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MECHANICAL CHARACTERISTICS OF ALUMINIUM SANDWICH PANELS WITH ALUMINIUM HONEYCOMB CORE

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Abstract: *The paper presents the results of testing the mechanical properties of aluminium sandwich panels with aluminium honeycomb core. The tests were performed under quasistatic conditions and monitored changes in mechanical characteristics at different crosshead speed rates. Determined mechanical characteristics were: FLATWISE Compressive Strength, EDGEWISE Compressive Strength and Flexural Properties of Sandwich Constructions (Flexural Stiffness and Core Shear Modulus). For tests were used aluminium panels different thicknesses (6,00 mm, 10,00 mm, 15,00 mm, 20,00 mm and 30,00 mm) and three test speeds were applied (6,00 mm / min, 200,00 mm / min and 400,00 mm / min). The results showed that there is no spread of deformation on the surface of the material and transfer along the core, so the deformation is exclusively of local character. This showed that the honeycomb core is an extremely good material in localizing deformation and has a positive effect on preserving the integrity of the remaining part of the structure that was not under the direct influence of external forces. It has been shown that in the case of deformation of the panel along the edge, the main load carrier is the surface sheet, while the core is a weak component of the system in the case when the sandwich panel is pressed or bent on the surface. Also, it was shown that between different test speeds applied on one panel thickness, there is no large deviation in the obtained maximum material strengths for a given mechanical characteristic.*

Keywords: *aluminium panel, honeycomb core, deformation.*

1. INTRODUCTION

One of the composite structure types, aluminium sandwich panels with metal core in the form of honeycombs first appeared in the late 1940s for the needs of the aircraft industry. Adhesively bonded, aluminium sandwich panels with a honeycomb core provided designers with a lightweight, strong, fatigue-resistant and aerodynamic material. Today's application of aluminium sandwich panels in aircraft secondary structures has progressed from the trailing edges of control surfaces to the entire assembly, including cargo doors, engine buffers, etc. [1]. Besides aircraft industry, these panels are widely used in the automotive, civil engineering and military industries due to their high load capacity combined with excellent energy dissipation properties [2]. Because of their characteristics, they have outstanding potential for ballistic purposes because they can absorb strong shock waves, retain fragments, they are light and portable. Compared to common materials used for kinetic absorption, composite materials provide an extra lightweight modular solution with low space consumption [3]. In addition, they can be easily repaired and replaced, which is very important in the field. Besides, they should be resistant to fire, they must withstand greater loads or be able to absorb greater vibrations, etc. Sandwich constructions, compared to conventional materials, provide the following key advantages: very low weight, high stiffness, durability, cost efficiency [4].

Sandwich construction generally consists of two facing sheets with a light core between them, Figure 1. These panels have the highest strength-to-weight ratio, unmatched by any other structural material. Their mechanical properties are controlled by the thickness of the facings and the characteristics of the honeycomb core (by the thickness the material foil from which core was made and also by the size and shape of the honeycombs themselves) [4]. As you can see in Figure 1, a sandwich panel with a honeycomb core consists of [2, 5]:

1. Face sheet – two thin plates,
2. Core – widely used honeycomb core – layer between two thin facings which also transfers the load from one to the other plate,
3. Adhesive - the primary role in joining the core and facings into a single structural unit and ensuring the rigidity and stability of the core.

Facing sheets are most often made of aluminium alloys, high strength steel, titanium alloys or composites [6]. The main role of the facings is to ensure the required strength and stiffness of the panel under conditions of axial loading, bending and shearing within it.

