IN-PLANE TRANSVERSAL STIFFNESS OF EXPANDED TRAPEZOIDAL CELLULAR STRUCTURE

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Abstract: *Metallic cellular cores have become widely designed and used for the construction of sandwich panels, in the past decade. In this regard, a low-density expanded trapezoidal cellular core has been proposed for investigation. Manufactured through a mechanical expansion procedure, from sheet metal stainless steel type 304 represents a cost-efficient solution by reducing material waste and manufacturing tooling. The in-plane transversal stiffness has been investigated by analytical and experimental means. The experimental testing has successfully validated the analytical model proposing the studied corrugation for further exploitation and optimization.*
Keywords: *Trapezoidal expanded cellular structure, analytical model, transversal stiffness*

1. INTRODUCTION

The sandwich concept has been intensively studied and has been proposed for use not only in the aerospace industry, but also in the naval, railway, civil and also automotive industries due to their high stiffness and strength while maintaining a significantly low structural weight [1, 2].
The most important component of a sandwich panel is represented by the cellular core. Its purpose it to maintain a constant distance between the two lateral sheets in order to prevent them from buckling while offering high stiffness and strength.
Throughout their development, cores used for sandwich panels have had different topologies, stohastic or periodic, and have been manufactured from different materials like: wood, plastic or metals [3].
Among the periodic topologies, we can remind: honeycomb, sinusoidal, triangular, trapezoidal, etc. Although the honeycomb is considered the best solution for cellular cores, other corrugated topologies with good mechanical properties have been designed and presented by the research of the past decade [4].
Research conducted at the Transilvania University of Brașov resulted in proposing a metallic corrugated core, manufactured through a simple mechanical expansion process. The newly developed structure has a promising capacity of reducing the material waste during the manufacturing process as well as the production costs.
From the relative density point of view [1] it has been proven to be more effective than a series of existing corrugations with similar dimensions due to its complex geometry and thin base material [5].
The purpose of this paper is to evaluate the transversal stiffness of the new expanded trapezoidal core. This objective has been achieved by developing an analytical model validated by experimental testing.

2. UNIT CELL

The design of the unit cell is inspired by the lattice truss corrugation. Existing research has successfully proven that this type of architecture offers outstanding mechanical properties such as load-bearing and energy absorption capacities [6]. In this regard, the mechanical expansion performed on a sheet metal profile resulted in obtaining an expanded trapezoidal cellular structure with a similar topology as the lattice-truss, but with the advantage of having a significant adhesion surface, presented in figure 1.

The cellular topology is defined by the following parameters: internal angle (*A*); expansion angle (*B*); length of the arm's base (*c*); length of the cell's arm (*l*), radius of the perforation (*r*), distance between two perforations (l_1), thickness of the base material (*g*), length of the unit cell (*w*); width of the unit cell (*t*), height of the unit cell (*h*).
In regard to these parameters, the dimensions defining the 3D corrugation (*h*, *t*, *w*) are computed with the help of the equations below [5]:

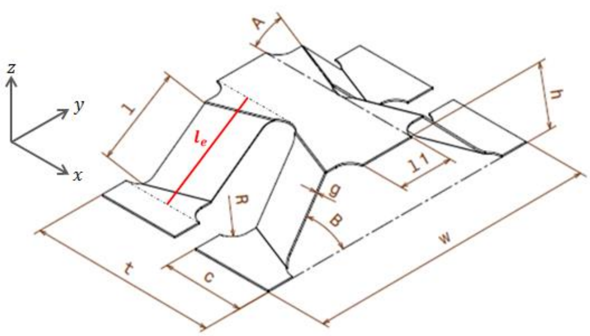

Figure 1: Topology of the cellular structure.

$$w = 2l_1 + 2l\cos(B) + c\tan(A) + 2R \tag{1}$$

$$t = 2c + z + 2\sqrt{l^2\cos(B)^2 - \left(R + 2g - l\cos(B) - \frac{c\tan(A)}{2}\right)^2} \tag{2}$$

$$h = 2g + l\sin(B) \tag{3}$$

$$l_e = \sqrt{R^2 = \cos(B)Rl + \frac{l^2}{4}} \tag{4}$$

* where l_e represents the equivalent trapezoidal length of the expanded unit cell.

3. ANALYTICAL MODEL

For the loading case a quarter of a unit cell was taken into consideration, figure 2, due to its symmetry on both expansion directions. The internal forces were computed for the two segments of the system, OC and CD.

