

2.3 Double-lap shear test (Shear-γ).

The laboratory set-up for the double-lap shear test is illustrated in Fig 6. Two specimens of sandwich panel are positioned between and glued to the three rigid steel plates. The force F acts on the middle plate and the vertical displacements w of the rigid plate are measured simultaneously.

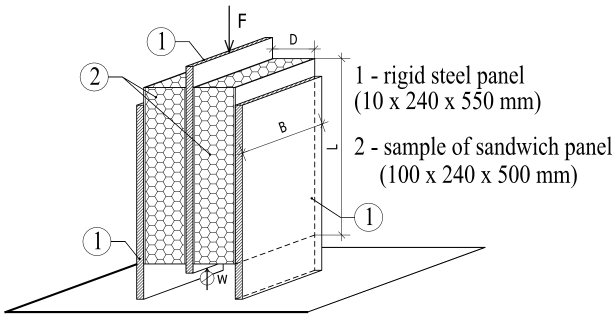


Fig 6. Double-lap shear test

The shear modulus G_C is determined according to instructions in the code PN-93/C-89072. The Authors modified the respective formula to the equation (7):

$$G_C = \frac{F \cdot d_C}{2 \cdot w \cdot B \cdot L}\,, \tag{7}$$

where B, L and d_C denote width, height and core depth of one specimen, respectively.

2.4 Measurement of angles of rotation (BgL-γ)

The relation between angles of deformation of sandwich element presented in Fig 2 has the following form

$$\gamma = \gamma_0 - \alpha_0\,, \tag{8}$$

where:
γ_0 – slope of the panel (effect of bending and shear); $\gamma_0 = w'$,
α_0 – angle of cross-section rotation,
γ – deformation angle due to shear.

The laboratory set-up is shown in Fig 7. Three laser pointers are attached to the simply supported sandwich panel loaded by the one-line force. Two pointers attached to upper and lower facings. They indicate γ_{01} and γ_{02}, the angles of upper and lower facing rotation, respectively. The middle one is attached to the section of a panel in such a way that it indicates the angle α_0. The positions of the laser light points at the levelling staff are recorded for increasing values of the load. The displacements of these light points divided by the distance of the levelling staff $L_1 + L_2$ give the tangent of the rotation angles. Simultaneously the deflection of the middle point of the panel was measured to compare the values of G_C resulting from different methods.

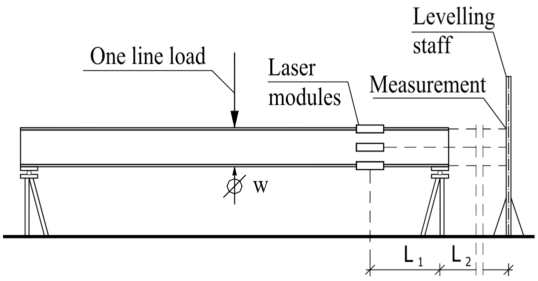


Fig 7. Testing stand

Using the equation (8) and knowing the shear force T, the shear modulus is calculated as follows:

$$G_C = \frac{T}{\gamma \cdot B \cdot d_C}. \quad (9)$$

2.5 Torsion tests (Torsion- φ)

The set-up for the torsion test is illustrated in Fig 8. The cylinder specimen is fixed to two steel rigid plates (on the left side of the picture). The left-hand side rigid plate is rigidly fixed and the right-hand side plate can rotate. The angle of rotation of a specimen is measured using laser pointer attached to the right plate and pointing at the levelling staff standing in front of the pointer. The sample is loaded by the torque. The scheme of the torque action is presented in Fig 9.

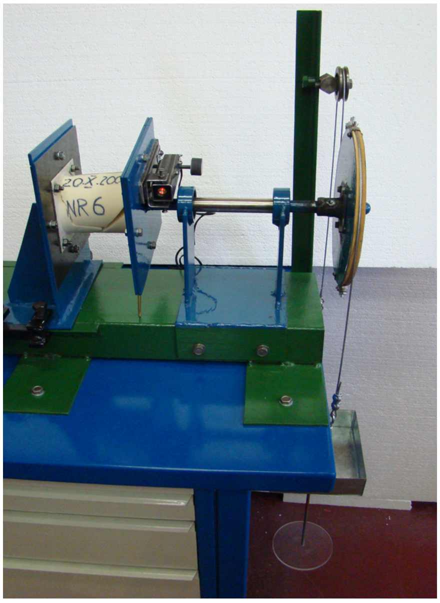


Fig 8. The set-up for the torsion test after the failure of the specimen

The shear modulus G_C is calculated using the following relation between torque M_S and angle of specimen rotation φ :

$$\phi = \frac{M_S \cdot L}{G_C \cdot I_0}, \quad (10)$$

where L and I_0 denote length of the sample and central second order moment of the area of the cylinder cross-section, respectively.

