REVISTA INTERDISCIPLINAR DE PESQUISA EM ENGENHARIA

CILAMCE 2016

XXXVII IBERIAN LATIN AMERICAN CONGRESS ON COMPUTATIONAL METHODS IN ENGINEERING

BRASÍLIA - DF - BRAZIL

EVALUATION OF THE STRUCTURAL BEHAVIOR OF ALUMINUM HONEYCOMB SANDWICH PANELS FOR MICROSATELLITES

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Abstract. *This work has as target the analysis of honeycomb structures by applying analytical models and numerical simulation that employ different finite element approaches: solid model for panel with equivalent honeycomb core properties, solid model of the honeycomb core and faces, and surface model of the honeycomb core and faces. There is also the standard test method for determination of the bending and shear properties of honeycomb sandwich samples whose results are employed for validation purposes. Thus, the main interest is to study the deformation of the honeycomb structures under shear load to devise a methodology to facilitate their design and manufacture. The prediction of the structural behavior of satellite components at real conditions of operation as well as the quality assessment of their manufacturing process requires this preliminary stress-strain evaluation of honeycomb sandwich panel samples. In this work, several tests were performed to access the behavior of the honeycomb structures and the results are consistent to the literature.*

Keywords: *Honeycomb sandwich structures, satellite solar panels, finite element modeling, bending and shear deflections, analytical and numerical models*

1 INTRODUCTION

Due to Brazil's vast territory, the dependence on aerospace technologies has increased, and the national aerospace industry has reached great technology maturity level in manufacturing satellite components. Recently, they received the demand for designing and building a Geostationary Satellite for defense and communication, and the university is an important partner in research and forming human resources. Nowadays, following the ideas such as fast access to space and costumed of the shelf, Brazilian universities in order to allow the students the contact to aerospace technologies have started the design of small satellites or platforms that emulate their features, an example is SERPENS (from Portuguese, Sistema Espacial para Realização de Pesquisa e Experimentos com Nanossatélites), (Cappelletti et al., 2014).

The design of satellites requires dominating the knowledge of several fields, and among them, the structure is essential due to certain characteristics as light weight and strength. For the design of such structures, honeycomb sandwich panels (HSP) are the most common solution, and they are usually employed as base for solar panels. In general, shear deflections are small in long spans and thin panels such as the case of deployable solar panels, where flatness and bending deflection are significant. However, fixed solar panels mounted on the satellite body have shorter spans and bigger thicknesses and then shear deflections are important. Therefore, this work has as main goal to study the deformation of the honeycomb structures under shear load. This is necessary to devise a methodology to model with high fidelity HSP for satellite applications.

Thus, the main interest is to study the deformation of the honeycomb structures under shear load to devise a methodology to facilitate their design and manufacture.

The honeycomb core is characterized by quite complex multi-cell thin-walled structure that makes it difficult to use real 3D model in computer-assisted simulations of mechanical behavior, mostly due to long duration of computation. Consequently, the real model of the core is substituted by homogenized orthotropic material that has the same rigidity in different directions as the real honeycomb core has. Several approaches of core homogenization are given in reference (Hu, Wang and Leng, 2012). However, now the efficiency of personal computers have been increased that it is possible to simulate the real honeycomb structures of such dimensions as the solar panels of microsatellites have. At the same time, the standard method for prediction of core shear properties exists (ASTM C393-00, 2000) and there is a number of other analytical methods for prediction of mechanical behavior of honeycomb structures described in reference (Bitzer, 1997).

The work covers determination of the shear properties of flat HSP subjected to flexure by various analytical and numerical models with the main aim to define the relative difference between obtained results. The objects of study are shear properties of the HSP: facing bending stress (FBS) and midspan deflection of the panel. The subjects of the study are specimens of HSP that consists of the two faces, the honeycomb core and the adhesive joints. There are various metallic and non-metallic materials applied for the face and core constituents of the honeycomb sandwich panels, among them are such common materials as aluminum, stainless steel, titanium, fiberglass, Nomex, Kraft paper (Bitzer, 1997). However, aluminum alloys remain the most widely used predominantly due to the most favorable performance-to-cost ratio (Marshall, 1998). The common alloys for the honeycomb panels of aerospace applications are 2024 T3 as a facing and 5056 H39 as a honeycomb core (Space Engineering, 2011), therefore these materials were taken for analysis and manufacturing of specimens together with adhesive films on the base of epoxy resin. The honeycomb core was of type HexWeb CRIII – Al 5056 – ¼ – 0.001P(10P).