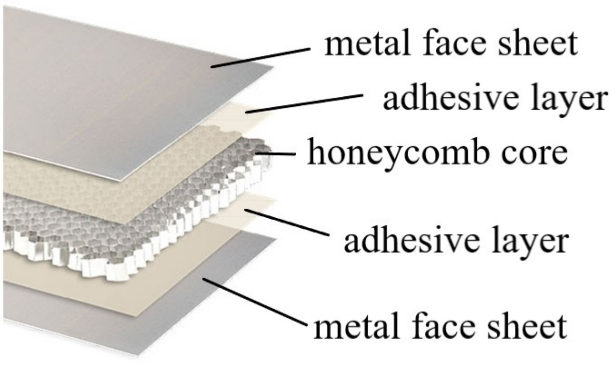


Figure 1. Layers of the aluminium sandwich panel

In order to meet the requirements and operating conditions for which facings are intended, it is also necessary to select adhesive in order to achieve a rigid connection between facings and the core. In addition to the basic load-bearing function, the selection of the facing material is also influenced by the required qualities for the surface of the panel itself. Accordingly, the given material must meet the requirements of roughness, wear resistance and corrosion resistance. In structural panels, both facing sheets usually have same thickness and such panels are called symmetrical sandwich panels. If the facings have different thicknesses (due to the requirement for different load on the panel itself), then they are asymmetric sandwich panels. Sheet thicknesses can range from 0,25 mm to 40,0 mm. In aluminium sandwich panels facing are usually made of high strength aluminium alloys from 7xxx and 2xxx series (alloys EN AW 7075, EN AW 2024, EN AW 2014,...), but also and from 5xxx series (EN AW 5083, EN AW 5754,...) [1, 3-6].

The core can be [3,6,7,8]:

1. The shape of honeycomb – made of thin foil strips in order to form a honeycomb. In the case of making a metal core, the most commonly used material is aluminium alloy EN AW 3003, but EN AW 5052, EN AW 5056, EN AW 2024 are also used. Honeycombs can be of different shapes, of which four are basic: hexagonal, circular, triangular and square. Conventional hexagonal honeycombs are commonly used for sandwich cores.
2. Foam or solid material as filling - cores made of these materials are cheap and involve the use of wood or some polymer foam.
3. Profiled core - these cores are made of some perforated profiled sheet.

In addition to connecting the core and surface sheets, the adhesive in sandwich panels also has the function of transferring shear and axial loads to and from the core. It should withstand the applied force and ensure that the connection between the core and the sheets does not break during exploitation. The adhesion for sandwich panels is chosen so that it has high strength and high binding power because it must bear a certain load. In most cases, when designing structures, core fractures (i.e., on the walls of the honeycombs themselves) represent more favorable cases than fracture at the point of attachment of components (i.e., fracture on the bonding agent). In accordance to that, the type of binding core is chosen adhesive should require high strength and a strong bond with minimal surface contact at the ends of the core material [6,8].

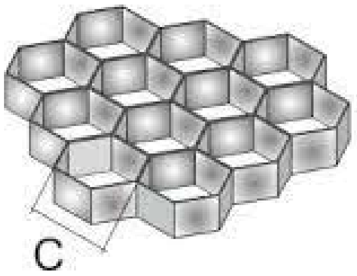
2. EXPERIMENTAL WORK

2.1. Material

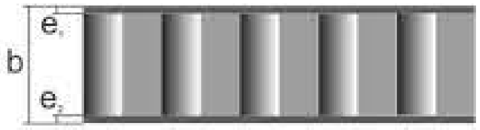
For the purpose of testing were used "LARCORE" aluminium panels from the Spanish manufacturer "Alucoil". For tests were used aluminium panels in 5 different thicknesses (6,0 mm, 10,0 mm, 15,0 mm, 20,0 mm and 30,0 mm). The basic characteristics of the whole panel as well as its individual components (facings, core and adhesive) were obtained from the manufacturer [9]. Table 1 gives an overview of the dimensions of the used panels, while Figure 2 shows a schematic representation of the characteristic. As you can see in Figure 2, the mark "c" represents the size of the honeycomb, the mark "b" corresponds to the total thickness of the sandwich panel, while the marks "e_1" and "e_2" indicate the thickness of the surface sheets.