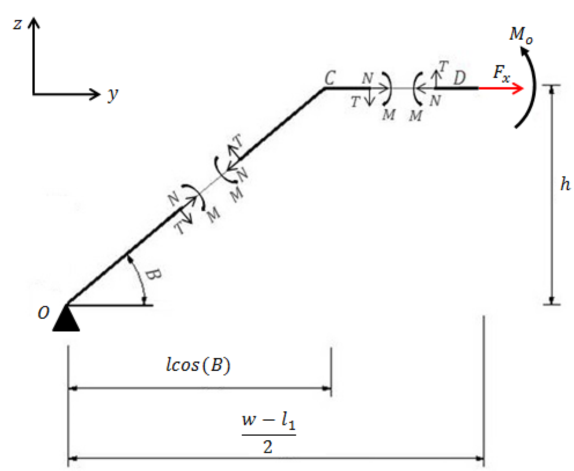

Figure 2: Analytical loading case.

For segment OC the inner forces are:

$$M_{OC} = F_x\left(h - x\tan(B)\right) - M_0 \tag{5}$$

$$N_{OC} = F_x \cos(B) \tag{6}$$

$$T_{OC} = F_x \sin(B) \tag{7}$$

For segment CD, the inner forces can be expressed as:

$$M_{CD} = -M_o \tag{8}$$

$$N_{CDC} = F_x \tag{9}$$

$$T_{CD} = 0 \tag{10}$$

Applying Castigliano's second theorem, on the OCD system, the expression for computing the transversal displacement can be determined as follows:

$$\delta_x = F_x\left(\frac{l_1}{2A_{CD}E} + \frac{l^2\sin(B)}{2I_{OC}E} - \frac{l\cos(B)}{A_{OC}E} + \frac{l\sin(B)}{A_{OC}Gk}\right) \tag{11}$$

Where I and A are the area and moment of inertia or the cross-section of the, k is the shear correction factor ($k = 5/6$) accepted for segments with rectangular cross-section and G is the transverse elastic modulus of the base material [7, 8, 9].

The stress and strain acting on the system is expressed with the following equations:

$$\varepsilon_x = \frac{2\delta_x}{(w - l_1)} \tag{12}$$

$$\sigma_x = \frac{F_x}{ht} \tag{13}$$

Taken into consideration the definition of the Young's modulus as σ_x/ε_x, the transversal stiffness can be computed with the following formula:

$$E_x = -\frac{A_{CD}A_{OC}GI_{OC}Ek(l_1 - w)}{ht\left(A_{OC}GI_{OC}kl_1 + 2A_{CD}A_{OC}El_e\sin(B) + A_{CD}A_{OC}Gkl_e^2\sin(B) + 2A_{CD}GI_{OC}kl_e\cos(B)\right)} \tag{14}$$

4. EXPERIMENTAL INVESTIGATION

The experimental model was built in order to validate the analytical expressions defined for computing the transversal stiffness of the expanded trapezoidal core. The material used for manufacturing the specimens was stainless steel 304 with a Young's modulus of $E_s = 2.01 \times 10^5$ MPa and with a sheet metal thickness of 0.3 mm.

The in-plane transversal stiffness of the expanded trapezoidal sandwich core was determined on an individual unit cell, by performing a series of traction tests. Three dimensional cases were taken into consideration for manufacturing the core samples, obtained from the combination between a set of fixed parameters and a variable one. This has resulted in a total number of three configurations, further named T1÷T3. The dimensions of the samples for the experimental testing are presented in table 1.

Table 1: Dimensions of the samples for the experimental testing

Configuration	w [mm]	t [mm]	h [mm]	B [°]	A [°]	l_1	c [mm]	l [mm]	R [mm]
T1	47	37	13.44	59	21.8	10	15	15	3
T2	51	37	14.19	59	28.1	10	15	15	4
T3	54	38	14.27	60	33.7	10	15	15	5

The tests were performed on an Instron 3360 testing unit and were displacement driven with a constant crosshead speed of 3 mm/min. For each dimensional case, a number of four samples were subjected to testing. The positioning of the samples during the tests is illustrated in figure 3.

Figure 3: Specimen positioning in the machine during the traction tests.

The load was measured using a 5kN load cell. The stress was calculated by dividing the measured load by the surface area of the unit cell ($h \times t\ mm^2$). The strain was computed by dividing the measured displacement by the cell's initial length.
The transversal stiffness was computed based on the obtained stress-strain curves, figure 4 and figure 5.