2 TEST SPECIMENS

There were 8 specimens of HSP, and they differ by the thickness of core and the geometry orientation along the length, while the geometry of the core cells remains the same, Table 1. The core ribbon directions are defined by the terminology provided in reference (Bitzer, 1997), Table 1. Mechanical properties of the honeycomb core were taken from data distributed by Hexcel (HexWebTM, 1999) and represented by SI units in Table 2. For the numerical simulations, the mechanical properties of the HSP constituent materials are also provided in Table 3.

Table 1. HSP specimens' data

Specimens	The core ribbon direction along HSP length	Dimensions of HSP [mm]			Thicknesses [mm]		Dimensions of core [mm]	
		Length	Width	Thickness	Face	Core	Foil thickness	Cell size
T1L	L	200	40	10	0.3	9.4	0.0254	6.35
T2L	L	200	40	15	0.3	14.4	0.0254	6.35
T3L	L	200	60	30	0.3	29.4	0.0254	6.35
T4L	L	200	75	40	0.6	38.8	0.0254	6.35
T1W	W	200	40	10	0.3	9.4	0.0254	6.35
T2W	W	200	40	15	0.3	14.4	0.0254	6.35
T3W	W	200	60	30	0.3	29.4	0.0254	6.35
T4W	W	200	75	40	0.6	38.8	0.0254	6.35

Table 2. Mechanical properties of the honeycomb core HexWeb CRIII – Al 5056 – ¼ – 0.001P(10P)

Nominal density [kg/m^3]	Compressive strength (bare) [MPa]		Crush strength [MPa]	Plate shear					
				L direction			W direction		
				Strength [MPa]		Modulus [MPa]	Strength [MPa]		Modulus [MPa]
	Typical	Minimum		Typical	Minimum	Typical	Typical	Minimum	Typical
36.8	1.65	1.00	0.69	1.24	0.90	221	0.69	0.43	103

Table 3. Mechanical properties of HSP constituent materials for finite-element simulations

Parameters	Al 2024 T3 **(ASM, 10)**	Al 5056 H191 **(MatWeb, 2016)**
Density [g/cm^3]	2.78	2.64
Tensile strength [MPa]	483	450
Yield strength [MPa]	345	435
Modulus of elasticity [GPa]	73.1	72
Poisson's Ratio	0.33	0.33

Due to absence of properties for 5056 H39, the data presented in the table is for 5056 H191.

3 METHODOLOGY

The methodology described in the ASTM C393-00 standard for flexural properties of sandwich constructions is at the core of the presented comparative analyses. The configuration of the three-point bending method was used for computational and experimental tests, where the load is applied at the middle of the panel span. The panel is supported by two pads with a distance of 150mm between them, Figure 1. Thus conditions of flatwise flexure of the HSP were reproduced in simulations and experiments.

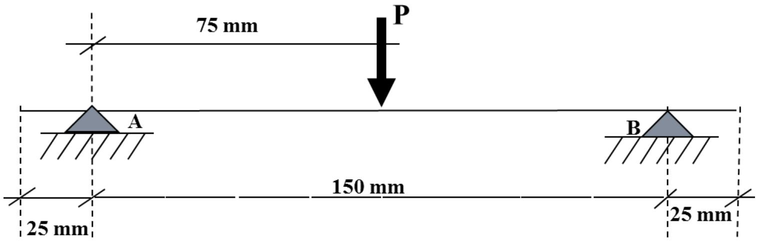


Figure 1. Single-point load test configuration

The equations of the standard method ASTM C393-00 had been taken for calculation of reference (nominal) values of flexural properties of the panel, and they were compared to values computed by other methods such as:

- analytical model where the equation of a simple supported beam with a point load in the middle is solved by employing isotropic properties determined by a non-destructive experimental methodology based in the impulse excitation technique;
- solid model for panel with equivalent honeycomb core properties simulated in Digimat;
- solid body and surface body models of HSP with real core geometry and properties of constituent materials simulated in Ansys Workbench.