Table 1. Overview of aluminium panels with honeycomb core

Sandwich panel	Panel thickness, b	Facings thickness, mm	
		e_1	e_2
1	6,0 mm	1,0	0,5
2	10,0 mm	1,0	0,5
3	15,0 mm	1,0	1,0
4	20,0 mm	1,0	1,0
5	30,0 mm	1,0	1,0



a) honey comb



b) panel cross section

Figure 2. Dimensions of the panel

In accordance to manufacturer's specification:

- facings are made of aluminium alloy EN AW 5754
- honeycomb core is made of aluminium alloy EN AW 3005; foil thickness 70 µm; honeycomb size c=9,52 mm.

2.2 Mechanical tests

The tests were performed at room temperature on an electromechanical tension/pressure test machine "Schenck-Trebel RM100" with a maximum load of 100kN with a computer system for data acquisition. Four different mechanical tests were performed in quasistatic condition with constant speed. Applied crosshead speed rates were 6,0 mm/min, 200,0 mm/min and 400,0 mm/min. Test specimens for all tests were taken from a direction parallel to the long side of the panel. The dimensions of the test specimens are in accordance to the applied standard and depend on panel thickness.

2.2.1. Flatwise compressive test

The test method is used to determine the compressive strength of a sandwich panel in the direction normal to its surface. The test was performed in accordance with the standard ASTM C365 - Standard Test Method for Flatwise Compressive Properties of Sandwich Cores [10]. The test results represent the mean value of at least 3 test specimens.

2.2.2. Edgewise compressive test

The test method is used to determine the compressive strength of a sandwich panel in the direction normal to its edge. The test was performed in accordance with the standard ASTM C364 - Standard Test Method for Edgewise Compressive Strength of Sandwich Constructions [11]. The test results represent the mean value of at least 3 test specimens.

2.2.3. Three and four point bending tests

The bending test was performed using two different methods - 3-point bending (single-point midspan load) and 4-point bending (two-point load). The test method is used in order to evaluate the strength of the panel when the load is introduced locally on the sandwich panel. The test was performed in accordance with the standard ASTM C393 - Standard Test Method for Flexural Properties of Sandwich Constructions [12]. Unlike the previous tests, here the bending test was performed at only one applied crosshead speed rate, namely 6,0 mm/min. The test results represent the mean value of at least 3 test specimens.

The distance between the supports during the 3-point and 4-point bending tests was L=130,0 mm.

The 3-point bending test was performed by placing the support points according to the scheme given in Figure 3.

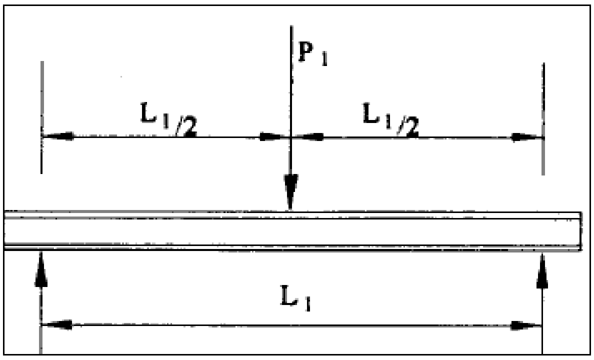


Figure 3. Schematic representation of 3-point bending – midspan loading

Based on the gain test results after 3-point test, calculation of flexural properties for sandwich panels and core materials can be written as follows [12]:
Core shear stress:

$$\tau = \frac{P}{(d+c)\cdot b} \qquad (1)$$

where:
τ – core sher stress, MPa
Pmax – max load, N
d – sandwich panel thickness, mm
c – core thickness, mm
b – sandwich width, mm.

