Australian Journal of Basic and Applied Sciences, 9(19) Special 2015, Pages: 20-26

ISSN:1991-8178

Australian Journal of Basic and Applied Sciences

Journal home page: www.ajbasweb.com

Axial Crushing of Thin-walled Structure with Crease Lines

[1,3]Siti Marhainis, A.M., [1,2]Nuraini, A.A., [1,2] Azmah Hanim, M.A., [1]Sahari, B.B.

[1]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.*
[2]*Laboratory of Biocomposite Technology, Institute of Tropical Forestry and Forest Products, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.*
[3]*Institute of Product Design and Manufacturing, Universiti Kuala Lumpur, 119 Jalan 7/91, Taman Shamelin Perkasa, 3 ½ Miles Cheras, 56100 Kuala Lumpur, Malaysia*

ARTICLE INFO

Article history:
Received 12 March 2015
Accepted 28 April 2015
Available online 2 May 2015

Keywords:
Thin-walled Axial crushing
Peak force Crease lines
Finite element analysis

ABSTRACT

Thin-walled structures receive much attention as energy absorbing device because of its cost advantage. Apart from being energy absorbent, efficient energy absorbing devices should also have low initial peak force, so that no excessive force is transmitted to the structures that needed protection. Thus, this paper focuses on the role of crease lines of patterns, applied to the surface of thin-walled structure to the produced initial peak force and collapse pattern. Two types of thin-walled structures which are pre-folded with horizontal and inclined crease lines are investigated with finite element analysis. The results show that thin-walled structures having pre-folded inclined with horizontal crease lines exhibit lower initial peak force when compared to the thin-walled structure with only pre-folded horizontal crease lines and benchmark thin-walled structure with no crease lines.

To Cite This Article: Siti Marhainis, A. M. , Nuraini, A. A., Azmah Hanim, M.A., Sahari, B. B. Axial Crushing of Thin-walled Structure with Crease Lines. ***Aust. J. Basic & Appl. Sci.,*** *9(19): 20-26, 2015*

INTRODUCTION

In recent years, researchers have shown large interest to the thin-walled structures as it is the basic form of most structures, be it in the automotive, aviation, or construction fields. Depending on the usage, the thin-walled structures can be objectified according to specific needs through modifying its parameters and it is increasingly difficult to ignore the capability of the thin-walled structure as energy absorbers. Extensive works have been done in the automotive field to the thin-walled structures, especially in improving its performance of energy absorbing feature in vehicle collisions (Qureshi and Bertocchi, 2013). Studies have shown that the thin-walled structure design parameters which comprise of and not limited to; cross section, thickness, materials, fillers, wall design and joints affect the total energy absorption of the thin-walled structure (Qiu and Yu, 2011) under impact.

Abramowicz (Abramowicz, 2003) have presented in his study that energy dissipation which is transmitted along the thin-walled structure surfaces came from three main sources, that is folding along stationary plastic hinge lines, propagation of travelling plastic hinge lines, and localized in-plane stretching in the toroidal surface which was linked with the traveling plastic hinge lines. These three conditions are necessary to keep the thin-wall structure having a kinematic continuity and they are also proven to be responsible for the energy absorption of the thin-walled structures (Wierzbicki and Abramowicz, 1983).

Apart from high energy absorption capability, evidence also suggests that ideal energy absorption devices should have low initial peak force and progressive and smooth collapse pattern (Ma and You, 2013a). This is mainly to reduce injuries of vehicle passengers during initial impact and to diminish the possibility of premature bending of the thin-walled structures (Ma *et al*, 2010). Consequently, several studies have suggested methods to reduce the initial peak force while providing the progressive and smooth collapse pattern through applying triggers and dents to the thin-wall structures and also with the usage of non-metallic material such as composites (Qiu and Yu, 2011)(Lee et.al, 1999). Even with the many suggested methods, the automotive industry is inclined with the application of dents and pattern to the crash-box which is assigned to absorbed impact energy. The dents and patterns that is stamped out on

Corresponding Author: Siti Marhainis Abu Mansor, Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.
Phone: +603-89464382; E-mail: marhainism@gmail.com

Australian Journal of Basic and Applied Sciences, 9(19) Special 2015, Pages: 20-26

the surface of the crash box is purposed to reduce the peak force and at the same time maintaining the progressive and smooth collapse mode (Ma and You, 2013b).