The facing bending stress (FBS) and midspan deflection are comprehended as primary flexural properties in the given work, since they can be determined by the standard ASTM C393-00. The values of flexural properties were determined by the above mentioned methods at several load values from 0.1kN to 1 kN, enough to represent the elastic region for every specimen. However for the sake of simplicity only the flexural properties related to the load of 1kN are presented in the text. Flexural properties of the panel under other loads are easily recalculated by linear proportion, since the analysis under consideration is elastic. The relative difference between flexural properties obtained by the reference method and the other proposed methods is defined by the following equation:

$$\varepsilon = \frac{|\alpha_{ASTM} - \alpha_i|}{\alpha_i} 100\% , \tag{1}$$

where α_{ASTM} is the value of the flexural property calculated by the equations of the standard ASTM C393-00; and α_i is the respective value of the property determined by one of the proposed methods.

3.1 Analytical Method - ASTM C393-00

The reference method is taken from the standard ASTM C393 “Standard Test Method for Flexural Properties of Sandwich Constructions”. This method states the procedures and equations to determine the properties of flat sandwich constructions under flatwise flexure. The test and modeling of three load conditions are purposed: single-point load, two-point load one-quarter span and two-point load one-third span. In this work only the single-point load configuration is considered.

The core shear stress in [MPa] in case of single-point midspan load (Figure 1) is calculated by equation:

$$\tau = \frac{P}{(d+c)b}, \tag{2}$$

where P is the load in [N], d is the sandwich thickness in [mm], c is the core thickness in [mm], and b is the sandwich width [mm].

The facing bending stress in [MPa] is calculated by

$$\sigma = \frac{PL}{2t(d+c)b}, \tag{3}$$

where t is the facing thickness in [mm], and L is the span length in [mm].

The sandwich beam deflection (single-point midspan load) is calculated by equation

$$\Delta = \frac{PL^3}{48D} + \frac{PL}{4U}, \tag{4}$$

$$D = \frac{E(d^3 + c^3)b}{12}, \tag{5}$$

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

where Δ is the total beam midspan deflection in [mm], G is the core shear modulus in [MPa], E is the facing elastic modulus in [MPa], D is the panel bending stiffness in [N-mm^2], and U is the panel shear rigidity in [N].

3.2 Analytical Method – Isotropic Material

Non-destructive tests are techniques used in the inspection of pieces and equipment components and in the measurement of materials properties without damaging the test specimens. These techniques are employed in the steps of fabrication, construction, mounting and maintenance, they are the main tools for quality control of materials and products. There are several non-destructive techniques such as acoustic impulse, ultrasound, magnetic particles, penetrant liquids, radiography and parasitic current (Carlsson, Adams and Pipes, 2002). For the present work, the technique of acoustic impulse excitation was employed by using the Sonelastic device (Sonelastic, 2016), Figure 2. This device consists in a transitory vibration analyzer, where magnitudes, frequencies and damping factors are extracted from measured signals. The Sonelastic device measures properties such as the elasticity and shear modules and the damping coefficient by capturing and post-processing an induced acoustic signal according to the standard ASTM E-1876 (Sonelastic, 2016).

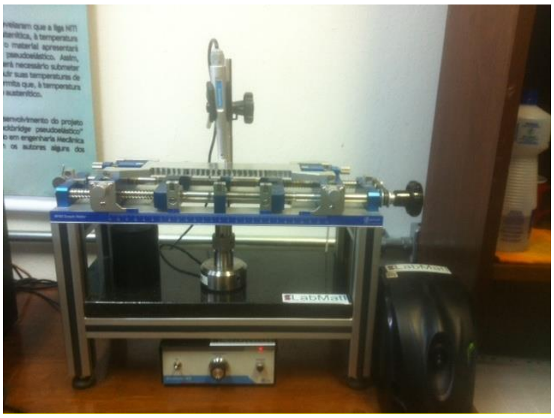


Figura 2. Setup of the acoustic impulse excitation device

The equation of a simple supported beam with a point load in the middle (Beer and Johnston, 2010) is solved to predict the midspan deflection of the test specimens:

$$\Delta = \frac{PL^3}{48\mathrm{E}I}\ , \tag{7}$$

where I is the moment of inertia, and E is the equivalent elastic modulus by considering the test specimen an isotropic material. For this application, the equivalent elastic modulus is determined experimentally, Table 4.