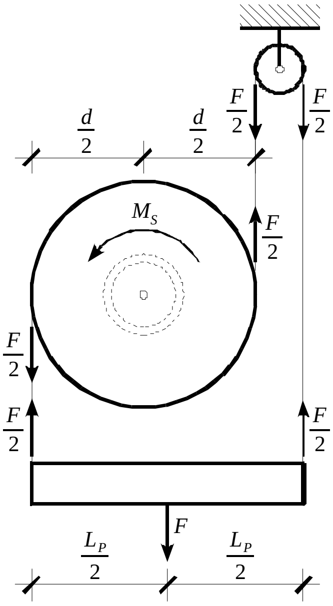


Fig 9. Scheme of force excitation in the torsion test

3. Numerical analysis

Basing on experimental and theoretical results, numerical model of sandwich panel was created. The numerical examples refer to structures investigated in real scale during laboratory experiments. Numerical models were prepared in ABAQUS system environment. The analysis was carried out for two various examples: L = 4.8 m (corresponding to BgL-w and BgL-γ) and L = 0.5 m (double-lap shear test), overall depth D = 98.5 mm, depth of the core d_C = 97.56 mm.

It was assumed that the flat facings have the thickness t = 0.47 mm and are made of an elastic-ideal plastic material: Young modulus E_F = 199 GPa, Poisson ratio ν_F = 0.3 and yield stress f_y = 270 MPa. The value of modulus of elasticity results from the fact that the facings consist of steel core coating with zinc. The core was modelled as a linear elastic material: Poisson ratio ν_C = 0.05 and shear modulus as the value obtained in the respective, real experiment.

The assumption of linear constitutive equation for the core material is allowed because in the case of bending, the typical failure has the form of facing wrinkling. Strains in the core part reach 0.07 %, which refers to linear behaviour of the core.

Facings were modelled using four node, doubly curved, thin or thick shell, reduced integration, hourglass control, finite membrane strains elements S4R. The core was modelled using eight node linear brick elements C3D8R. Important point of the model is a connection between facings and core elements. The TIE interaction was applied, which keeps all active degrees of freedom equal at two nodes.

Support conditions refer to real structures. The scheme of the bending model is presented in Fig 10. The panel is supported by two basing plates modelled as rigid bodies. For the left supporting base plate all three translations and the rotations with respect to axes *x* and *z* are equal to zero. Unconstrained rotation with respect to the axis *y* is assumed. The right base plate has additionally the possibility of the translation in the direction *x*.

The scheme of the double-lap shear model is presented in Fig 12. The same material parameters were used for the double-lap shear test as for the bending test. The thickness of three rigid steel plates is t = 10 mm. The side rigid plates are supported on the bottom in such a way that only rotation around the axis *x* is possible and all other displacements are restrained.

***Example 1* Bending test, *L* = 4.8 m, flat facings**

In this example we considered simply supported one-span sandwich panel with the length L = 4.8 m and width B = 1.0 m. Width of the supports is b = 100 mm. The sandwich structure is subjected to one-line load acting in the mid-span. The load is distributed on 60 mm wide strip on the upper facing. Used shell finite elements have dimensions 5 × 5 cm and thickness t = 0.47 mm. Brick elements have dimensions 4 × 4 × 4 cm.

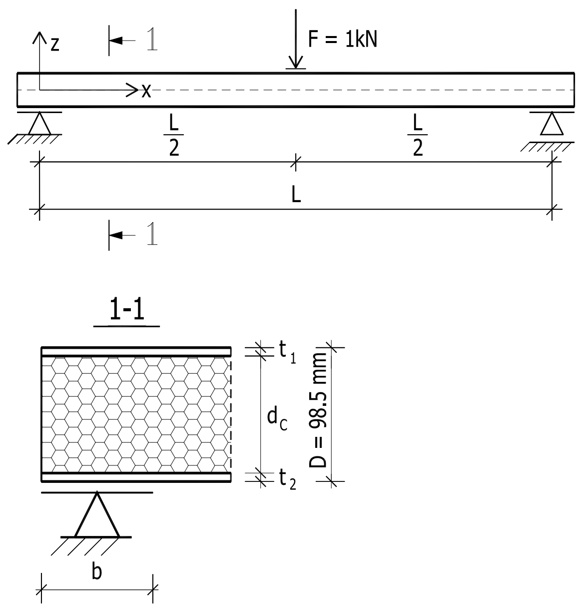


Fig 10. Scheme of loading system used in bending test

The vertical displacements of the panel are presented in Fig.11. This figure and detailed analyses demonstrated nearly uniform distribution of displacements, strains and stresses in the direction of the width of the slab. This observation can be used in verification and validation of methods basing on bending tests. It is important because it suggests that the extended Timoshenko beam theory can be used in some classes of tests, what makes these tests relatively simple.