Facing bending stress – calculate the facing bending stress as folllows:

$$\sigma = \frac{P\cdot L}{2t\cdot(d+c)\cdot b} \qquad (2)$$

where:
σ – facing bending stress, MPa
t – facing thickness, mm
L – span length, mm

Total sandwich beam deflection calculate as follows:

$$\Delta = \frac{P\cdot L^3}{48D} + \frac{P\cdot L}{4U} \qquad (3)$$

where:
Δ – total beam midspan deflection, mm
G – core shear modulus, MPa
E – facing modulus, MPa
D – panel bending stiffness, N mm^2
U – panel shear rigidity, N

Since facings were made of the same alloys but different thicknesses (at sandwich panels of 6,0 mm and 10,0 mm total thickness), this must be taken into account when calculating the coefficient D. Accordingly, to calculate D for sandwich panels:
1. for total thickness 6,0 mm and 10,0 mm

$$D = \frac{E\cdot t_1 E\cdot t_2 (d+c)^2 \cdot b}{4(E\cdot t_1 + E\cdot t_2)} \qquad (4)$$

2. for total thickness 15,0 mm, 20,0 mm and 30,0 mm

$$D = \frac{E\left(d^3 - c^3\right) \cdot b}{12} \tag{5}$$

Panel ridigity calculate as follows:

$$U = \frac{G\left(d + c\right)^2 \cdot b}{4c} \tag{6}$$

The four-point bending test was performed by placing the support points according to the scheme given in Figure 4.

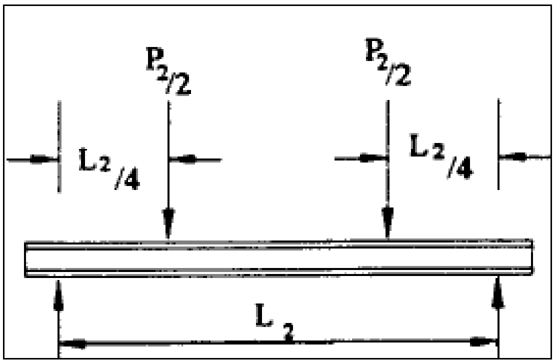


Figure 4. Schematic representation of 4-point bending – two-point loading

Calculation of flexural properties for sandwich panels and core materials after 4-point bending test can be written as follows [12].:

Core shear stress is calculate in accordance with equatation 1.

Facing bending stress – calculate the facing bending stress as folllows:

$$\sigma = \frac{P \cdot L}{4t\left(d + c\right) \cdot b} \tag{7}$$

Total sandwich beam deflection calculate as follows:

$$\Delta = \frac{11P \cdot L^3}{768D} + \frac{P \cdot L}{8U} \tag{8}$$

The determination of D and U values is performed in accordance with relations 4, 5 and 6.

If deflection of the same sandwich panel are determined under central load (3-point bending) and also under total load applied at 4-point bending, the flexural stiffness *D* and core shear modulus *G* may be determined from simultaneous solution of the deflcetion equatation as follows:

$$D = \frac{P_1 L_1^3 \left[1 - \left(\frac{11 L_2^2}{8 L_1^2}\right)\right]}{48 \Delta_1 \left[1 - \left(\frac{2 P_1 L_1 \Delta_2}{P_2 L_2 \Delta_1}\right)\right]} \tag{10}$$

$$G = \frac{P_1 L_1 c \left[\frac{8 L_1^2}{11 L_2^2}\right]}{\Delta_1 b\left(+c\right)^2 \left[\left(\frac{16 P_1 L_1^3 \Delta_2}{11 P_2 L_2^3 \Delta_1}\right) - 1\right]} \tag{11}$$

3. RESULTS AND DISCUSSION

During the tests it has been noticed that in the case of panels total thickness of 6,0 mm, a greater adhesive wetting on the walls of the honeycomb core compared to the other tested panel thicknesses. This was probably occurred during the panel production process itself. This is important because in case of panel 6,0 mm it cannot be precisely estimate what is the contribution to strength due to over wetting honeycomb core walls. It cannot be distinguished contribution of adhesive to strength of sandwich panel.

