Numerical and Experimental Investigations of a Twin Sheet Thermoplastic Structure with Rectangular Frusta

Stefan Tabacu[1,2(✉)], Claudiu Diaconescu[2], and Alexandru Oltean[2]

[1] University of Pitesti, Pitesti, Romania
stefan.tabacu@upit.ro
[2] ALSECA Engineering, Bucharest, Romania
{claudiu.diaconescu, alexandru.oltean, stefan.tabacu}@alseca.com

Abstract. Thin walled structures with rectangular frusta discussed by this study are manufactured using vacuum formed thermoplastic sheets that finally define a unitary structure that is a highly efficient solution providing outstanding performance by means of using small amounts of materials and high-tech, low energy consumption equipment. Sample parts formed by 2 × 2 cells with a cell dimension of 10 × 10 mm and a total height of 18.3 mm were tested in compression. Average crushing force and energy absorbed were calculated. Numerical models of the structure were developed and solved using Ls-Dyna explicit and implicit capabilities. Generally, both implicit and explicit solver provided good results in terms of crushing force and energy absorbed, while the failure pattern was better reproduced by the implicit solver. The implicit solver requires longer runtimes and this may add some constrains, thus for the explicit solution the simulation time was investigated in order to setup a parametric analysis. It was found that by using smaller cells the total energy absorption can be increased with respect to the available design volume, yet a limitation is added by the manufacturing process regarding the depth of the shape, draft angle and thickness of the part.

Keywords: Cellular structures · Twin-sheet forming · Axial crushing · Explicit and implicit simulations · Parametric analysis

1 Introduction

Cellular or patterned structures are of a particular interest due to high energy absorption performances during crushing while maintain a low specific weight. This way the structures may be a candidate for demanding industry activities like the automotive field [1, 2] where keeping a low vehicle weight is a major concern. The particular shape of the finished parts gives the required strength (crushing force) and energy absorption performances. The work of Bartl et al. [3] addressed a composite with a porous mineral granulate embedded in polyamide, Kathiresan et al. [4] a composite with laminated fibers, Zou et al. [5] a honeycomb structure and Sashikumar et al. [6] an aluminum egg-box structures. A specialized structure that uses the SKYDEX® material was

A. Chiru and N. Ispas (eds.), *CONAT 2016 International Congress of Automotive and Transport Engineering*, DOI 10.1007/978-3-319-45447-4_2

investigated by Zhu et al. [7]. Akisanaya and Fleck [8], Gupta [9] and Mamalis et al. [10] investigated the deformation process and structural performances of conical frusta structures. The egg-box structures are closely related and prove to be a reliable solution for energy absorption devices as presented by Lam et al. [11] for thermoplastic composites and by Nowpada et al. [12] for a metallic material. Twin sheet thermoplastic structures are highly efficient solutions that provide outstanding performance by means of using small amounts of materials (shaped in rather complex geometry) and high-tech, low energy consumption equipment. The structures are manufactured using vacuum formed sheets that finally define a unitary structure. The manufacturing process is presented in Fig. 1.