Table 4. Test specimens elastic modulus

Test Specimens	T1L	T1W	T2L	T2W	T3L	T3W	T4L	T4W
Elastic Modulus, E [GPa]	10.744	9.8928	6.5324	6.6428	2.8764	2.4796	3.1916	2.2168

3.3 Numerical Method - Digimat

Digimat is a commercial software that has a multi-scale tool to simulate honeycomb sandwich structures. The tool is capable to model bending and in-plane shear tests of sandwich panels by using homogenized material properties and a traditional finite element solver. The geometry of the honeycomb cells and their material properties are used to compute homogenized properties of the core. The same procedure can be applied to the faces (skins). The faces can be composed by one kind of material (metallic or not) and they can be composed by several layers with different thicknesses and orientations. Each layer can also be defined at the macro or micro level. For computing the homogenized properties in Digimat, the necessary information about the geometry and the material properties of the specimens are presented on Tables 1, 2 e 3.

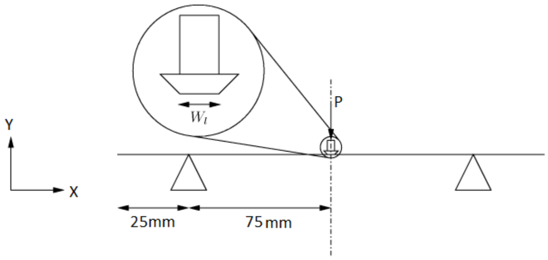


Figure 3. Single-point load test configuration - Digimat

In order to avoid numerical singularities, the force boundary conditions are applied on an area, and it is required the definition of the width of the loading pad W_l which for this work is equal to 5mm, Figure 3. As the mesh generation is automatic and to guarantee the quality of the results, the mesh refinement was set to the greatest value possible.

3.4 Numerical Method – ANSYS Workbench

The geometry model of the HSP specimen for the numerical simulations using ANSYS Workbench consists of the following elements: top and bottom faces, and core. The layer of glue that bonds the core to the faces is not accounted in model, once its thickness is small and thus its effect on the results of modeling is negligible.

Two models of honeycomb sandwich panel were used for analysis in ANSYS Workbench 14.5: *solid body* (3D solid body) and *surface body* (2D solid body). The solid body theoretically provides more accurate results, but requires greater computation time in comparison with surface body. Moreover, solid body requires additional computation resources for satisfactory meshing since the thickness of the cell walls is very small 0.0254 – 0.0508 mm. Thus, a study of mesh quality of isolated core element 14.7 × 11.5 × 9.4 mm was fulfilled for the determination of optimal mesh parameters. The skewness parameter, which is one of the primary quality measures for a mesh according to reference (ANSYS, 2012) was chosen as a criterion for mesh quality. According to the results of the mesh study (Table 5) the sweep method with 8 divisions along core thickness with dropped nodes at edges of all elements and element size 0.6 mm was accepted as satisfactory. Smaller element size provides high number of elements that increases computational time. The elements of the mesh are predominantly Solid185 (quadrilateral and triangular prisms). For the element size 0.6 mm, it provides near 4 thousand nodes (corresponds to near 250000 nodes at the specimen's core) and good average mesh quality. The meshed core element is shown in Figure 4, where the elements that caused high values of maximal skewness are also shown.

The procedure to generate the mesh for a surface body is not complicated as for a solid body. Thus, the mesh parameters for surface body were chosen by the results of convergence analysis of one of the specimens. It seems that at the element size of 0.5 mm (number of nodes is near $3.5 \cdot 10^5$) the deflection convergence of the T2W specimen is quite adequate, Figure 5, a. The convergence analysis for solid body model is shown also in Figure 5, b. The element size 0.6 mm corresponds to $2.7 \cdot 10^5$ nodes.