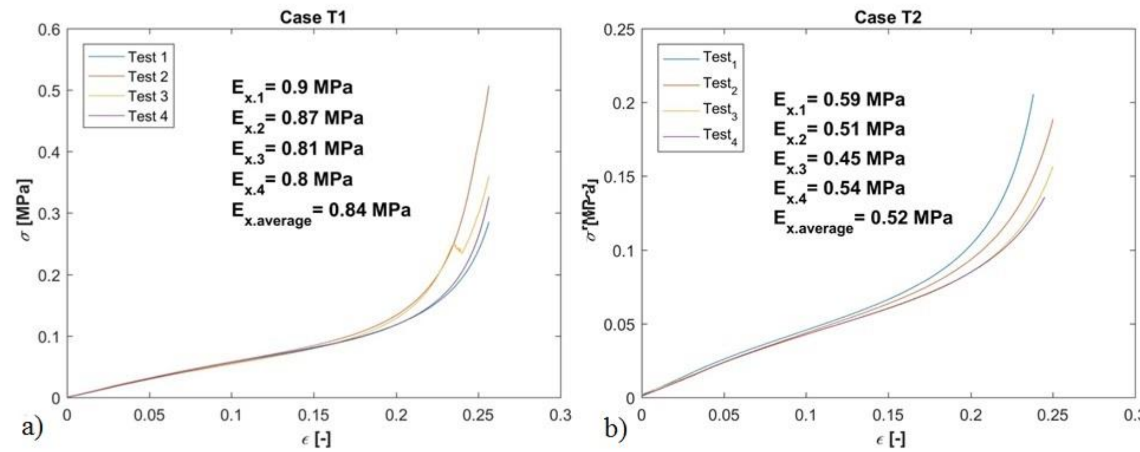

Figure 4: Stress-strain response and in-plane transversal stiffness for T1 a) and T2 b) configurations.

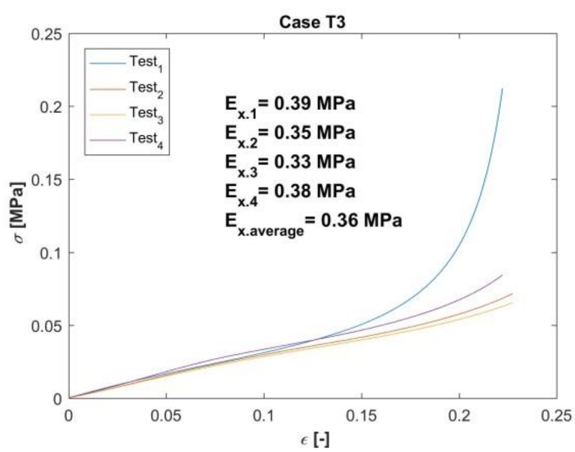

Figure 5: Stress-strain response and in-plane transversal stiffness for T3 configuration.

5. RESULTS AND DISCUSSIONS

The in-plane transversal traction tests have provided values for the stiffness on the transversal direction. The results obtained during the experimental testing have been compared to the theoretical ones and are presented in table 2. The comparative study shows that both of the developed models, theoretical and experimental, are in close correlation. This outlines that the analytical model was validated through the experimental testing within acceptable limits.

Table 2: Analytical and experimental results

Configuration	E_z [MPa] Analytical model	Experimental tests	Difference
C1	0.92	0.84	9.5%
C2	0.62	0.52	16%
C3	0.4	0.36	10%

The registered experimental values for the stiffness are slightly higher than the theoretical ones (Table 2). The difference may be interpreted as a consequence of the following major fact: in order to simplify the analytical model, the value for the bending radius is considered to be 0, while, in the case of the experimental testing, the bending radius is 1 mm. This radius contributes in avoiding the crack propagation in the sheet metal during the expansion process.
In addition to this, the 3D dimensions of the corrugation are slightly different between the two models, due to the presence of the bending radius mentioned above as well as geometrical imperfections of the cell's legs obtained during the manufacturing process.

6. CONCLUSIONS

The main purpose of this study was to evaluate the transversal stiffness of the expanded trapezoidal cellular structure. A theoretical model has been developed in order to define the in-plane transversal behavior. In this regard, expressions for computing the stiffness were defined with the help of an analytical model, which was validated through experimental tests.
As a conclusion of the conducted study, it can be stated that the presence of the internal angle A, influences the in-plane transversal mechanical properties, decreasing with the increase of the radius of the perforations. This behavior is influenced by the slenderness of the cell's legs.
A future objective of the current research would be to investigate the behavior and the mechanical properties of the corrugation on the longitudinal direction of expansion.
Another direction would be to increase the base material thickness in order to enhance the structural properties.

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