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FINITE ELEMENT SIMULATION OF POLYGONAL RECTANGULAR SQUARE COMPOSITE COTTON REINFORCED POLYESTER COMPOSITES

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Abstract
In this paper the collapse behaviors of composite cotton fiber reinforced polyester were developed and analyzed. The crush studies with various regular polygonal cross-sections were numerically investigated under axial compression using the finite element method program code of LS-DYNA version 3.71. The effects of wall thickness and velocity rate of impact on the crush behavior were also investigated. Crush strength increases as the number of corners of the cross-section increases, though it was almost saturated for the number of corners beyond 10. Cross-sectional shapes with less than five corners should be avoided to take a regulated collapse pattern. The effect of number of polygonal corners on enhancement in crush strength becomes more prominent as the initial wall thickness decreases. The validation finite element modeling was carried out with experimental analysis technique to ensure that the data results from numerical analysis will provide sufficient accuracy.

Keywords: Composite Structure, Finite Element Simulation, Axial Crushing

1. Introduction

The use of thin-walled multi-corner columns cross-sections is growing continuously in civil engineering, automotive engineering, shipbuilding, and other industries, because of their high strength–weight ratio, low cost, and excellent energy-absorption capability during crashworthiness analysis. Such columns most appear in truss and frame structures as major energy-absorbing components and absorb a substantial amount of crash energy when the impact occurs. Therefore, such columns receive a lot of research interests and previous literatures have demonstrated their responses and performances during crashworthiness analyses. In designing such columns, maximizing their energy-absorption capability should always be a major objective. As presented in previous researches, there are two approaches to enhance the performance of the multi-corner thin-walled columns: either using advanced materials with high mechanical properties or designing optimized wall thickness and cross-sectional dimensions for such columns that can provide the best crash performances. Hou and other co-researchers presented the optimal designs of straight hexagonal thin-walled columns with singly celled and triply celled configurations, which provided the maximum energy-absorption capability during the crashworthiness analyses. However, little effort has been spent on the optimization of the cross-sectional dimensions of the octagonal thin-walled columns. Thus, in this article, an optimum design is first performed for the cross-sectional profiles of such columns to maximize their capability of energy absorption.

On the basis of the previous researches, the response surface method with the polynomial basis functions are used in this paper to obtain the optimum design for the thin-walled octagonal section columns. To seek for the optimal crashworthiness design a set of designs are sampled from the design space using the factorial design, which have different cross-sectional dimensions. Finite element models are created for those designs and used for computer crashworthiness analyses to provide crash responses of those design samples, based on which the response surface methods are constructed . Next, the optimal design for the curved hexagonal columns is derived following the same design approach. The optimized hexagonal cross-section for the curved columns obtained in this study is compared to the one for the straight columns, which was presented by Hou to compare the crashworthiness designs for straight and curved thin-walled columns. Besides the design optimization, parametric studies are performed to investigate the influences of the cross-sectional dimensions on the columns' crash performances. In this project, the finite element modeling is used to build up the geometric beam models and the explicit solver LS-DYNA is used to generate the finite element models and perform the crashworthiness analyses. In this paper, numerical simulations of axial crush of the multiple corners of straight tube structures with various regular polygonal cross-sections are carried out using the finite element modeling code of the public domain version of LS-DYNA version 3.71. The main objective is to investigate the effect of the cross-sectional shape on the crush behavior, where the deformation pattern and the crush strength are examined. Furthermore, validation has been carried out based on finite element modeling with the same geometries to ensure that the finite element modeling code is sufficiently accuracies. All modeling geometries was centralized or constraint with the same radius of straight hollow cylindrical cross-section which are cotton fiber polyester composite structure. The velocity of dynamic impact of axial compression was varied from 10 to 30 m/s. various kinds of wall thicknesses of the structure are examined.