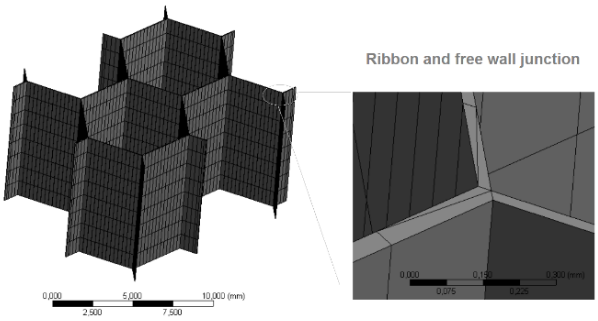
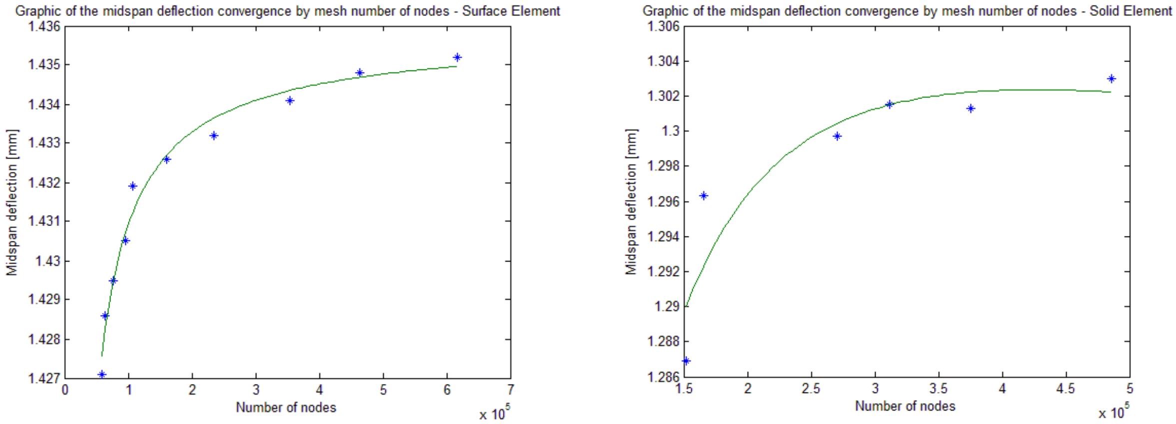


Figure 4. Meshed core element of solid body model

Table 5. Results of the study of mesh generation (all element midsize nodes are dropped)

Description of method			Statistics		Mesh quality – skewness			
			Number of		Average		Maximal	
Method	Free face mesh type / Mapped mesh type	Element size [mm]	Nodes	Elements	Value	Cell quality	Value	Cell quality
Default	Quad/Tri	1.0	3366	1670	0.33	good	0.96	bad
		0.6	8058	3968	0.26	good	0.91	bad
		0.3	28314	14208	0.25	excellent	0.84	poor
Hex Dominant	Quad/Tri	1.0	4882	6679	0.89	poor	0.99	bad
		0.6	10799	9211	0.73	fair	0.99	bad
		0.3	37950	26235	0.59	fair	0.99	bad
MultiZone	Hexa/Prism	1.0	2585	1670	0.57	fair	0.99	bad
		0.6	5083	3136	0.47	good	0.98	bad
		0.3	15510	8384	0.36	good	0.98	bad
Sweep 8 divisions	Quad/Tri	1.0	2754	1320	0.30	good	0.97	bad
		0.6	4266	1984	0.26	good	0.91	bad
		0.3	7722	3584	0.26	good	0.84	poor



a b

Figure 5. Convergence of midspan deflection for specimen T2W: (a) surface body model, (b) solid body model

Since the adhesive joint between core and facings was not modelled, it was substituted by bond connection. The core of the solid body was modelled as one integral element, where the thickness of ribbons was doubled in comparison with free walls, Figure 4. The core model of surface body was sectioned in zig-zag integral surfaces representing free walls and multiple ribbon surfaces between them. The model was simplified by omitting connections between ribbon and free walls surfaces.

The surface for load application was imprinted at the middle of top facing across HSP width. The width of loaded surface was 4 mm. The support surfaces were imprinted at bottom facing across HSP width and were arranged symmetrically about loaded surface. The width of support surfaces was the same as for loaded surface. The support surfaces are fixed in direction of load application and free to slide in other two perpendicular directions.

The midspan deflection was determined by maximal deflection of bottom facing in the direction of applied load. The FBS was defined in the center of bottom facing surface. The values of equivalent stress were taken as maximal von-Mises stresses of free walls and ribbons of one of the closer-to-center cells, whose projection crosses the loaded surface.

3.5 Experimental Test

The results obtained by mentioned methods were validated by experimental testing. Two specimens with the same dimensions and constituent materials, but with different orientation of honeycomb core denoted by T1L and T1W were tested in the three point loading configuration. As indicated in the Figure 6, both loading pad and support pads have tips of round shape with radius 25mm. The distance between support pads is 150 mm and the load was applied at the middle span of the specimen. The loading speed was 1 mm/min.