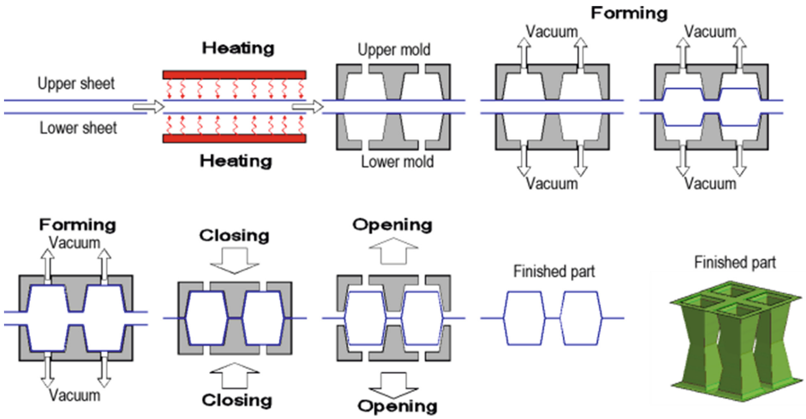


Fig. 1. Twin sheet structures. Manufacturing process

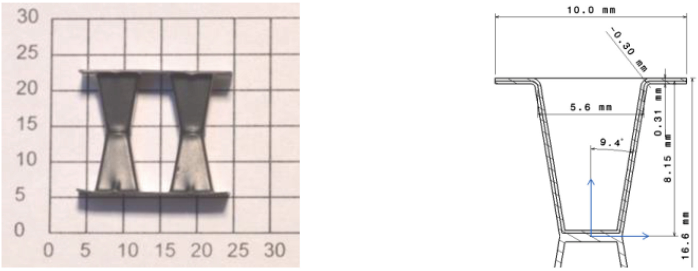
The thermoplastic sheets are heated up to the process temperature (glass transition phase) and then inserted in the forming machine. Using vacuum the sheet are individually shaped according to the design specification and finally the upper and lower molds are closed, in order to fuse the top and bottom sections, giving the unitary structure of the part.

2 Experimental Investigation of the Twin Sheet Structures

Experimental tests were performed on existing structures (http://www.hombach-kunststofftechnik.de). Figure 2(a) presents a photographic image of the part and Fig. 2 (b) presents the main dimensions associated to the structure.

The total height of the structure is 18.6 mm and the walls have a thickness of 0.31 mm. The draft angle of the rectangular frustum is of 9.4°. The frustum joins the flat surface by a filleted section with a radius of 0.30 mm.

The cellular structure sets of four cells (disposed in a 2 × 2 cells configuration) were cut and used for the compression test, performed using an universal testing machine.



a) *b)*

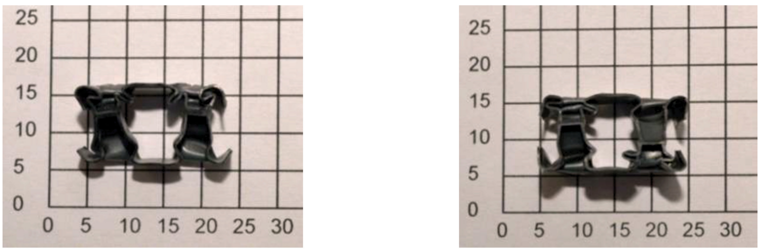
Fig. 2. Cellular structure *(a)* cellular structure (scale in mm); *(b)* main dimensions.

The speed of the moving plateau was set to 2.5 mm/min and the total travel (tool displacement) was limited to 9 mm in order to avoid the increase of the force due to heavily compaction of the sample. Figure 3 presents the crushing process.

a) *b)* *c)* *d)* *e)*

Fig. 3. Experimental testing *(a)* initial configuration; *(b),(c)* stage I - deformation of the flanges; *(d)* stage II - collapse of the columns; *(e)* compaction.

Figure 4 shows a section of the collapsed structures.



a) *b)*

Fig. 4. Collapsed structure *(a)* folds created on top; *(b)* folds created on bottom.

The first stage of the crushing process consists in the deformation of the flanges of the cellular structure. Once buckling occurs, folds are created on the wall of the frusta sections. The crushing force was recorded during the experiments (Fig. 5).

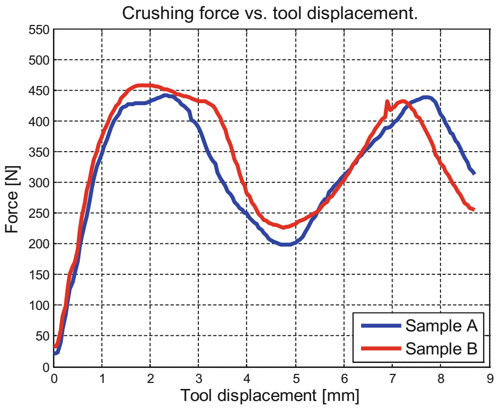


Fig. 5. Measured crushing force

The average crushing forces $P_{m,expA}$ and $P_{m,expB}$ were computed using available experimental data. For the first case the average value is of 326 N while for the second case the average value is of 338 N. Results are listed in Table 1.