Also, it was shown that there is no great deviation in the obtained maximum strengths of the material for a given mechanical characteristic between different applied crosshead speed rates for the observed thickness of the panel. This confirms that the characteristics of sandwich panels are influenced by the mechanical characteristics of the alloy chosen for the facings because it is the carrier of strength. As mention above, facings at used sandwich panels, are made of aluminium alloys, which are known to be unaffected by deformation rates, so tacking that into account obtained results are expected.

3.1. Flatwise compressive test

Figure 5 shows the appearance of the specimen for flatwise compressive testing with the normal load to the surface of the aluminium sandwich panel.

The test results are given in Table 2, while Figure 6 shows the dependence of the maximum compressive strength (Rmp) for different crosshead speeds.

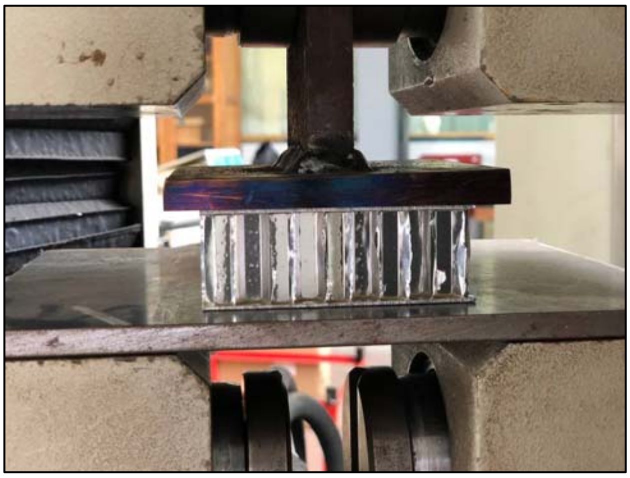


Figure 5. Sample during the flatwise compression test

Table 2 Results from flatwise compressive test

Panel tickness, mm	Crosshead speed rate, mm/min	Fmp, kN	Rmp, MPa
6,0	6,0	17,7	2,4
	200,0	18,7	2,6
	400,0	12,6	1,7
10,0	6,0	14,4	2,0
	200,0	13,9	1,9
	400,0	8,8	1,2
15,0	6,0	13,9	1,9
	200,0	14,0	1,9
	400,0	12,6	1,7
20,0	6,0	14,3	2,0
	200,0	13,4	1,9
	400,0	13,4	1,8
30,0	6,0	13,8	1,9
	200,0	13,7	1,9
	400,0	12,6	1,7

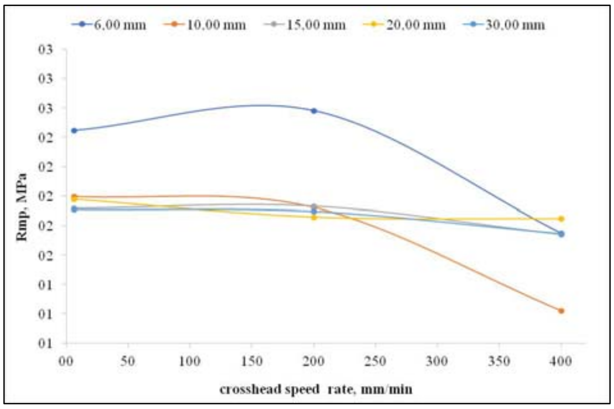


Figure 6. The dependence of the maximum compressive strength (Rmp) for different crosshead speed ratess for each panel thickness.

The obtained results indicate that the change in the crosshead speed has almost no effect on the compressive strength of sandwich panels. Also, the compressive strength does not depend on the change in the thickness of the sandwich panel. Based on the test results, it can be seen that the mean value of compressive strength for almost all thicknesses and crosshead speeds is about 1.9 MPa. The mean compressive strength for the 6.0 mm panel thickness is 2.4 MPa, 2.6 MPa and 1.7 MPa for 6.0 mm/min, 200.0 mm/min and 400.0 mm/min crosshead speed rates respectively. The given results are expected because it is a characteristic of the facing material itself [13]. Based on this, it can be concluded that the flatwise compressive strength of aluminium sandwich panels depends only on the mechanical characteristics of the alloy from which it is made. These results were also obtained by other authors [7,14,15].