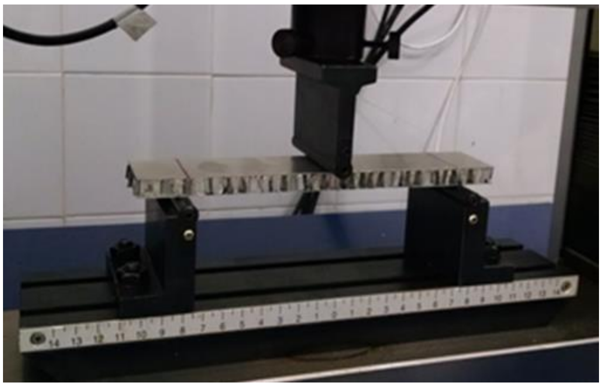
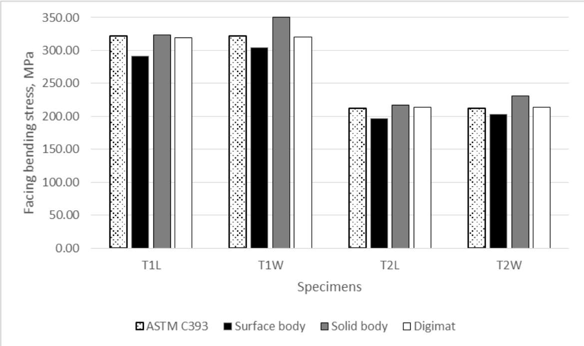


Figure 6. Installation of specimen in three-point loading (Barcelos et al., 2015)

4 RESULTS AND ANALYSES

As it is shown in Figure 7, all methods employed in the work show the same values of FBS with quite moderate relative difference in relation to values predicted by ASTM C393-00. For relatively small thicknesses of the core (specimens T1L/W and T2L/W), the relative difference does not exceed 10% for all methods, at the same time the Digimat provides the smallest relative difference, which is less than 1% (Figure 9, a). However, for the thick core specimens (specimens T3L/W and T4L/W) Digimat gives the highest values of relative difference up to 30%. It is necessary to note here that solid body model provides values of FBS that are closer to the values of the standard, since the relative difference for all specimens does not exceed 10%.



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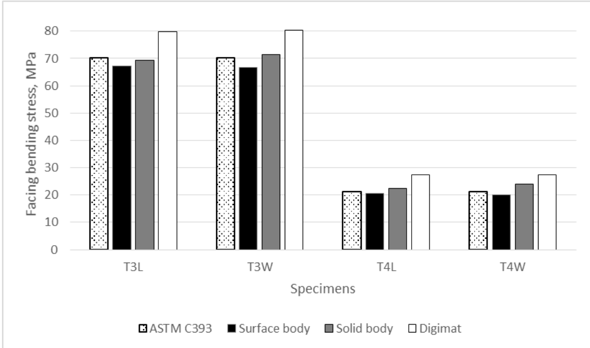
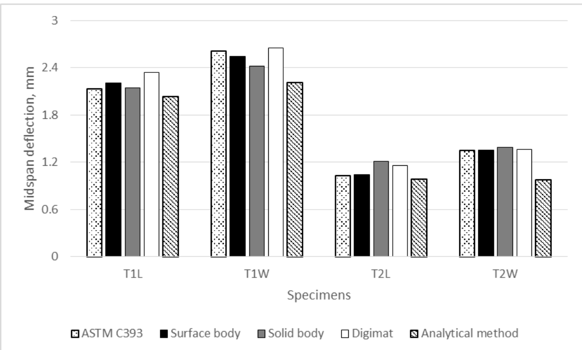


b

Figure 7. Comparison of values of FBS obtained by various models: a) specimens T1(L/W) e T2(L/W); b) specimens T3(L/W) e T4(L/W)

The results of the midspan deflection are given in Figure 8. Specimens with W configuration of cells have less rigidity along the length of the specimen and that is why the deflections are greater in comparison with specimens of L cell configuration. For the specimens T1L/W, T2L/W, T3W and T4W, the values of the midspan deflection predicted by the surface model are very close to the values calculated by the equations of the standard method, since the relative difference is less than 5% (Figure 9, b). The solid body model provides relative difference less than 20% for all specimens except T4L, where this parameter is above 30%. Digimat predicts practically the same values of deflection as ASTM C393-00 does for W specimens (relative difference less than 5%), but it has high discrepancy to the standard in relation to L specimens (relative difference from 10 to 85%). The relative difference of analytical method (equivalent isotropic elasticity modulus) is gradually growing with the thickness of the core from 5% for thin cores up to 50% to thick cores.