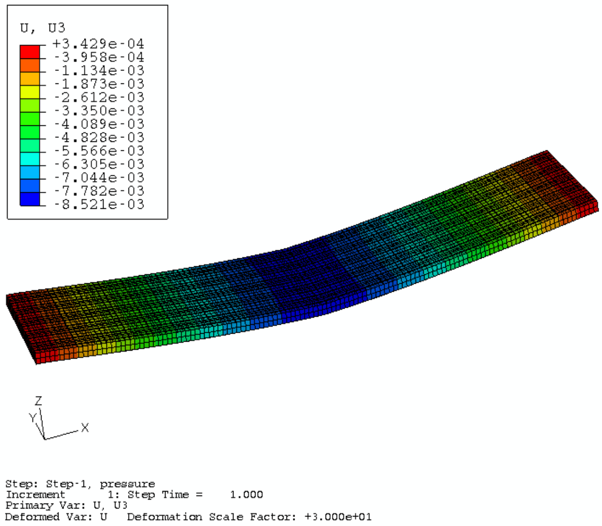


Fig 11. Deformation and displacement of long sandwich panel (test BgL) subjected to a one-line load

***Example 2* Double-lap shear test, *L* = 0.5 m**

The scheme of the structure is presented in Fig 12. The system is subjected to one-line load acting on the middle rigid plate. Shell elements S4R used for facings have dimensions 2.5 × 2.5 cm. Brick elements have dimensions 1.25 × 1.25 × 1.25 cm. Three steel rigid plates were modelled using shell elements S4R 2.5 × 2.5 cm with thickness 1.0 cm.

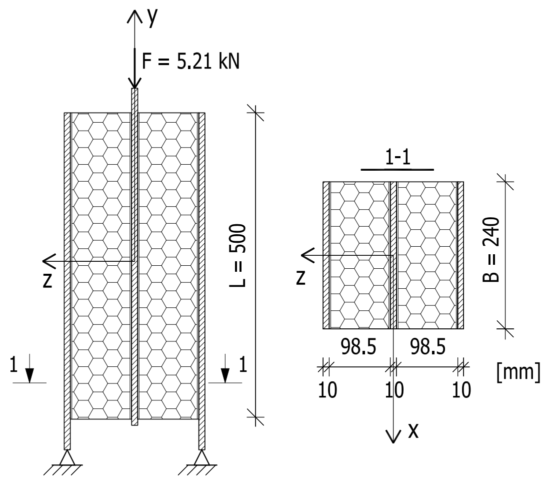


Fig 12. Scheme of loading system used to shear test

The results of the numerical test can be observed in Figs. 13 and 14. Distribution of the shear stress is almost uniform except for the upper and lower parts of the core. The shear stress τ_{yz} equals zero on the respective core surfaces. It results in the observed disturbances of the deformation and shear stress distribution (Fig 13). Surprisingly, in the same corners of the sample relatively large normal stresses appeared (Fig 14). Maximum value is σ_z = 51.91kPa, whereas the maximum shear stress for the same load is τ_{yz} = 24.3kPa. It can highly influence the value of failure load in practise.