2. Finite Element and Material Modeling

Based on multi corners straight tube of composite structure, finite element models are created for these columns and the finite element models are used for the crashworthiness analyses. Finite element analysis results of energy absorption and the maximum displacement of deformed composite structure are obtained from the analyses and will later be used for constructing corresponding models. During the analyses the columns impacted onto a rigid wall at an initial velocity of 15 m/s. A 500 kg mass is attached to the free ends of these columns during the analyses so that their axial buckling can be clearly observed. Figure 1 show nominal stress-strain curve material used in this study. The finite element models are composed of the full integration shell element: 4-node Belytschko–Tsay shell element with three integration points through the thickness.

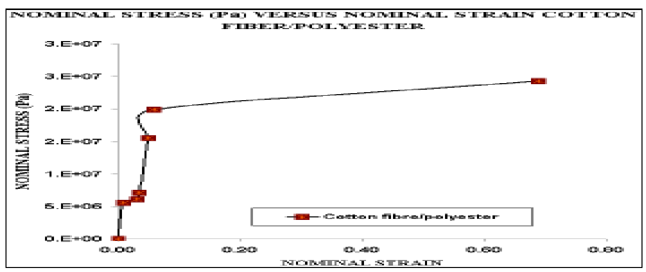


Figure 1: Finite element model of 8 corners descriptions

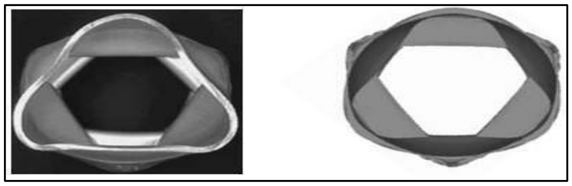
2.1 Finite element validation

The material of validation of the columns is mild steel whose density of 7830 kg/m^3, Young's modulus of 207 GPa, Poisson's ratio of 0.3, yield stress of 200 MPa, and tangent modulus is 630MPa illustrated in Table 1. The column length of 300 mm remains as a constant in this finite element model. Tables 1 list all the relevant conditions and information of the properties material of validation columns and the finite element analysis for these case studies. In the analysis time is set as 0.02 s, which is enough for presenting an entire force curve. As shown in Table 2, during the axial crushing of the straight thin walled 8 corners mild steel column with a radius circle of 44 mm and wall thickness of 1.6 mm, the peak crushing force (96 kN) appeared right after the impact occurred and after that the force dropped down quickly and stabilized at around 20–30 kN. It shows that the computing time of 0.02 s is enough for capturing the most important crash responses and behaviors. The results in Table 2 indicate that the percentage of error numerical and experimental analysis was less than 5%. The good agreement with both of the results and prediction of finite element model with experimental analysis can be accepted. The explicit finite element solver LS-DYNA is applied to create the finite element models and run the crash analyses. In LS-DYNA, the columns' material is modeled as the plastic kinematic hardening model material type of 3 and then the impact contacts among the self-shell elements during these analyses are predicted using the automatic single surface contact algorithm.

Table 1: Material properties of cotton fiber/ polyester and mild steel

Material properties	*Mild Steel*
E (Pa)	207E9
ρ (kg/m^3)	7800
υ	0.3

	Stress (σ)(Pa)	*Strain (ε)*
	1.59E08	0
	1.63E08	0.015
	1.86E08	0.033
	1.93E08	0.044
	2.02E08	0.062
	2.07E08	1.5



Experimental **Numerical modeling**

Figure 2: Validation of deformation pattern of experimental and numerical modeling of mild steel column with 8 corner view on the top side.