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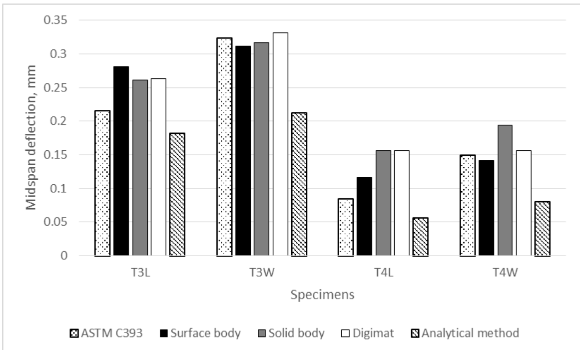
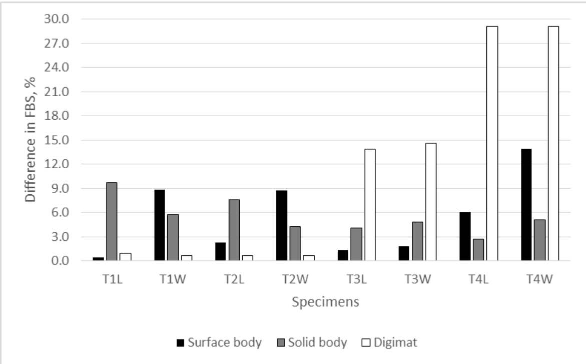
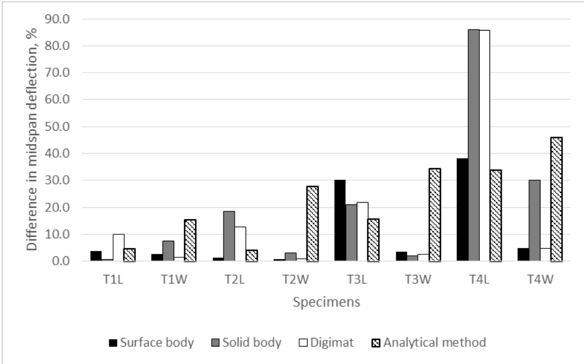


b

Figure 8. Comparison of values of midspan deflection obtained by various models: a) specimens T1(L/W) e T2(L/W); b) specimens T3(L/W) e T4(L/W)

Since shear parameters of the thin core specimens are characterized by low relative difference, the validation of the calculated results by experimental test have been done for the T1L/W specimens only. The results of experimental tests are given in the form of load-deformation plot shown in Figure 10. In accordance to the theory of the failure load, for the L specimen it is greater than for the W specimen, however the midspan deflection at the failure load is practically the same for both specimens. The appearance of the specimen after the test is shown in Figure 11.





a **b**

Figure 9. Relative difference between values of FBS and midspan deflection calculated by ASTM standard and other models

According to the results of comparison between midspan deflections in the experimental tests and the numerical simulations showed in Figure 12, the Digimat simulations provide values of the midspan deflection very close to the experimental ones. At the same time, the relative difference between experimental and numerical data is significant even for results predicted by Digimat: the minimum value for T1L specimen is 15.8% and for T1W specimen is 25.6%.

Such results may be explained by the incorrect setup of the experiment: the failure mode of the specimen (Figure 11) reminds local indentation more than core shear failure that is expected in the test. In the given specimen, the top skin deflected after failure has a shape similar to that of the loading pad, which is characteristic for the local indentation failure mode (Petras, 1998). Thus, this failure mode requires detailed analysis to be avoided in future.

