EXPERIMENTAL ASPECTS OF THE APPLICATION OF STRAIN GAUGES ON SANDWICH TYPE CIRCULAR PLATES FROM POLYMER COMPOSITE MATERIALS IN PRESSURE VESSELS

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The paper presents the experimental results following hydraulic pressure tests of the circular sandwich plates made from polymer composite materials with triangular cellular lattice type core, used in the experimental pressure vessel model, by monitoring their mechanical behaviour on internal pressure and the imminent appearance of the deformation up to the time of fracture failure. The experimental tests had the goal to show the pressure – deformation behaviour diagrams, corresponding to sandwich composite structures with cellular lattice type core, achieved by additive manufacturing of four distinct types of polymeric materials: ABS, PC, PLA and CF, with the layer thickness 5 mm. Using strain gauges, it was possible to measure with high precision the deformation of the analysed composite structures under actual load conditions at different values of pressure, so that the obtained experimental results provided a clear evidence for optimal operating decisions.

Keywords: polymeric composite, cellular core, sandwich panel, strain gauge, composite pressure-vessel.

1. Introductory considerations

The development of lightweight and ultra-lightweight polymer composites *sandwich* structures used successfully in many industries (aeronautics, aerospace, naval, railway, automotive etc.), represents a direction of scientific research in full ascension. Cellular materials made of polymeric materials are now available very easily, although prices are higher compared to standard products, and they

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continue to have a massive introduction to the market, because of the manufacturing processes evolution. Such cellular materials are used in a variety of applications: for the sandwich panel cores, starting from simple and cheap parts up to complex and advanced components from the aerospace domain [1]. The word "cell" derives from the Latin "*cella*", a small compartment or an enclosed space. In the case of groups of cells, which the Romans called ”*cellarium*”, a less elegant translation is solid cells. After Gibson and Ashby [2], a cellular solid is composed of an interconnected system of solid ties or plates that form the edges and faces of cells.

For the construction of a polymer composite sandwich panel three main components are generally involved (Fig. 1): two polymer facings, with the same thickness, a rigid and strong structure, separated by a thick light cellular structure in comparison with outer facings [3 - 6].

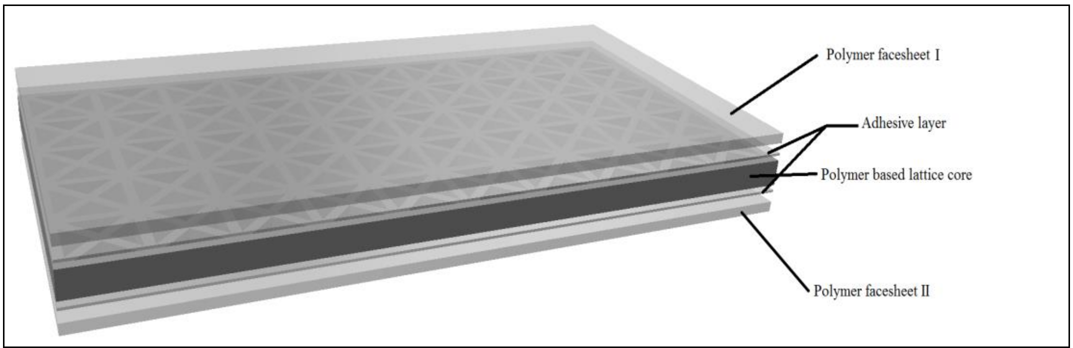


Fig. 1 – The layered structure of a composite sandwich panel

In the literature, the cell structure is known as core, due to its location in an assembly comprising the sandwich core in two sheets disposed one on the either side of the cellular core together with the adhesive joining the core and the facesheets (example: bonding with adhesives in thin film layer and ultra-sticky).

This additional ultra-thin layer forces the core and facings to behave as an unique structure, thus transferring axial and transverse loads to and from the cellular core which provides ~~a~~ sufficient rigidity to maintain an equidistance between the outer layers.

From a structural point of view, the main function of the cellular core in the sandwich structure is to stabilize the facesheets to avoid buckling and deformation and to withstand the shear loading along its thickness. Facesheets are transferring the tension and compression stresses. Their main function is to offer higher bending stiffness and plane shear to the sandwich structure. The facesheets also carry a part of local stresses. To maintain the link between the cellular core and the facesheets, thus facilitating the transfer of shear forces, the end result from component joining must withstand mainly shear stresses.