Numerous numerical and experimental studies on the effectiveness of wall patterns to the energy absorption and subsequently the initial peak force and collapse pattern of a thin-walled structure have been done. Zhang *et al* (Zhang *et al*, 2007) presented the pyramid pattern on the surface of the thin-wall square tube with recorded numerical analysis success even though that the experimental results of the same pattern by Ma *et al* (Ma *et al*, 2010) revealed that the expected octagonal collapse mode is difficult to trigger and very sensitive to manufacturing imperfections, apart from the complexity on developing the pyramid pattern on the wall surface.

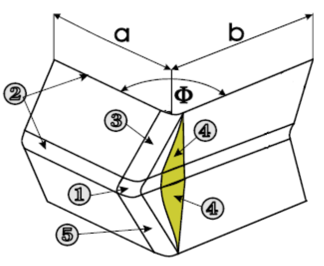
Ma and You (Ma and You, 2013b) on the other hand proposed a pre-folded pattern that uses specifically designed developable origami mimicking the symmetric collapse mode. This study presented that the pre-folded pattern is applicable in reducing the initial peak force while allowing the thin-walled structure to collapse progressively smooth and at the same time giving high energy absorption when the thin-walled structure in under axial impact. Apart from that, Song *et al* (Song *et al*, 2012) and Qureshi and Bertocchi (Qureshi and Bertocchi, 2013) also presented patterns that were applied to the wall of the thin-wall structure which give positive results.

While a variety of patterns have been presented, no comparative study on the patterns and how it affects the value of the initial peak force of an axially crushed thin-wall structure has been found. Thus, in this paper, the effectiveness of crease lines applied to the wall of the thin-wall structures is studied using numerical analysis as an initial attempt of the patterns comparative study. The crease lines represents the pre-folded pattern creases from previous studies and the crease lines were also derived with reference to the stationary plastic hinge lines and travelling plastic hinge lines presented by Abramowicz of the folding mode of the thin-walled structure under axial crushing (Abramowicz, 2003). The initial idea is that the stationary plastic hinge line is presented by a horizontal crease line while the traveling plastic hinge line is presented by an inclined crease line.

MATERIAL AND METHOD

1.1Geometric Modelling:

According to Abramowicz (Abramowicz, 2003), when a square thin-walled structure is axially crushed, three main deformation mechanism exists, that is stationary plastic hinge line in both the symmetric and extensional modes, traveling plastic hinge line in the symmetric mode, and circumferential extension in the extensional mode. These mechanisms are interpreted as an element, namely Superfolding Element (SE), shown in figure 1 which represents a section of the folding pattern of crushed square thin-walled structure.



(1) - Deformation of a floating toroidal surfaces.
(2) - Bending along stationary hinge lines.
(3) - Rolling deformations.
(4) - Opening of a conical surfaces.
(5) - Bending deformations along inclined, stationary, hinge lines following locking of the travelling hinge line (3).
a - length
b - length
Φ - central angle

Fig. 1: Idealized deformation mechanism of a Superfolding Element, (SE) (10).

Therefore, with reference to the deformation mechanism presented, two thin-walled structures with different crease line orientation are created to investigate the collapse mode and the initial peak force developed when they are axially crushed. A straight square thin-walled structure was used as a benchmark. The width, height and wall thickness of the straight square thin-walled structure C-00, were b = 93mm, H = 300mm, and t = 2.0mm. All of the models of the thin-walled structure are built using a CAE software Altair Hypermesh, firstly using nodes and lines, and then the surface is generated from the lines. Figure 2 shows the straight square thin-walled structure.

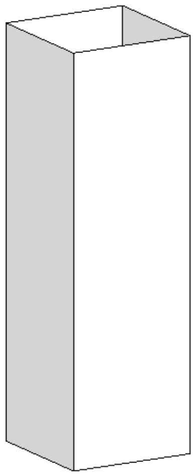


Fig. 2: Straight thin-walled structure, C-00.

