Axial Crushing of Origami Pattern Metal and Polymer Composite Thin-Walled Structures Using Finite Element Method

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ABSTRACT

Many industries such as automotive used thin-walled structures as an energy absorbing structure. Tubes structures with circular and rectangular shapes have received the most attention. Nevertheless, the regular symmetric folding process of the tubes is often disturbed by incorrectly design members and a structure may undergo premature bending collapse. In overcoming this premature bending this paper will investigate stress and displacement of the pre-folded rectangular thin-walled structure with diamond origami pattern behavior subjected to axial crushing. Three different materials which are mild steel, polyetheretherketon with glass fibre and polyetheretherketon with carbon fibre of the thin-walled with origami pattern will be used and analyzed using finite element method. Results shows that polyetheretherketon with glass fibre gave the most displacement and energy absorption at 1.325 mm and 3.572 kJ respectively. As to conclude, all three materials show that they are susceptible of collapsing according to the origami pattern infused to the wall.

INTRODUCTION

Nowadays, research on thin-walled structures as an energy absorbent has been conducted in various industries, especially in the automotive industry. Many parts of the automotive structures were made from thin-walled such as doors, roof, crash box and others.

These thin-walled automotive parts are expected to dissipate the impact energy in a controlled manner as to enhance the automotive crashworthiness. A vast amount of research has been done on tubes structures with circular and rectangular shapes that received most attention. The energy absorption characteristics of the tube structures are focused on the cross-section, shape and material.

Through significant amount of studies on the axial impact of the thin-wall structure, it is found that the energy dissipation is controlled by three main sources. The three main sources are folding along the stationary plastic hinge lines, propagation of travelling plastic hinge lines and localized in-plane stretching in the toroidal surface [1, 11] It is also found that an impact with progressive and stable collapse pattern would give high energy absorption. However, the regular symmetric folding process is usually disturbed by premature bending as a result of poor design thin-wall structure [3].

To overcome the premature bending, a pre-folded origami pattern is applied to the thin-wall structure. Through this, the pre-folded pattern would guide the structure to collapse according to the pattern progressively [4]. It is also identified that by altering the origami pattern, the collapse mode and energy absorption would also change. Diamond origami pattern which is placed the corners of a square thin-walled structure and equilateral trapezoid origami pattern have been applied in previous research [3, 8]. The previous studies concluded that smooth crushing force history is obtained and the crushing of the structure follows the pre-folded origami pattern. Other preliminary study [7] is the linear static analysis of unpattern and diamond pattern mild steel thin-wall. It shows that the pattern thin-walled able to withstand up to 65 MPa stress compared to 4.73MPa for unpattern thin-walled.

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In crashworthy structural application, metals such as mild steel are mainly used due to their plastic deformation characteristics compared to polymer composite materials. This is due to the fact that the polymer composite materials such as glass fibre reinforced polyester and polyester resins are inherently brittle. Nevertheless, researchers have shown experimentally that polymer composite materials absorb more energy per unit mass of material if they are properly designed. Carbon fibre/PEEK composite material displayed the highest specific energy of approximately 200 kJ/kg [6].

Apart from microstructural variables and the fabrication conditions of the polymer composite material, the tube geometry is also one of the variables that influence the energy absorption. Therefore, applicability of the origami pattern infused thin-wall structure with the polymer composite as the material is tested. The axial crushing is done using linear static analysis in order to imitate the quasi-static testing. This initial analysis is done to compare the collapse pattern, the displacement and the maximum stress experienced by the polymer composite and metal. The chosen polymer composite materials are PEEK with carbon fibre filled and PEEK with glass fibre filled while the metal material is mild steel.

**MATERIALS AND METHODS**

**Geometric Modelling:**

Generating a geometric model is the first step to accomplish before the analysis could be done in computer aided engineering (CAE) software. 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. The dimension of the thin-walled structure is kept 372mm for its perimeter and 300 mm for its length, while the thickness is 2mm.

The origami thin-walled structure model is done based on Equation 1 derived by J.Ma and Z. You [3]. This origami shape is chosen to be the initial shape as it is the collapse pattern of any square thin-walled structure that undergoes impact analysis [1].