Intense concerns from international academics, demonstrated by a considerable number of scientific papers published and supported by results obtained in various industrial applications, reflect practicality of polymer composite sandwich panels [7]. However, due to the small degree of automation in manufacturing technologies of cellular cores, on difficulties recorded in the formation of assemblies, as well as higher costs, the use of composite sandwich panels is still limited. In addition, there are industries where, despite the advantages it can offer, sandwich panels are not very much used. The reasons, in addition to the excessive cost and structural integrity, are mainly the manufacture and fitting of panels or the manufacturing of complex shapes and geometries in space. For example, in the context of increased attention granted to environment, land vehicles (road and rail), maritime, or future cosmic, will need to be more efficient in terms of fuel consumption, and therefore lighter, thus forming the use of materials and structures for high performance. An obvious path towards this aim is the extension of the use of sandwich panels with integrated functions. This new concept involves the use of a single sandwich panel for several types of mechanical stresses (static and dynamic), thermal, acoustic, etc. The need, resulting in a constructive solution easier and less expensive, opposite to the use of a separate material for each of the requirements. Also, sandwich panels made in three or more layers, with the inclusion of integrated functions, could represent an efficient technical solution in terms of thermal energy consumption and can be easily accomplished in a brief time at a lower cost in comparison to current existing solutions.

2. Experimental part

2.1. Materials and methods

The mechanical structure proposed for the current study are the circular sandwich plates with cellular lattice type core, composed of the following materials [8]:

- the core cellular polymer made of 4 different types of polymeric materials: ABS (acrylonitrile butadiene styrene), PC (polycarbonate), PLA (polylactide) and CF (carbon fiber), thickness: 5 mm; cell length (*l*): 15 mm, cell wall thickness (*t*): 2 mm (Fig. 2);
- synthetic glass - Guttagliss Hobyglass (PAD) for polymer facesheets, thickness: 2 mm;
- transparent adhesive for bonding adhesive in a thin ultra-adherent layer – Polymax / crystal express BISON.

These three layers that make up the composite sandwich panel adhere to each other by means of the adhesive, abovementioned.

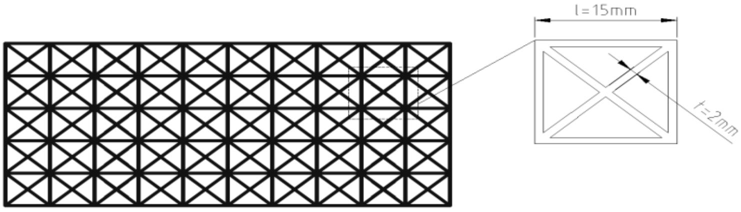


Fig. 2. The orientation and size of cells constituting the core of crosslinking polymer cell [8].

The triangular lattice type polymer based structures for the cellular polymer core is fabricated by additive manufacturing technology/3D printing (Fig. 3) from 4 different types of polymer based materials, above-mentioned, with dimensions of Ø 215 x 5 mm (Fig. 4).

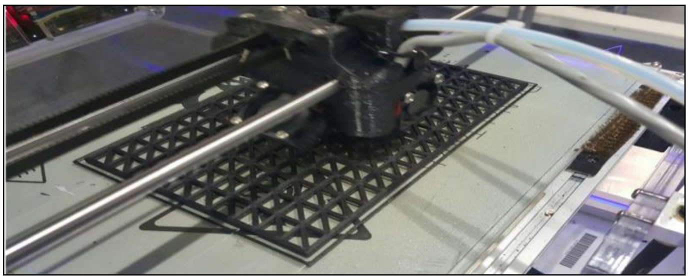


Fig. 3. Additive manufacturing technology (3D printing) polymeric composites structures of cell monolayer type frame [8].

The manufacturing of the polymer-based structures that will constitute the core of the composite cell was done on a machine type *Airwolf 3D HD2DX* [18], using the fused deposition modelling (*FDM*), through laying down of successive layers of melted plastic [13-17].

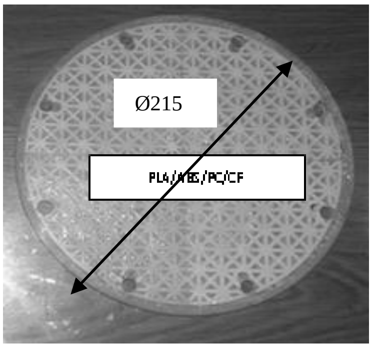


Fig. 4. The 3D geometric model configuration of a structural core, to achieve the cellular polymer based core of the composite panel (PLA5/ABS5/PC5/ CF5) [8].