Five sections are created on the thin-walled structure which encompasses nine crease lines for structure C-H1. The horizontal crease lines represent the stationary plastic hinge lines which appeared in the thin-walled structure deformation mode. Figure 3 shows a section of structure C-H1. The dihedral angle, θ of the crease lines is decided to be 178° to give the thin-walled structure the least pre-folded crease lines.

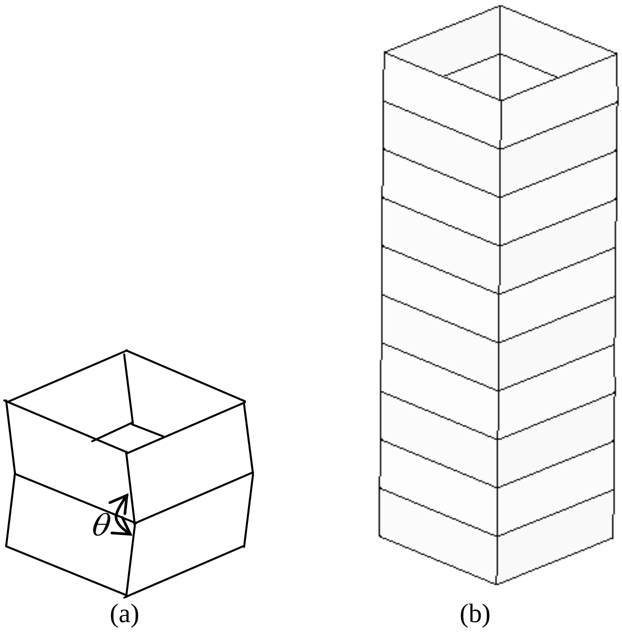


Fig. 3: Thin-walled structure with horizontal crease lines, C-H1: (a) a section of C-H1; (b) complete C-H1.

On the other hand, to represent the traveling hinge lines, inclined crease lines are added to the existing straight square thin-walled structure. However, the inclined crease lines could not be visualized without the existence of the horizontal crease lines, as the sole application of inclined crease lines would alter the cross section of the thin-walled structure. Thus, the horizontal crease lines are maintained, with the addition of inclined crease lines at the corners of the thin-wall structure. The thin-walled structure with inclined crease lines, labelled C-V1 is shown in figure 4 where the dashed lines represent the additional inclined crease lines. The dihedral angle, θ is kept 178° and based on Equation 1 derived by Ma and You (Ma and You, 2013) the corner width c, is calculated to be 2mm.

$$\theta = 2\cos^{-1}\left[\left(\sqrt{2}-1\right)\frac{c}{l}\right] \qquad \text{Eq.1}$$

where, l is the module length.

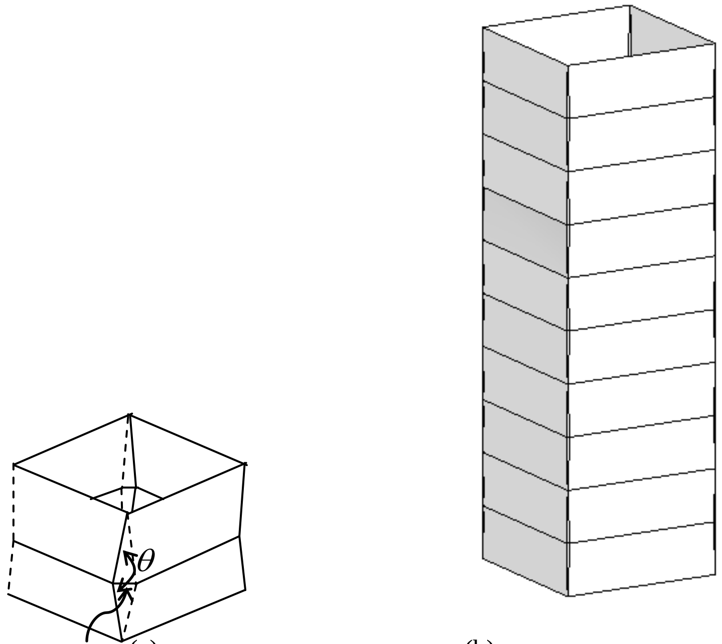


Fig. 4: Thin-walled structure with incline crease lines, C-V1: (a) a section of C-V1; (b) complete C-V1.