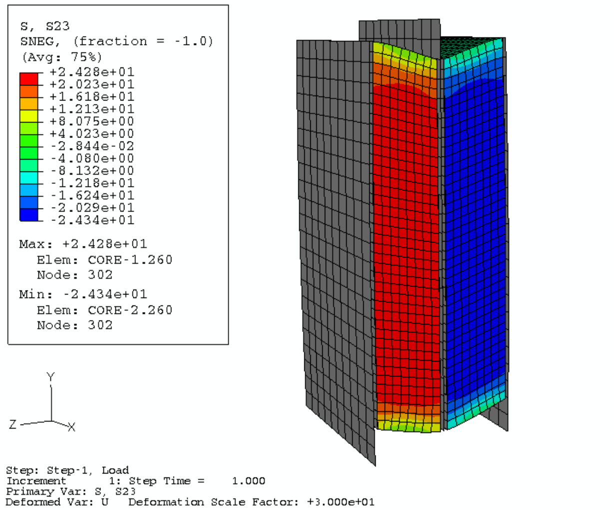


Fig 13. Shear stress τ_{yz} distribution in double-lap shear test

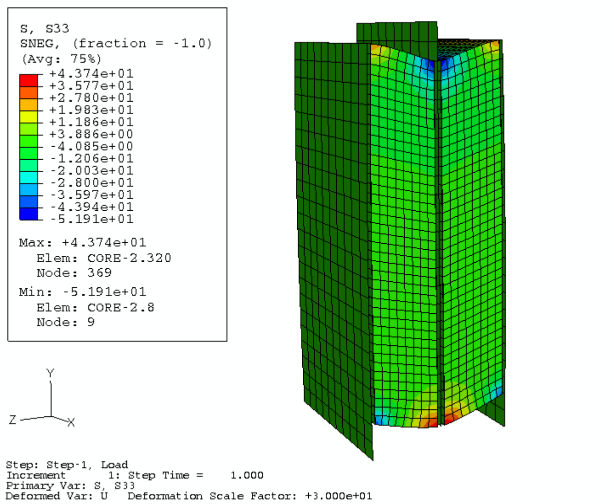


Fig 14. Local effects of normal stress in double-lap shear test

4. Laboratory tests for determining the shear modulus G_C – results and analyses

For all experimental bending and shear tests (BgS-*w*, BgL-*w*, BgL-γ, Shear-γ, Torsion-φ) the samples were cut out from the polyurethane sandwich panel produced on the line with the same parameters of the production process.

The tests were carried out on the specimens with the same total depth $D = 98.5$ mm. The flat or micro-profiling facings had the thickness $t_1 = t_2 = 0.47$ mm. This dimension includes the steel plate and the zinc coatings. It should be emphasized that in all tests longitudinal edge profilings of facings were cut off. This operation was necessary in order to minimize the effect of edge stiffening on sandwich behaviour. The dimensions of the specimens are presented in Table 1. Torsion tests (section 2.5) were carried out on the cylinder samples with total depth 98.5 mm and radius $R = 40$ mm.

Table 1. Specification of the samples used in experimental tests

Type of test	Description in the text	Type of facings	***B*** [mm]	***L*** [mm]
BgS-*w*	Section 2.2	Flat (F/F)	99.1	600
BgL-*w*	Section 2.2		998	4790
BgL-γ	Section 2.4			
BgS-*w*	Section 2.2	Micro-profiled (L/L)	99.2	600
BgL-*w*	Section 2.2		998	4800
BgL-γ	Section 2.4			
Shear-γ	Section 2.3	-	240	504

Displacements and forces were measured in the tests using displacement transducers HBM WA L 100 mm and tensometer force transducers HBM C6A 200 kN class 0.5, respectively. Recording and results analyses were done using HBM Catman 3.1 Professional program. Angles of rotation were measured using laser modules ML-33S-635-1 (diameter of laser beam 2 mm) and precision levelling staff (accuracy 1 mm). The obtained results are presented in Table 2.

Table 2. Experimental results of G_C

Type of test	Type of facings	***F*** [kN]	γ [rad]	***w*** [mm]	G_C [MPa]
BgS-*w*	Flat (F/F)	0.13	-	0.40	3.41
BgL-*w*		1.0	-	8.37	3.74
BgL-γ		1.0	0.001425	-	3.60
BgS-*w*	Micro-profiled (L/L)	0.13	-	0.50	2.72
BgL-*w*		1.0	-	8.77	3.43
BgL-γ		1.0	0.001515	-	3.39
Shear-γ	Flat	5.21	0.00738	0.721	2.93
Torsion-φ	Flat	0.056	-	-	2.45

The results of BgL-*w* and BgL-γ tests demonstrate that two different methods give similar shear modulus. The similarity was not observed in the paper (Chuda-Kowalska *et al.* 2008), where the panels with longitudinal edge profilings were tested. The comparison of the experiments carried out on panels with and without edge profiling will be presented on the conference.

Interesting is that the results obtained during bending of short panels (BgS-*w*) are lower than in BgL tests. Drastic reduction of the shear modulus for panels with micro-profiled facings may be explained by the differences between the core parameters taken from different parts of the panel. In fact, the specimens taken from the edge region indicate the reduction about 20 % in shear modulus comparing to the samples taken from the middle region. The problem is still investigated.

Very interesting and unexpected is that the value of G_C is much lower in case of micro-profiled facings. It is rather inexplicable, unless the cores are different.