2.2. Apparatus used

The experiments were conducted in the laboratories of "Regional centre for determining and monitoring the performance of technical condition of tubular material used in the oil industry" of the Faculty of Mechanical and Electrical Engineering at the Petroleum - Gas University of Ploiesti. These consisted of the hydraulic pressure test of the mechanical loading system by the possibility of measuring the specific deformations, ε [μm/m] corresponding to the location of the strain gauges depending on the hydraulic pressure, p_h [MPa], whose ascendant evolution corresponds to the maximum moment of failure by cracking.

For conducting experiments, were use the following equipment, apparatus and software for testing [9 - 12]:

a) the mechanical loading system, represented by the experimental model of the pressure vessel, in Fig. 5, having the composite bolted endplate at the top and a welded endplate at the bottom;

Fig. 5. The experimental model of the pressure vessel [8].

b) hydraulic actuation of the mechanical loading system, composed of a hydraulic cylinder driven by a hydraulic pump, the oil tank, electro-valve, single-way valve and related pipes (Fig. 6):

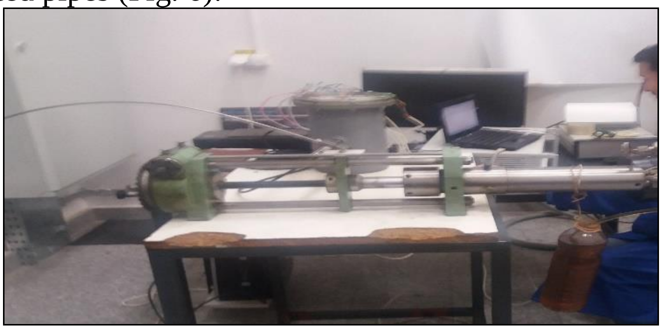


Fig. 6. Hydraulic actuation of the mechanical loading system [8].

c) the modern and fully configurable data acquisition system MGCplus, which can use any kind of strain gauges and sensors (strain gauges TER 1/1, 1/2, 1/4 tensometric bridge) and provides analogue measurement and high resolution digital acquisition (Fig. 7):

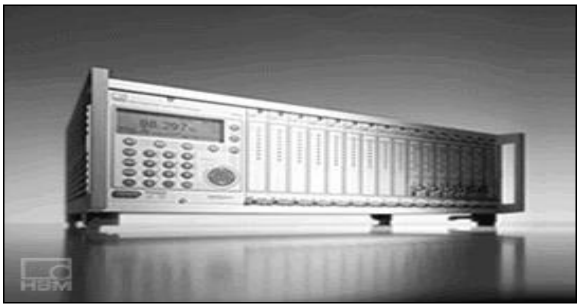
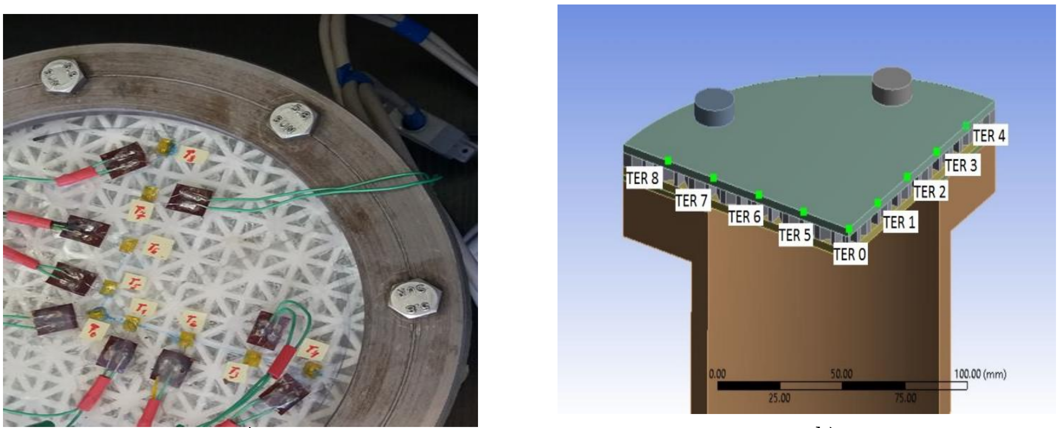


Fig. 7. The data acquisition system MGCplus [8].