1.2Numerical Model:

Two thin-walled structures with crease lines that have been presented in previous section were analyzed to investigate the initial peak force and the collapse mode and a straight square thin-walled structure without crease line was used as the benchmark. The initial peak force of a structure that is axially crushed is the highest load required to cause significant permanent deformation. Figure 5 shows the force displacement characteristics of an axially crushed thin-walled structure. The initial peak force of each structure was generated from the results of numerical model. Commercial finite element analysis software package LS-DYNA was applied to simulate the axial crushing process. Preceding the meshing processes using the Altair Hypermesh, the model surface is first being cleaned up as to have a better model continuity and meshing quality. Element type for this model is mixed which consist of tetra and tria elements while the element size for all elements used is 5mm.

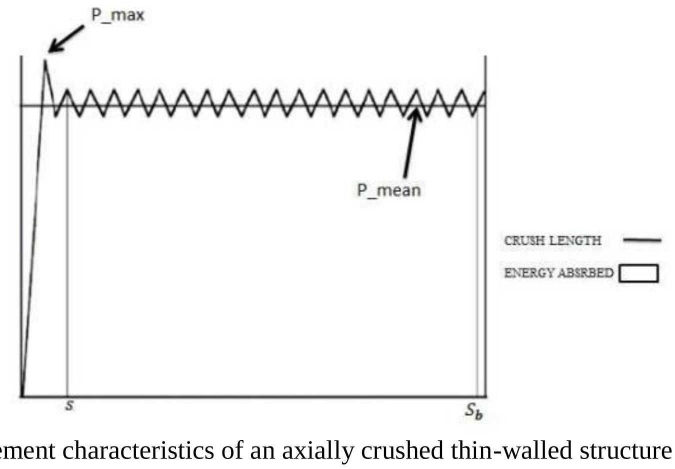


Fig. 5: Force displacement characteristics of an axially crushed thin-walled structure (Tarlochan, 2013).

The crushing scenario was modelled as a thin-walled structure standing on a surface and being compressed by a moving rigid wall having initial impact velocity that is set to be 15.6 m/s with an impacting mass of 275 kg (Tarlochan *et al*., 2013) and is shown in figure 6. The boundary conditions on the other hand, were assigned to the tube lower edges by six, translational and rotational degrees of freedom. The model with loading and boundary condition is also shown in Figure 6. Mild steel is chosen as the material and the mechanical properties of the materials are: density, $\rho = 7830\, kg/m^3$; Young's Modulus, $E = 200GPa$; Poisson's

Ratio, $\nu = 0.3$; $\sigma_y = 207\,MPa$; $\sigma_u = 400\,MPa$ and ultimate strain, $\varepsilon_u = 15\%$ (MatWeb, n.d.).

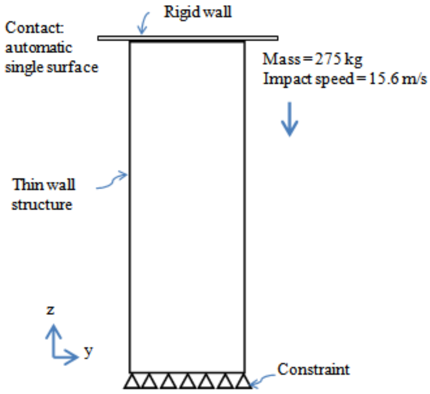


Fig. 6: The analysis set-up for axial crushing.

RESULTS AND DISCUSSION

The straight thin-walled structure, C-00 was analysed to set a benchmark to the investigation of the initial peak force of the thin-walled structures with crease lines. The axial crushing of C-00 is shown in figure 7 where C-00 collapses from the upper end and gradually folds three times when subjected to an axial load. This is due to the propagation of the horizontal stationary plastic hinge lines and inclined travelling plastic hinge lines reviewed in earlier sections. The force versus displacement curve of C-00 is plotted in figure 8. The recorded initial peak force of C-00 is 209.21 kN and it is followed by a number of crests and troughs.