In experiment, crush strength in the symmetric accordion collapse mode is larger than that in the diamond collapse mode. This is also true in the computation, because a jump in the crush strength is seen at the point where the collapse mode changes. The decreasing of value computation with experiment may be the effect of fabricated of specimens on experimental analysis will be attributed to the material fracture occurring at the corner region. This result is consistent with that of the computational result for the axial compression of the structures with regular polygonal cross-sections mentioned above. The used computer code of LS DYNA version 3.71 is a nonlinear dynamic explicit finite element code. The structural member computed is fully modeled, though the cross-section has an axis of mirror symmetry. It is compressed dynamically in the axial direction. The bottom edge of the structure is constraints fixed with flat plate moving rigid body with mass of 500 kg. The top edge is compressed with the constant velocity of 10, 20 and 30 m/s, as illustrated in Table 1. Computed cross-sectional shapes are the polygons with 5 corners to 10 corners.

Table 2: Validation of experimental and numerical analysis

Parameters	Experimental	Numerical	Error (%)
Total compression (mm)	190	178	6.3
Peak load (kN)	105	96	8.5
Mean load (kN)	45	40	11
Absorbed energy (kJ)	15	13.2	7.8

Each length of the polygon cross-section is 200 mm, and circumference surface top and bottom of a circle with the diameter of 30 mm. The wall thickness t is set to be 1.0, 1.5 and 2.0 mm. The structure is thin-walled and thus modeled with the four-node shell elements formulated by Belytschko and Tsay. The lateral length of each element ranges from 2.0 to 3.0 mm. The effect of the element size on the computational result was checked and finally 3.0 mm of element size was suitable. The total work done (W) during the axial crushing of the cones are equal to the area under the load/displacement curve and is evaluated as:

$$W = \int P ds \qquad (1)$$

where, P is the force acting on the tube. Therefore the specific energy absorption per unit mass, E is recognized as:

$$E = \frac{W}{m} \qquad 2)$$

where, m is the crushed mass of the thin-walled tube.

It was assumed that thin-walled aluminum extrusion has only isotropic strain hardening, and for quasi-static loading, the strain rate effects on the yield strength were neglected due to the relatively low overall average load rate used in the tensile tests. For dynamic loading, the effect of strain rate was included in the finite element model using the Cowper–Symonds constitutive equation given by the following relation:

$$\dot{\varepsilon}_p = D^t \left(\frac{\sigma_d}{\sigma_s} - 1 \right)^{q^t} \quad for \mapsto \sigma_d \geq \sigma_s \tag{3}$$

where σ_d is the dynamic flow stress at a uniaxial plastic strain rate ε_p, σ_s, the associated static flow stress, and the constants D^t and q^t are tube material parameters. Equation (3) is an overstress power law that was incorporated into the finite element model.

Table 3: Dimension of column finite element modeling

Type (polygonal)	*Length (mm)*	*Velocity (m/s)*	*Thickness (mm)*
5 corners	200	10, 20, 30	1, 1.5, 2
6 corners	200	10, 20, 30	1, 1.5, 2
7 corners	200	10, 20, 30	1, 1.5, 2
8 corners	200	10, 20, 30	1, 1.5, 2
9 corners	200	10, 20, 30	1, 1.5, 2
10 corners	200	10, 20, 30	1, 1.5, 2

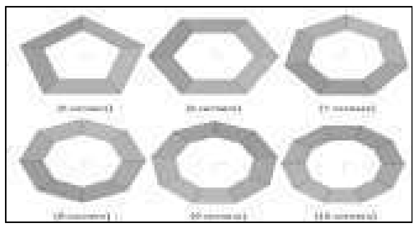


Figure 3: Description of column shell model of 5, 6, 7, 8, 9, and 10 of corners.

3. Results and Discussion

The collapse patterns observed in numerical simulation are shown in Figure 5. The diamond collapse mode appears except in those two cases in spite of the initially axisymmetric cross-section. It may be said that the collapse mode is actually sensitive not only to the wall thickness but also to the other conditions. On the other hand, in the numerical result, the symmetric accordion mode is observed for the thickness of 2 mm. From the numerical results, it seems a natural tendency that the number of corners induced in a progressive collapse mode increases as the initial wall thickness decreases. It may be attributed to that the accelerating decrease of bending resistance in decreasing the wall thickness tends to allow generating more bent corners in a diamond collapse mode. This result is considered almost equivalent to that the deformation pattern becomes more orderly as the number of corners in polygonal cross-section increases for thinner cylindrical structure as mentioned above. Progressive collapse patterns are depicted from Figure 4 in case of wall-thickness of 1.0 mm and velocity of 10 m/s.