In addition to the above, the tests showed that the core is the weakest part of the aluminium sandwich panel, because the yielding first occurred in it. Specimens inspection after test revealed yielding in an area that corresponds to half the height of the honeycombs themselves, figure 7. Yielding was observed between the honeycomb cell walls.

Figure 7. Appearance of the specimen after flatwise compression testing

3.2. Edgewise compressive test

Figure 8 shows the test specimen before edgewise compressive testing. The test results are given in Table 3, while Figure 9 shows the dependence of the maximum compressive strength (Rmpi) for different crosshead speed rates for each panel thickness.

Figure 8. Sample before edgewise compressive test

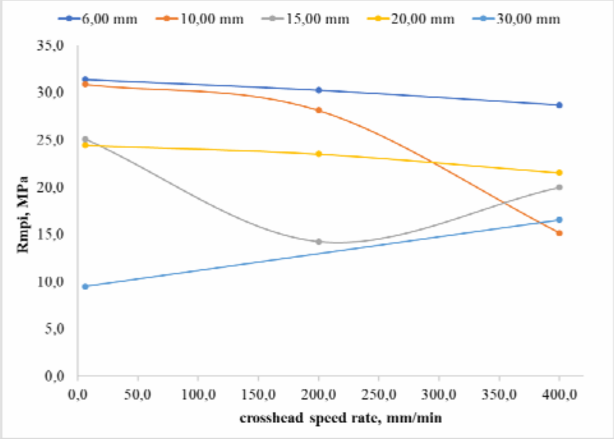


Figure 9. The dependence of the maximum compressive strength (Rmpi) for different crosshead speeds for each panel thickness

Table 3. Results from edgewise compressive test

Panel tickness, mm	Crosshead speed rate, mm/min	Fmpi, kN	Rmpi, MPa
6,0	6,0	9,4	31,4
	200,0	9,1	30,2
	400,0	8,6	28,7
10,0	6,0	15,4	30,9
	200,0	14,1	28,1
	400,0	7,6	15,1
15,0	6,0	18,8	25,1
	200,0	10,7	14,2
	400,0	15,0	20,0
20,0	6,0	24,4	24,4
	200,0	23,5	23,5
	400,0	21,5	21,5
30,0	6,0	14,2	9,5
	200,0	-	-
	400,0	24,8	16,5

Based on the obtained results, it can be seen that on the 6,0 mm panel thickness, change in the crosshead speed does not affect the value of the compressive strength. Also, this panel thickness gives the highest value of compressive strength (of about 30,0 MPa) compared to other thicknesses. However, taking into account the above, it is difficult to assess whether this is a real strength value or whether its contribution was influenced by the strengthening of the honeycomb walls due to the mutual reaction with the adhesive.

With other panel thicknesses, the strength does not have a constant change trend, its changes in relation to the applied test speeds. The greatest influence of the crosshead speed was observed in panels with a thickness of 10,0 mm, where at the lowest speed of 6,0 mm/min the compressive strength is 30,9 MPa, while at the maximum speed of 400,0 mm/min the compressive strength is 15,1 MPa. The 20,0 mm thick panel showed the least sensitivity to the applied crosshead speed, so the difference between the strength value at the minimum and maximum crosshead speed is about 12% (6,0 mm/min - Rmpi = 24,4 MPa; 400,0 mm /min - Rmpi = 21,5 MPa).