Table 1. Experimental data.

Parameter	Sample A	Sample B	Notes
Height [mm]	18.6	18.6	Geometrical features of the parts
Wall thickness [mm]	0.31	0.31	
Draft angle [º]	9.4º	9.4º	
Configuration	2 × 2 cells	2 × 2 cells	
Average force [N]	**326**	**338**	Tool travel speed: 2.5 mm/min
Maximum force [N]	**440**	**457**	
Energy [J]	**2.83**	**2.94**	

Experimental data were used also to identify the polypropylene material parameters of the formed material (www.matweb.com). The mean crush force is dependent of the value of yield stress (Abromowicz and Jones [13], Jones [14], Wierzbicki et al. [15]) while the failure strain gives the amount of internal energy accumulated by the structure. Equation (1) gives the average (mean) crushing force.

$$P_m = 4 \cdot M_0 \cdot \left(9.6 \cdot \sqrt[3]{c_{i-1}/t} + \pi \cdot \tan\theta\right) \quad (1)$$

where $M_0 = 1/4 \cdot \sigma_0 \cdot t^2$ is the fully plastic moment per unit length; σ_0 is the flow stress for the material; t is the thickness of the part and c_{i-1} is the sum of half width and half breadth defined as $c_{i-1} = \frac{l+w}{2}$.

Using experimental results Eq. (2) was used to identify the value of flow stress of the material used to manufacture the samples.

$$\frac{\left(P_{m,expA} + P_{m,expB}\right)}{2} = 4 \cdot M_0 \cdot \left(9.6 \cdot \sqrt[3]{c_{i-1}/t} + \pi \cdot \tan\theta\right) \quad (2)$$

where $P_{m,expA}$ and $P_{m,expB}$ are the average values of the experimental crushing forces listed in Table 1. A value of $34.5MPa$ was assigned for the flow stress and further used for the numerical simulations considering a bilinear material model with a null hardening modulus. A simple material model (isotropic with kinematic hardening - *MAT_003) was selected and by fitting experimental data, a value of 1500 MPa was assigned to the Young's modulus and 1.5 (150 %) for the strain at failure following the experimental behave of the structures. The strain rate effect was neglected for the selected material models.

3 Numerical Investigation of Twin Sheet Thermoplastic Structures

The structures with rectangular frusta were investigated using numerical methods. A Matlab [16] code was developed in order to define a parameterized numerical model for the analysis used both for material identification phase and parametric study. Based on the extensive capabilities of Ls-Dyna [17] both explicit and implicit simulation were performed. For the simulation cases mentioned before (implicit and explicit solvers), the computed crushing force obtained using the numerical models are presented in Fig. 6.

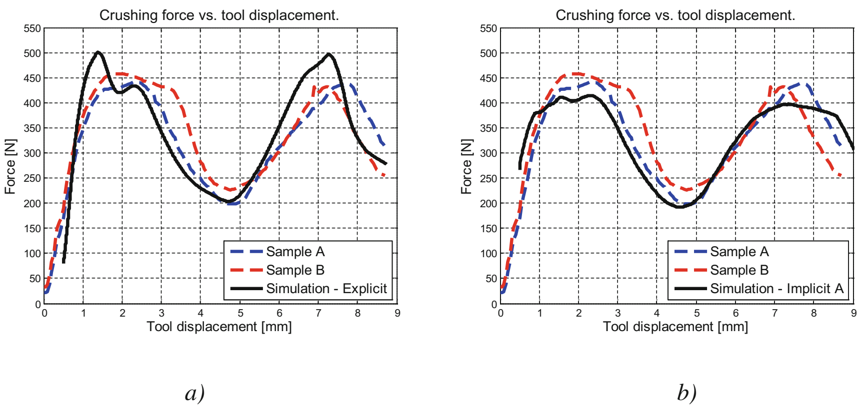


Fig. 6. Experimental and numerical crushing force *(a)* **Explicit** analysis; *(b)* **Implicit** analysis