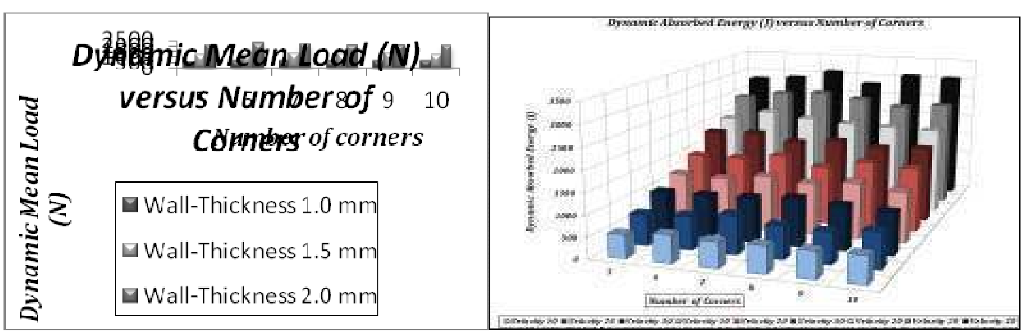


Figure 4: Dynamic Mean load (N) and absorbed energy (Joule) of 5 to 10 corners (velocity of 10, 20 and 30 m/s)

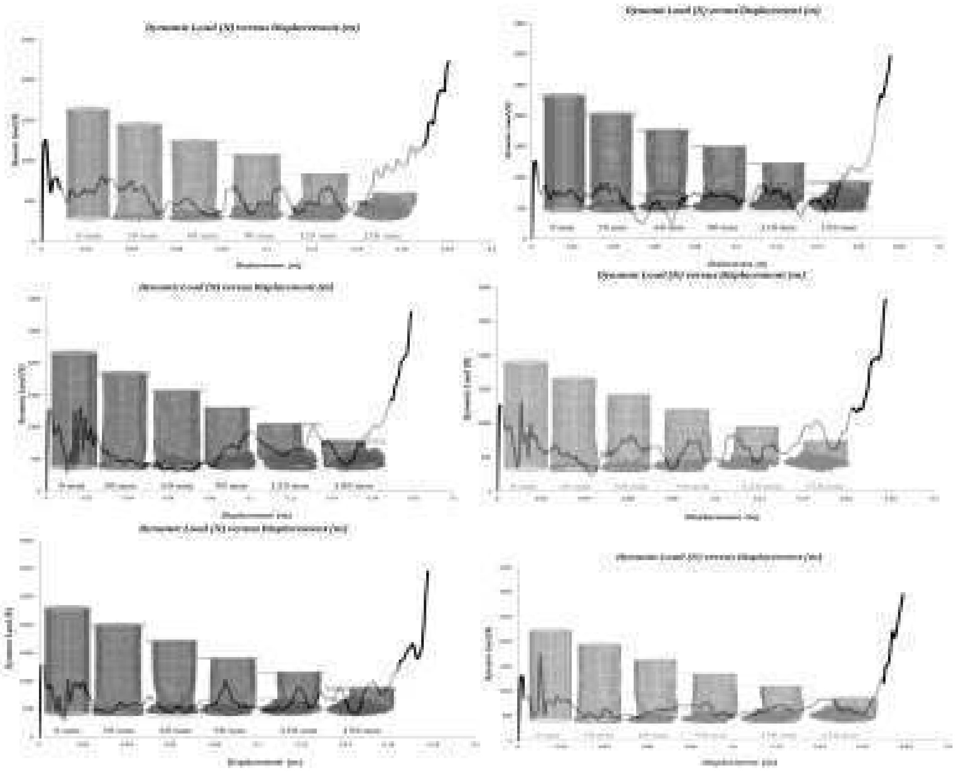


Figure 5: Dynamic load (N) versus displacement (m) of 5 to 10 corners (wall-thickness of 0.001 m and velocity of 10 m/s)