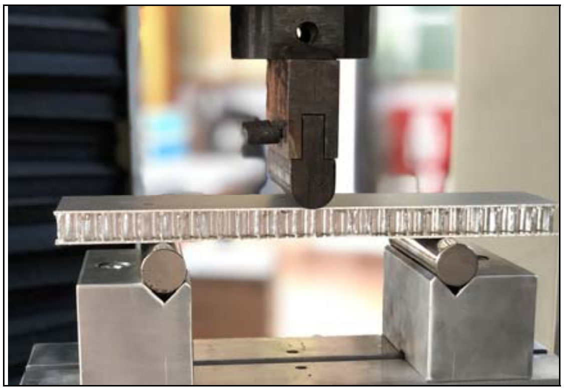
An important difference in relation to compress tests on the surface of the panel is that the compressive strength is up to 10 times higher in the case of the edgewise compressive test. This indicates that in the case of load along the edge of the panel, the strength depends mostly on the mechanical characteristics of the facing material, while in the case of load on the panel surface, the strength depended exclusively on the core. The impossibility of differentiating the main carrier to the strength contribution is reflected in the scattering of the strength results under conditions of the same test speeds, similar confirmations were also given by the authors [14, 15].

In addition to the above, the tests showed that when the maximum strength is reached, the material yield only in the places of contact with the pressure surfaces of the testing machine, i.e. places of load induction. Characteristic yielding takes place first by breaking the bond between facings and core, mainly by the bonding agent, followed by local twisting or splitting of the panel. The given yielding of sandwich panels has also been observed by many authors [6,14-16]. Figure 10 shows the characteristic appearance of the specimen after testing.

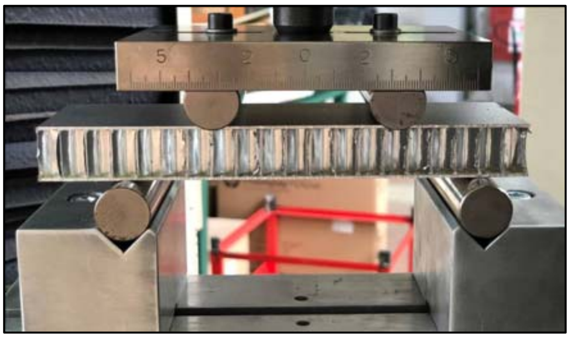
Figure 10. Appearance of the specimen after flatwise compression testing

3.3. Three and four point bending tests

Figure 11a shows the arrangement of the test specimen for 3-point bending tests, while Figure 11b shows the specimen for 4-point bending.



a) three point bending test



b) four point bending test

Figure 11. Appearance of the specimen before bending tests

The results obtained during bending tests are used to determine the bending stiffness of the sandwich panels, the shear resistance of the core and the shear modulus or the compressive and tensile strength of the facings. It is important to note that the mechanical characteristics of the core are most precisely determined in the case when the core is tested separately, as an independent component, in accordance with the methods defined within the MIL-STD-401 and ASTM C273 standards.
As within this test it is only possible to test the panel as a whole, the obtained results will be analyzed based on the precise relations given in the ASTM C393 standard.

An examination of the test specimen after applied bending test found that there is local deformation of the panels at the points of load induction, i.e. the contact of the mandrel on the panel, while the remaining ligament of the sample remains undeformed. This behavior of the same type of sandwich panel has been noted by several authors [6,7,15] and can be considered as one of the main characteristics of the panel.

In order to follow the influence of the thickness of the facings for panels of 6,0 mm and 10,0 mm thickness, tests were performed with a change in the position of the facings thickness in relation to the direction of load induction. Tests have shown that there is no influence of the orientation of the sides with a thinner or thicker facing. In both cases, changes in maximum force are negligible. Thus, in the case of panels marked 1, the mean value of Fmax in the case of placing a surface with a thicker facing opposite to the direction of load induction is about 0,87 kN, while in the opposite case (thinner towards the direction of load induction) the mean value of Fmax = 0,84 kN.

a) three point bending test

b) four point bending test

Figure 12. Appearance of the specimens after tests

The results of testing and calculation of the characteristic properties of the panels are given in tables 4, 5 and 6. Jung's modulus of elasticity (E=68 GPa) of the facing material and shear modulus of the core material (G=26 GPa) are characteristics of the material itself and are taken from the manufacturer's specification. Figure 12 shows characteristic appearance of specimens after testing.