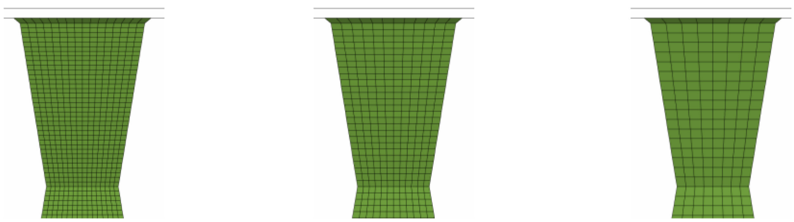
The total simulation time is closely related to the required or computed timesteps used during the simulation. Time unit is constrained by the set of consistent units assigned to the numerical model, defined for the proposed model as kg, mm, ms. The simulation time was set, by a number of trial and error simulations, to 40 ms. For the implicit analysis the maximum time step (parameter DTMAX) was set to 0.05 ms (Implicit A Cases) for a short runtime and to 0.01 ms (Implicit B Cases) for results improvements. Based on the definition of the numerical model, the timestep for the explicit analysis was defined by the solver without triggering the mass scaling procedure. The numerical model was developed using shell elements of type Belytschko-Tsay. A number of 32 elements were defined along the edges of the cell and 36 elements along the edge of the rectangular frustum. Contacts were defined at the interface of the cellular structure with the stationary wall (ground) and with the flat moving wall. A self-contact was defined for the cellular structure. The coefficient of friction was set to 0.30 for the single surface contact and to 0.7 for the contact between the part and the walls.

For the analysis of the results the reference value for the average force and energy was calculated as the median of the results obtained from the experiments. Results are summarized in Table 2 (Fig. 6).

The results obtained using the numerical simulation are similar to the experimental data. For the average crushing force the maximum value was obtained for the Implicit analysis B. The computed internal energy accumulated by the structure is similar for all simulation cases with the experimental results. The current mesh size (32 × 36 elements) was defined by multiple runs in order to provide reliable results for the solver

Table 2. Numerical results. Comparison with experimental data.

	Average force [N]	Error [%]	Energy [J]	Error [%]
Experiment A	326	–	2.83	–
Experiment B	338	–	2.94	–
Experiments A, B	**332**	Reference	**2.89**	Reference
Simulation – Expl.	329	–0.75	2.82	–2.25
Simulation – Imp. A	331	–0.15	2.89	0.17
Simulation – Imp. B	349	5.28	2.83	–1.19



a) *b)* *c)*

Fig. 7. Mesh density (cell x frustum edge) *(a)* 32 × 36 elements; *(b)* 22 × 24 elements; *(c)* 16 × 18 elements.

types and parameters used for the numerical analysis. The influence of the mesh density was investigated in order to identify a reliable solution for the numerical analysis.

Implicit analysis (Implicit A) with a larger maximum timestep (DTMAX = 0.05 ms) required the shortest simulation times and for the numerical model with a dense mesh (32 × 36 elements) it provided good results in terms of average crush force and total deformation energy. Plots of the crushing force obtained from the simulations are presented in Fig. 8.

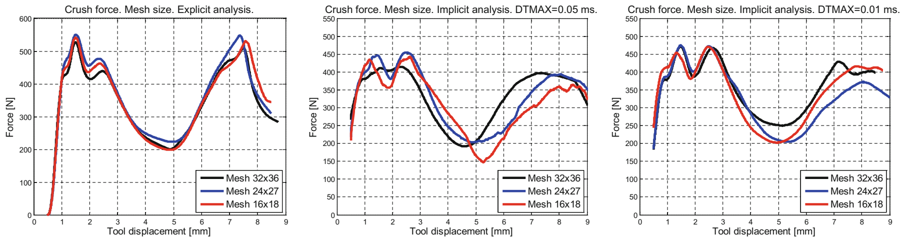


Fig. 8. Crushing force. Models mesh size. *(a)* **Explicit** analysis; *(b)* **Implicit** analysis **A**; *(c)* **Implicit** analysis **B**

The force plots obtained for the model with a mesh size of 16 × 18 show the it failed to match the deformation pattern for Implicit cases A.