It is observed that the deformation pattern becomes collapse patterns initial (unloading), displacement of 30 mm until final collapse of 150 mm. Linear hardening rate less than F = 4 kN. Initial wall thickness of 1.0 mm more orderly when the number of corners in cross-section changes from 6 to 7 because this may be attributed to that the constraint on the deformation increases as the length of each side shortens. Further, when the number of corners is 10, irregularity occurs for the reduction ratio larger than 20%, where the deformed cross-section becomes dissimilar to the initial polygon. On the other hand, all cross section were collapse quasi progressively in the case of thin-walled less than 1mm, when collapse deformation reach at 100 mm, sliding slip will occur onto impact surface because cotton fiber/ polyester has a low density and modulus elasticity.

For the initial wall thickness of 2.0 mm, the deformation patterns are more disordered than the cases with thicker wall, especially for square cross section. It may be generally stated that the cross-sectional shape with less than 6 corners should be avoided to achieve the orderly collapse pattern. And if we compare the deformation patterns among the structures whose number of corners is rather than 10 corners. It should be noted that the larger plastic hardening rate force stabilizes the collapse pattern in the viewpoint that the axisymmetric cross-sectional shape is unchanged during deformation. In other words, the bifurcation causing a diamond collapse mode does not take place. Thus, it is very important to take into account the strain hardening property of the material used for the structure as well as the initial yield stress. Of course, it is well known that the strength of the structure strongly depends on the initial yield stress. The actual structure absorbs the kinetic energy by a cyclic buckling deformation, and the oscillatory force is observed after initial peak at the onset of deformation. Dynamic absorbed energy (J) in Figure 5 for every condition were analyzed with every variable parameters in term of number of corner, wall-thickness and dynamic velocity. Plots for a symmetric accordion collapse mode are separated from unloading until final collapse of 150 mm. For the cross-section wall-thickness of 1.5 and 2 mm, the crush strength in dynamic load analysis versus displacement not illustrated in this paper but can be summarized that the good agreements and fairly well with that where both of them exhibit the symmetric accordion mode. Thus, the strain-rate effect of the material is small. Moreover, the crush strength in computation agrees well with the corresponding experimental result, validating the numerical model.

4. Conclusion

This paper presents the crashworthiness design for thin-walled cotton fiber/ polyester composite multi-corner columns, including the 6 different cross section shape start from 5, 6, 7, 8, 9 and 10 corners as well as variable on wall-thickness. For the straight multi-corner columns the incremented side length will reduce the structure's

capacity in absorbing impact energy, while will cause a higher peak crushing force during the analyses. For the curved multi-corner columns, the incremented side length will improve the structure's energy-absorption capability and, similarly, result in a higher peak crushing force. The research methods and techniques employed in this paper can be applied to other applications, such as the crashworthiness design of other thin-walled structures. The conclusions drawn from this paper are helpful in better understanding the crash performances of regular thin-walled structures and can also be observed from other crashed thin walled columns.
(1) Crush strength increases as the number of corners in the cross-section increases. It almost saturates beyond 10 corners. The cross-sectional shape with less than five corners should be avoided if we wish to realize a regulated collapse pattern.
(2) The effect of the number of polygonal corners on enhancement in the crush strength becomes more prominent as the initial wall thickness decreases.
(3) Higher plastic hardening rate stabilizes more the collapse pattern and causes a symmetric accordion mode in circular cross-section, while otherwise a diamond collapse mode occurs.

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