C-H1 and C-V1 structure collapse profiles are shown in figure 7. C-H1 structure having only horizontal crease lines, collapse from the upper end similar to the benchmark model and progressively folded three times axially. The pre-folded horizontal crease lines that was applied to the thin-walled structure guides the collapse where the initial peak force recorded was slightly lower than the benchmark initial peak force value, that is 209.15 kN. C-V1 on the other hand had much lower initial peak force compared to the other two thin-walled structures that is 184.27 kN. The collapse of C-V1 structure also begins at the upper end and it is gradually folded three times with clear exemplification of the initiated horizontal stationary plastic hinge lines and inclined travelling plastic hinge lines through the pre-folded crease lines. The curves of the force-displacement for both C-H1 and CV1 are plotted in figure 8.

It can be observed that the folding of the structures were also guided by the crease lines created and the crushing analysis resulted that thin-walled structures with creased lines had lower initial peak force compared to the straight thin-walled structures. Inclined and horizontal crease lines also produces lower initial peak force compared to only horizontal crease lines.

From the numerical analysis, it is shown that when pre-folded horizontal crease lines were added, there is only slight reduction of initial peak force, which is 0.03%. This may be due to the angle of the horizontal crease lines are not large enough that the structure is behaving almost as the straight thin-walled structure. However, when the inclined lines are added, the reduction of the initial peak force value reduces dramatically, that is 11.92 % lower than the benchmark value. The resistance of the thin-walled structure to the crush load is minimize due to the inclined crease lines created at the thin-walled structure corners, hence resulting the low initial peak force. The obtained numerical results are summarized into table 1.

Table 1: Obtained numerical results of the axially crushed thin-walled structures.

Structure	(mm)	θ (deg)	Peak force (kN)	Peak force reduction (%)
C-00			209.21	
C-H1		78	209.15	0.03%
C-V1	2	78	184.27	11.92%

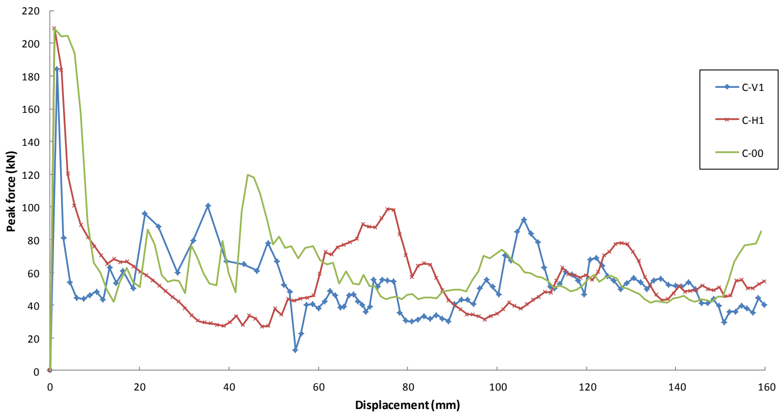


Fig. 7: Force - displacement curves of C-00, C-H1 and C-V1 thin-walled structures.