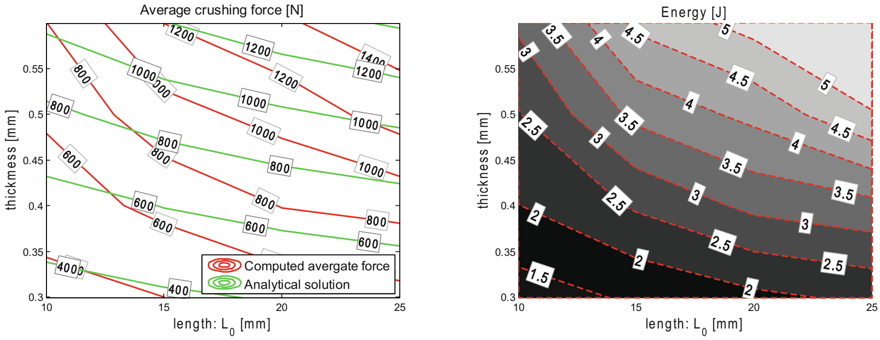
4 Parametric Analysis

Based on the results and findings presented by now a parametric analysis was performed (on a pack of 2 × 2 structures) and the following parameters were investigated: cell size and sheet thickness (of the formed structure, mainly the thickness of the rectangular frustum). The length of the cell ranges from 10 to 25 mm in steps of 5 mm, the draft angle is set to 9.4°, while the thickness of the formed part ranges from 0.3 to 0.6 mm in steps of 0.1 mm. The travel of the moving wall was limited to half of the cell's height (Fig. 2*b*)).

Figure 9 presents the results recorded during the computer simulation using the explicit solver in order to speed up the process (results show that the average force is well estimated). For the preliminary process of structure dimensioning the analytical solution may provide the starting point while the numerical analysis will complete and improve the design.

The energy absorption increases while decreasing the cell's dimensions. For a cell with edge's length of 10 mm and a thickness of 0.5 mm the energy absorbed is of 2.5 J. For a cell with edge's length of 20 mm and a thickness of 0.5 mm the energy absorbed is of 4.0 J. This show that for the same available space using smaller cell the energy absorbed will be higher due to the increased efficiency of the structure. Furthermore the absorbed energy can be increased with the wall's thickness.

Overall, the methods of improving the structural response can be derived from the analysis of the mean crushing force. The only limitation is related to the dimensions of



a) *b)*

Fig. 9. Energy absorbed and Specific energy absorption. *(a)* average crushing force; *(b)* energy absorption.

the structure as the height of the cell and draft angle give the thickness of the part and manufacturing process requirements.

5 Conclusions

Twin sheet thermoplastic structures were investigated using experiments and numerical simulation. Sample parts were tested in compression in order to determine the average crushing force and the energy absorbed. The data were used also for a parameter identification of the material model used for the numerical simulations.

Results were evaluated in terms of average crushing forces, energy absorbed and failure pattern. For dense mesh definitions, results obtained using the implicit solver are more accurate, although one major shortcoming resides in the long runtime required for the model to provide a solution. When the maximum timestep was increased the implicit solver failed to provide an accurate solution. Therefore the performances of the explicit solver were evaluated. As the material model was not strain rate sensitive the influence of simulation time was investigated. Varying the simulation time from 10 ms to 50 ms the outputs were in a close range. As a consequence based on the explicit solver a parametric analysis was performed. The length of the cell ranged from 10 mm to 25 mm while the thickness of the part varies from 0.3 mm to 0.6 mm. Average crushing force was computed and compared with the analytical solution. It was found that for the preliminary investigations of such structures the analytical equation provides a good start point. Also the parametric analysis pointed that whenever possible the energy absorption performances can be increased by using structures with small cell. One limitation may be added by the geometry of the part (depth and draft angle) and the manufacturing process.