The values of shear modulus obtained from the double-lap shear and torsion tests are lower than in other experiments. It turns out that in the shear-γ test, the shear effect coincides with unpredictable bending effects. In case of torsion, significant time dependence of the G_C is observed. The material stiffness regularly decreases with time. All these phenomena require further studies.

The analysis of measurement errors shows that the best accuracy is obtained for the torsion test (about 1 %). In spite of high precision of measurement of angles of rotation, the accuracy of the BgL-γ test is about 7 %.

5. Comparison of the experimental, analytical and numerical results

At the first stage, the numerical model of bending panel with flat facings was verified. Therefore, the shear modulus $G_C = 3.60$ MPa obtained from laboratory tests BgL-γ and $G_C = 3.74$ MPa from BgL-w were introduced. The chosen values of the numerical analysis, namely the shear angle γ and the panel deflection w are presented in Table 3. The numerical values are compared to the experimental and analytical results. The last one was calculated using the model presented in Stamm (1974). Please note that in the analytical model, the values of Young modulus and Poisson ratio of the core are not required.

Table 3. Results from long panel with flat facings (L = 4.8 m)

		Assumed values	Results	
		G_C	γ	w
		[MPa]	[rad]	[mm]
Experimental model	BgL-γ	-	0.001425	-
	BgL-w	-	-	8.37
Analytical model	BgL-γ	3.60	0.001410	8.53
	BgL-w	3.74	0.001359	8.41
Numerical model	BgL-γ	3.60	0.001450	8.58
	BgL-w	3.74	0.001420	8.45

Analytical model provides lower results of γ and w than the numerical one. For G_C equals 3.74 MPa we are able to calibrate numerical model to simultaneously fulfil measured displacements w and γ. Differences in γ are about 0.35 %, in w are 0.96 %.

At the next stage, the numerical model corresponding to the double-lap shear test was verified. Please note that the value $G_C = 2.93$ MPa was introduced into the numerical model. The results of the analysis are presented in Table 4.

Table 4. Results from double-lap shear test (L = 0.5 m)

	Assumed values		Results	
	E_C	G_C	w	G_C
	[MPa]	[MPa]	[mm]	[MPa]
Experimental model	-	-	0.721	2.93
Numerical model	6.0	2.93	0.826	2.56

It was very surprising that relation between acting force and vertical displacements in the numerical model gives another value of the shear modulus. The received value $G_C = 2.56$ MPa differs from the introduced one by about 14.5 %. It means that some elements of the employed method are improper. It is expected that the problem consists in geometrical dimensions of the specimen and/or improper support conditions. The influence of these parameters is currently examined.

Concluding remarks

The development of the suitable experimental method of the determination of shear modulus and its application is very important. This modulus plays the crucial role in functional response of sandwich panels such as load-bearing capacity, maximum permissible span and deflection. Wide range of application of sandwich structures and tendency to cost optimisation require using of modern engineering tools in calculations. Computational mechanics allows creation of advanced models, but they work only if the input parameters are properly defined.

In order to precise assessment of the shear modulus, laboratory and numerical experiments were conducted and analytical calculations were done. Surprisingly, different empirical methods of G_C identification lead to different results.

The double-lap shear test seems to have the best theoretical grounds, but the numerical simulations prove that in this case the complex stress state exists. The assumption that there is a pure shear is false. The obtained shear modulus is about 14.5 % lower than the assumed value. The last analyses show that changing of the geometrical proportions of the sample and boundary conditions results in substantial increasing of the modulus.

The experiments basing on vertical displacements and angles of rotations measurements give higher values of G_C. These laboratory tests are in good agreement with the results obtained from the numerical and analytical models. Rather small differences can be interpreted by the shear correction factors of generalized Timoshenko theory and participation of facings in shear. It should be emphasized that the bending tests do not require particular specimen's preparation nor complicated apparatus.

The previous paper (Chuda-Kowalska *et al.* 2008) showed discrepancy about 30 % between results of BgL-w and BgL-γ tests. It is explained by the influence of longitudinal edge profiling which highly influences not only the shear modulus assessment, but also the wrinkling stress. The ongoing tests on next slabs with the profiling are expected to provide information on the quantitative contribution of longitudinal edges to the total stiffness of slabs.

In the torsion tests the lower value of G_C was obtained. The stiffness of the core material regularly decreases during the test. The influence of the phenomenon on the correctness of the experiment is studied.

The Authors plan to continue the research aimed at the improvement of the method of shear modulus determination. The laboratory tests will be finished and the results will be presented and discussed in the presentation at the conference.

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