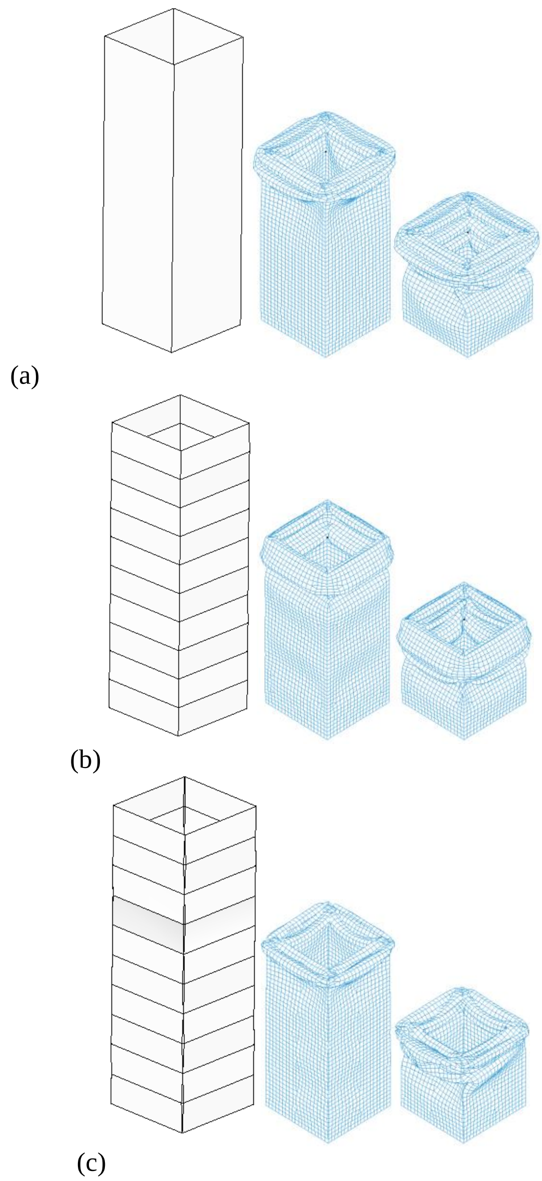


Fig. 8: Profiles of thin-walled structure at different stages of crushing process: (a) C-00; (b) C-H1; (c) C-V1.

Conclusion:

The idea of investigating the crease lines came from the presented three main deformation mechanism that exists when a square thin-walled structure is axially crushed. The stationary plastic hinge line is presented by horizontal crease lines while the traveling plastic hinge line is presented by an inclined crease lines that were applied to the surface of the thin-walled structure.

The numerical results presented that both horizontal and inclined crease lines are an important factor to the initial peak force value. It is shown that even though the horizontal crease lines directs and initiates the collapse mode, the initial peak force value does not differs much from the benchmark thin-walled structure that has no crease lines. Consequently, with the addition of the inclined crease lines to the thin-walled structure, the initial peak force is reduced effectively.

More attention should be given to the inclined crease lines and parametric studies should be done, especially to investigate the effects of geometric parameter, which consists of dihedral angle θ and corner width c, to the initial peak force. The findings, would assist in constructing better crease patterns to the wall of the thin-walled structure in obtaining lower initial peak force, progressive smooth collapse mode and furthermore, high energy absorption.

ACKNOWLEDGEMENT

The author acknowledged the support of Universiti Putra Malaysia under Putra Grants (GP-IPS), GP-IPS/2013/9392800 for this research.

REFERENCES

Abramowicz, W., 2003. Thin-walled structures as impact energy absorbers. Thin-Walled Structures, 41: 91-107.

Lee, S., C. Hahn, M. Rhee and J. Oh, 1999. Effect of triggering on the energy absorption capacity of axially compressed aluminium tubes. Materials and Design, 20: 31-40.

Ma, J. and Z. You, 2013a. Energy absorption of thin-walled beams with a pre-folded origami pattern. Thin-Walled Structures, 73: 198-206.

Ma, J. and Z. You, 2013b. Energy Absorption of Thin-Walled Square Tubes With a Prefolded Origami Pattern—Part I: Geometry and Numerical Simulation. J. Appl. Mech., 81(1): 011003.

Ma, J., Y. Le and Z. You, 2010. Axial Crushing Tests of Thin-walled Steel Square Tubes with Pyramid Patterns. 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA 2010-2615.

MatWeb, LLC., n.d. Retrieved December 12, 2014 from http://www.matweb.com/search

Qiu, X.M. and T.X. Yu, 2011. Some Topics in Recent Advances and Applications of Structural Impact Dynamics. Applied Mechanics Reviews, 64: 030801.1-12.

Qureshi, O.M., and E. Bertocchi, 2013. Crash behavior of thin-Walled box beams with complex sinusoidal relief patterns. Thin-Walled Structures, 53: 217-223.

Song, J., Y. Chen and G. Lu, 2012. Axial crushing of thin-walled structures with origami patterns. Thin-Walled Structures, 54: 65-71.

Tarlochan, F. and F. Samer, 2013. Design of thin wall structures for energy absorption applications: Design for crash injuries mitigation using magnesium alloy. International Journal of Research in Engineering and Technology, 2(7): 24-36.

Wierzbicki, T and W. Abramowicz, 1983. On the Crushing Mechanics of Thin-Walled Structures. Journal of Applied Mechanics, 50: 727-734.

Zhang, X., G. Cheng, Z. You and H. Zhang, 2007. Energy absorption of axially compressed thin-walled square tubes with patterns. Thin-Walled Structures, 45: 737-746.