Table 4. Results from 3-point bending tests

Spec.	F_{max}, kN	τ_1, MPa	σ_1, MPa	D_1, $\times 10^3$GPa	U_1, MN	Δ_1, mm
1 TA*	0,87	1,38	119,68	37,49	9,56	1,07
1 TD**	0,84	1,33	115,56	37,49	9,56	1,03
2 TD	0,93	0,84	72,61	116,37	15,70	0,37
2 TA	0,98	0,88	76,52	116,37	15,70	0,39
3	1,31	0,78	50,68	400,52	23,52	0,15
4	1,74	0,76	49,61	737,12	31,29	0,11
5	2,05	0,59	38,29	1716,32	46,86	0,06

- *TA - thicker facing up in the direction of the load induction
- **TD – thinner facing up in the direction of the load induction

Table 5. Results from 4-point bending tests

Spec.	F_{max}, kN	τ_2, MPa	σ_2, MPa	D_2, $\times 10^3$GPa	U_2, MN	Δ_2, mm
1 TA*	1,22	1,94	83,92	37,49	9,56	1,03
1 TD**	1,14	1,81	78,41	37,49	9,56	0,96
2 TD	1,28	1,15	49,97	116,37	15,70	0,35
2 TA	1,33	1,20	51,92	116,37	15,70	0,36
3	1,72	1,02	33,27	400,52	23,52	0,14
4	2,08	0,91	29,65	737,12	31,29	0,09
5	2,92	0,84	27,27	1716,32	46,86	0,05

- *TA - thicker facing up in the direction of the load induction
- **TD – thinner facing up in the direction of the load induction

Table 6. Panel bending stiffness (D) and core shear modulus (G)

Specimen	D, $\times 10^3$GPa	G, GPa
1 TA*	37	26
1 TD**	37	26
2 TD	116	26
2 TA	116	26
3	400	26
4	737	26
5	1716	26

- *TA - thicker facing up in the direction of the load induction
- **TD – thinner facing up in the direction of the load induction

Based on the obtained results, it can be seen that the shear stress of the core is higher in the case of 4-point bending, while the stress of the facings is higher in the case of 3-point bending.

The stiffness of the aluminium sandwich panel is the highest in the case of a panel with a thickness of 30,0 mm, 1716×10^3GPa. Contrary, the panel with a thickness of 6.0 mm has the lowest stiffness 37 $\times 10^3$GPa.

As can be seen from the table 6, the shear modulus of the core (G) has the same value for all sandwich panel thicknesses, namely 26 GPa. As could be expected, shear modulus of the panel core is equal to the value for the core base material (alloy EN AW 3005, G=26 GPa). Taking all the previous tests and the analysis of the specimens after them, it can be said that during flatwise compression tests and bending, the sandwich panel always first break in the core, which made it a weak component of the sandwich panel under the given conditions. Theoretical and experimental confirmations were also noted by other authors [17].

4. CONCLUSION

Tests at different crosshead speed rates showed that testing speed rates have no great effect on the obtained mechanical characteristics of aluminium sandwich panels. In case of panel deformation along the edge, the main load bearers are facings.

It was shown that during the load induction on the sandwich panel, the deformation is not transmitted through the entire system, but is exclusively of a local character, i.e. only at the places of the load induction.

The aluminium sandwich panel with a thickness of 6,0 mm has the lowest stiffness, of 37×10^3GPa.

The aluminium sandwich panel with a thickness of 30,0 mm has the highest stiffness, of 1716 $\times10^3$GPa.
Core shear modulus (G) for all sandwich panel thicknesses is 26GPa, which is equal to the shear modulus of the base core material, EN AW 3005 alloy.

The core is a weak component of the system in the case when the sandwich panel is subjected to compression or bending normal to its surface.

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