References

1. Tarlochan, F., Samer, F., Hamouda, A.M.S., Ramesh, S., Khalid, K.: Design of thin wall structures for energy absorption applications: enhancement of crashworthiness due to axial and oblique impact forces. Thin Walled Struct. **71**, 7–17 (2013)
2. Tanlak, N., Sonmez, F.O.: Optimal shape design of thin-walled tubes under high-velocity axial impact loads. Thin Walled Struc. **84**, 302–312 (2014)
3. Bartl, F., Klaus, H., Dallner, R., Huber, O.: Material behaviour of a cellular composite undergoing large deformations. Int. J. Impact Eng **36**, 667–679 (2008)
4. Kathiresan, M., Manisekar, K., Manikandan, V.: Performance analysis of fibre laminated thin conical frusta under axial compression. Compos. Struct. **94**, 3510–3519 (2012)
5. Zou, Z., Reid, S.R., Tan, P.J., Li, S., Harrigna, J.J.: Dynamic crushing of honeycombs and features of shock fronts. Int. J. Impact Eng. **36**, 165–176 (2009)
6. Sashikumar, S., Chirwa, E.C., Myler, P., Qian, P., Matsika, E.: Numerical investigation of the collapse behaviour of an aluminium egg-box under quasi-static loading. Int. J. Crashworthines **17**, 582–590 (2012)
7. Zhu, F., Dong, L., Ma, H., Chou, C.C., Yang, K.H.: Parametrized optimal design of a novel cellular energy absorber. Int. J. Mech. Sci. **86**, 60–68 (2014)
8. Akisanya, A.R., Fleck, N.A.: Plastic collapse of thin-walled frusta and egg-box material under shear and normal loading. Int. J. Mech. Sci. **48**, 799–808 (2006)
9. Gupta, P.K.: A study on mode of collapse of varying wall thickness metallic frusta subjected to axial compression. Thin. Wall. Struct. **46**, 561–571 (2008)
10. Mamalis, A.G., Manolakos, D.E., Ioannidis, M.B., Kostazos, P.K., Hassiotis, G.: Finite element simulation of the axial collapse of thin-wall square frusta. Int. J. Crashworthines **6**, 155–164 (2001)
11. Lam, S.W., Tao, X.M., Yu, T.X.: Comparison of different thermoplastic cellular textiles composites on their energy absorption capacity. Compos. Sci. Tech. **13–14**, 2177–2184 (2004)
12. Nowpada, S., Chirwa, E.C., Myler, P., Chinnaswamy, G.K., Matsika, E.: Egg-box panel for commercial vehicle front-compressive loading test. Int. J. Crashworthines **15**, 59–70 (2010)
13. Abramowicz, W., Jones, N.: Dynamic axial crushing of square tube. Int. J. Impact Eng **2**, 179–208 (1984)
14. Abramowicz, W., Wierzbicki, T.: Axial crushing of multi corner sheet metal columns. J. Appl. Mech. - T. ASME **56**, 113–120 (1989)
15. Wierzbicki, T., Recke, L., Abramowicz, W., Gholam, T.: Stress profile in thin -walled prismatic columns subjected to crush loading - I Compression. Comput. & Struct. **51**, 611–623 (1994)
16. The MathWorks Inc. MATLAB. Natick, Massachusetts, United States (2009)
17. Hallquist, J.O.: LS-DYNA Keyword User's Manual. Version 970. Livermore Software and Technology Corporation, Livermore CA (2003)

http://www.springer.com/978-3-319-45446-7

CONAT 2016 International Congress of Automotive and Transport Engineering
Chiru, A.; Ispas, N. (Eds.)
2017, XVII, 898 p. 725 illus., 596 illus. in color.,
Hardcover
ISBN: 978-3-319-45446-7