d) the strain gauges with foil of the type 6/120 LY 11, manufactured by *Hottinger*. These have one direction (*L*), according to the code, the polyamide resin support (*Y*), measuring gauge length of 6 mm, electrical resistance of 120 Ω ± 0,2%, the thermal coefficient $\alpha = 11 \cdot 10^{-6}$ K^{-1} (for steel), including data in the prospectus; *k* and temperature range, between -70˚C and +200˚C. For each circular end plate from the experimental model above mentioned (ABS 5, PC5, PLA 5 and CF5) there were used 9 strain gauges (TER_0, TER_1, ..., TER_8), placed equidistant to the centre of the plate, on the two measuring directions: ρ (TER_0, TER_1, TER_2, TER_3, TER_4) and θ (TER_0, TER_5, TER_6, TER_7, TER_8), conformable Figure 8, below.



a) b)

Fig. 8. Placing strain gauges on end plate of the experimental model, on the two measuring directions [8].

e) laptop (*PC*), having installed specialized software (*Catman*) for connecting portable data acquisition systems and processing test results (Spider 8).

Standard measurement method for strain applications based on the use data acquisition system *MGC plus*, is schematically represented in Figure 9, below, which comprises two basic components:

- the test composite endplate having attached on it the strain gauges, bolted-up to the mechanical loading system or the pressure vessel for being tested as to determine the values of deformation/strain generated by mechanical loadings;

- data acquisition system *MGC Plus*, along with your *PC*.

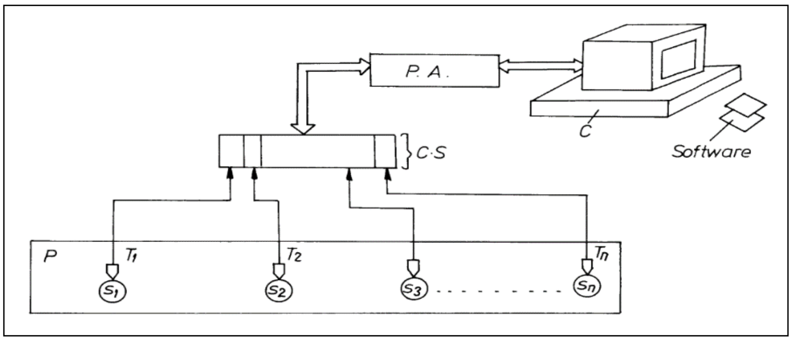


Fig. 9. Typical measurement scheme [8].

2.3. Results and discussions

The above experimental model of the pressure vessel in Figure 5, tested in hydraulic condition has used four types of sandwich type circular end plates from polymeric composite materials with cellular lattice type core (*ABS5*, *PC5*, *PLA5* and *CF5*) and respectively, as a reference structural plate with noncellular core (continuous structure with 3 layers of the same type and geometry), from *PMMA3* (plexiglass).

On each end plate, 9 transducers have been equidistant placed (TER_0,................TER_8), with TER_0 in the origin of the axes (P_0) of the two measuring directions (ρ and θ), according to Figure 8, above.

Following experimental tests done with the equipment described above, there were obtained the results listed in Table 1.

According to experimentally processed data, respectively strains, ε_ρ (μm/m) and ε_θ (μm/m), determine the stress values (σ_1 and σ_2), in (MPa), using relations:

$$\sigma_1 = \frac{E}{1-\nu^2}\left(\varepsilon_p + \nu\varepsilon_\theta\right) \quad (1)$$

$$\sigma_2 = \frac{E}{1-\nu^2}\left(\varepsilon_\theta + \nu\varepsilon_p\right) \tag{2}$$

in which: E represents the module of longitudinal elasticity (MPa) and ν – the transverse contraction coefficient (*Poisson's* ratio).

Equivalent stress (σ_{ech}) for flat plates is determined with the following von Mises criterion for principal place stresses or fourth strength theory:

$$\sigma_{ech}^{IV} = \sqrt{\sigma_1^2 - \sigma_1\sigma_2 + \sigma_2^2}\ . \tag{3}$$