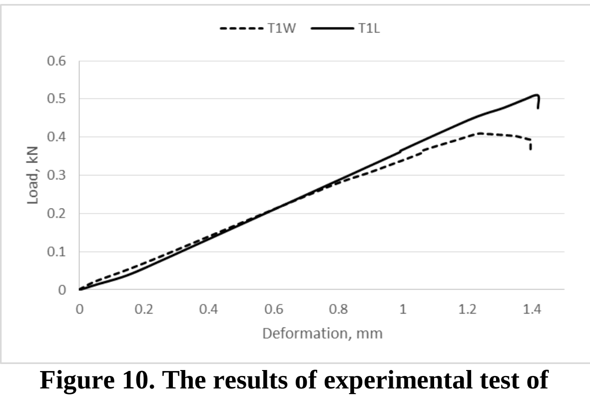
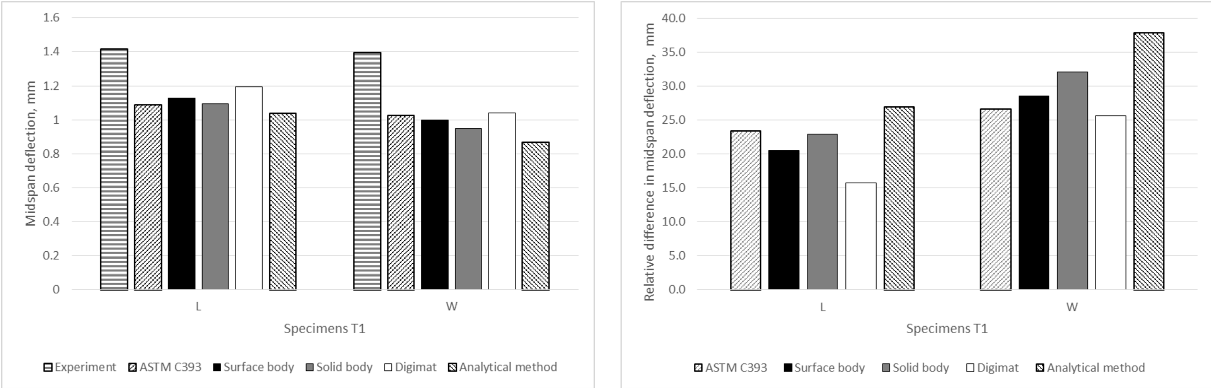


Figure 10. The results of experimental test of specimens T1L and T1W

Figure 11. Photo of specimen T1L after test

In addition, it is necessary to note, that core shear stresses of the specimens T1L and T1W at the experimental failure load are correspondingly 0.66 and 0.51 MPa. These values are less than the ones of the core shear strength declared by the manufacturer: 1.24 and 0.69 MPa respectively for L and W directions (HexWebTM, 1999).



a **b**

Figure 12. Comparison of experimental and numerical/analytical data for the T1L/W specimens: a) midspan deflection, mm; b) relative difference in midspan deflection, %

It was expected also, that the values of equivalent stress would reach the yield strength of the core material in simulations with solid and surface body models at the experimental failure loads, however this condition also was not fulfilled as it is shown in Table 6.

Table 6. Maximal equivalent stresses of central cell in MPa

Specimen	Experimental failure load, N	Model	
		Solid body	Surface body
T1L	510	306.5	301.2
T1W	392	270.3	345

5 CONCLUSIONS

Some conclusions can be taken about the purposed methods for prediction of deflections and equivalent stresses in honeycomb sandwich structures. This information is important to help to devise a methodology of structural characterization with high fidelity honeycomb sandwich panels for satellite applications.

For every method studied, the FBS does not have significant variation. For small thicknesses specimens, Digimat provides one of the best approximations for FBS, less than 1% difference to the reference. The solid elements in ANSYS lead to the computation of FBS the closest to the reference.

As expected due to the double wall along the length and higher rigidity, the midspan deflections for L specimens are lower than the ones for W specimens. For smaller thickness specimens and W specimens, the midspan deflections computed by the ANSYS surface model are the closest to the reference. Digimat predicts midspan deflections closer to the reference for W specimens. For the analytical method the difference of the midspan deflection with respect to the reference values increase gradually with the thickness of the core. It is necessary to note that due to high values of relative difference of midspan deflection honeycomb sandwich panels with increased thickness (30 and 40 mm) require detailed analysis of shear properties.

The failure mode observed in the experimental test is due to face and core indentation, different to core shear as expected in the standard. The measured midspan deflections for T1L and T1W in the experimental tests have a significant difference to the values obtained by the purposed methods. The load configuration predicted at the failure point in the experimental test does not lead to stress levels over the yielding stress limit neither for the core material nor for the face material. Therefore, the experimental tests have to be reviewed in order to increase de reliability of the measured results.

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