Table 1

Measurement results

The mechanical characteristics, specific to the cellular polymer structure	Measuring points (P_0, ……, P_8) corresponding of placement of the transducers TER_0, …., TER_8		p = 0,25 MPa					Max. press.
			Strains		Calculated Stresses / Equivalent stress (σ_{ech})			
	Direction ρ	Direction θ	ε_ρ (µm/m)	ε_θ (µm/m)	σ_1 (MPa)	σ_2 (MPa)	σ^{IV}_{ech} (MPa)	p_{max} (MPa)
ABS5 (E = 2414 MPa; ν = 0,36)	P_0/ TER_0	P_0/ TER_0	966,04	966,04	3,643	3,643	3,643	0,2534
	P_1/ TER_1	P_5/ TER_5	540,28	426,29	1,924	1,721	1,830	
	P_2/ TER_2	P_6/ TER_6	1030,1	1365,2	4,219	4,814	4,545	
	P_3/ TER_3	P_7/ TER_7	377,77	923,40	1,969	2,938	2,592	
	P_4/ TER_4	P_8/ TER_8	222,15	149,49	0,751	0,636	0,700	
PC5 (E = 2323 MPa; ν = 0,37)	P_0/ TER_0	P_0/ TER_0	3568,0	3568,0	13,156	13,156	13,156	0,2533
	P_1/ TER_1	P_5/ TER_5	1044,3	3034,4	5,832	9,206	8,066	
	P_2/ TER_2	P_6/TER_6	2807,9	0,0000	7,557	2,796	6,617	
	P_3/ TER_3	P_7/ TER_7	2008,0	1969,8	7,366	7,301	7,333	
	P_4/TER_4	P_8/ TER_8	-10,28	1,650	-0,026	-0,005	0,023	
PLA5 (E = 3096 MPa; ν = 0,365)	P_0/ TER_0	P_0/ TER_0	1823,1	1823,7	8,889	8,890	8,890	0,2518
	P_1/ TER_1	P_5/ TER_5	305,79	3498,6	5,653	12,895	11,195	
	P_2/ TER_2	P_6/TER_6	1736,1	2356,4	9,273	10,680	10,050	
	P_3/ TER_3	P_7/ TER_7	1178,1	0,0000	4,208	1,535	3,688	
	P_4/TER_4	P_8/ TER_8	122,00	6572,5	9,004	23,635	20,660	
CF5 (E = 3647 MPa; ν = 0,365)	P_0/ TER_0	P_0/ TER_0	1457,0	1457,0	8,367	8,367	8,367	0,2526
	P_1/ TER_1	P_5/ TER_5	3108,0	0,0000	13,077	4,773	11,461	
	P_2/ TER_2	P_6/TER_6	2233,4	6358,4	19,162	30,183	26,454	
	P_3/ TER_3	P_7/ TER_7	891,56	0,0000	3,751	1,369	3,287	
	P_4/TER_4	P_8/ TER_8	706,26	528,42	3,783	3,307	3,568	
PMMA3 (E = 2760 MPa; ν = 0,37)	P_0/ TER_0	P_0/ TER_0	3735,7	3735,7	16,365	16,365	16,365	0,5025
	P_1/ TER_1	P_5/ TER_5	-	-	-	-	-	
	P_2/ TER_2	P_6/ TER_6	-	-	-	-	-	
	P_3/ TER_3	P_7/ TER_7	-	-	-	-	-	
	P_4/TER_4	P_8/ TER_8	-	-	-	-	-	

3. Conclusions

From the analysis of measurement results, according to Table 1, the maximum stress values calculated with relations (1), (2) and (3) can be noticed. These correspond to strains measured in the points of location of the strain gauges for the four structural types of polymeric composites with cellular core (*ABS5*, *PC5*, *PLA5* și *CF5*), as well as for structural variant reference with non-cellular core in PMMA*3*.

Thus, depending on the values of the equivalent stresses of the tested composite structures, a hierarchy has been obtained by the mechanical strength behaviour of the structural types with a cellular polymer core, as follows: *CF5* (σ_{ech} = 26,454 MPa), *PLA5* (σ_{ech} = 20,66 MPa), *PC5* (σ_{ech} = 13,156 MPa) and *ABS5* (σ_{ech} = 4,545 MPa).

Also, it has been found that the maximum strain, ε_{max} [μm/m] for tested composite structures have been obtained at different points corresponding to the two directions of measurement: P_6 (*CF5* and *ABS5*), P_8 (*PLA5*) and respectively, P_0 (*PC5* and *PMMA3*).

The carbon fiber configuration (CF5) has shown better strength in all tests, given by its mechanical properties. Although carbon fiber is well known as a strong material, the major issues were the cost and manufacturing process. By implementing new technologies and new materials, like in this case using a process that is becoming more and more used at much lower prices, and a mixture of two different materials – 60% PLA (polilactic acid) and 40% CF (carbon fiber), which combines into a stronger, but less brittle material as carbon fiber.

Therefore, the experimental results obtained in this paper, can be a conclusive evidence in the case of decisions making for optimal use of manufacturing materials for different component parts of the pressure equipment used in process industries.

Acknowledgement

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