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

Where, \(c\) is the corner width and \(l\) is the module length. The calculated \(\theta\) gives the dihedral angle when the origami thin wall is formed. The cross-section of the thin-walled structure is square, the corner width, \(c\), is chosen to be 20mm and the total length is divided into 5 module which gives a total of 60mm module length, \(l\). The dihedral angle for each module of the crash-box is obtained as 147.94°. Figure 2 shows the origami pattern module model and Figure 3 shows the origami pattern crash-box model.

**Finite Element Model:**

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.

**Material Properties:**

The applied material properties tabulated in in Table 1 (MatWeb, n.d.). The material applied is linear elastic.
Table 1: Material properties for the thin-walled structure.

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson ratio</th>
<th>Density (g/cc)</th>
<th>Tensile strength, Yield (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>200</td>
<td>0.3</td>
<td>7.85</td>
<td>478.32</td>
</tr>
<tr>
<td>PEEK + glass fibre filled</td>
<td>3.86 - 25.5</td>
<td>0.34 - 0.45</td>
<td>1.30 - 1.84</td>
<td>91 - 220</td>
</tr>
<tr>
<td>PEEK + carbon fibre filled</td>
<td>1.00 - 1.38</td>
<td>0.30 - 0.44</td>
<td>1.30 - 1.75</td>
<td>86.2 - 2070</td>
</tr>
</tbody>
</table>

Boundary Conditions and Loading:

The axial crushing analysis is to mimic the quasi-static testing. Therefore the thin-walled structure is constrained at x, y and z degree of freedom at its base. The load case applied to the thin-walled structure is a distributed axial load in the direction of −z axis and the value of the impact load (P_m) is 2696N. The load value is obtained from the initial impact velocity that is set to be 15.6 m/s with an impacting mass of 275 kg [9]. The complete meshed model with loading and boundary condition is shown in Figure 4.

Fig. 4: The finite element model of the origami pattern thin-walled structure.

Processing:

After completing all preparation for the linear static analysis, Radioss solver is used to run the analysis. From the analysis, results of displacement (δ) will be used to obtain the absorbed energy, E (kJ) according to Equation 2 derived by B. Bartczak, et al. [2],

$$P_m = \frac{E}{\delta}$$

Eq. 2

Results:

The obtained results as tabulated in Table 2 shows that glass fibre/PEEK has the most displacement at 1.325 mm when the same load is applied, compared to carbon fibre/PEEK that has only 0.2801 mm displacement. While the mild steel has the least minimum of displacement at 0.09355 mm. Mild steel has higher von Mises value at 65.02 MPa while carbon fibre/PEEK has 62.94 MPa and glass fibre/PEEK has 62.08. The calculated E for glass fibre/PEEK has the highest energy absorption at 3.572 kJ compared to other composite and mild steel. The displacements and stress contours of all analyzed materials are shown in Figure 5 and 6 while Figure 7 displaying the origami pattern thin-walled structure before and after deformation for all materials tested. All three materials show that they are susceptible of collapsing according to the origami pattern infused to the wall.
Fig. 5: Displacement contours of origami pattern thin-walled structure with materials; (a) Mild steel, (b) Carbon fibre/PEEK, (c) Glass fibre/PEEK.

Fig. 6: Stress contours of origami pattern thin-walled structure with materials; (a) Mild steel, (b) Carbon fibre/PEEK, (c) Glass fibre/PEEK.

Table 2: Obtained results of the origami pattern thin-walled structure with mild steel, carbon fibre/PEEK and glass fibre/PEEK.

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum Displacement (mm)</th>
<th>Maximum Von Misses (MPa)</th>
<th>Energy Absorption (kJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel</td>
<td>0.09355</td>
<td>65.02</td>
<td>0.252</td>
</tr>
<tr>
<td>PEEK + carbon fibre filled</td>
<td>0.2901</td>
<td>62.94</td>
<td>0.755</td>
</tr>
<tr>
<td>PEEK + glass fibre filled</td>
<td>1.325</td>
<td>62.08</td>
<td>3.572</td>
</tr>
</tbody>
</table>

Fig. 7: Origami pattern thin-walled structure deformation (a) before (b) after for all materials tested.

Discussion:
Through the performed analysis, the results show that the carbon fibre/PEEK thin-wall structure and glass fibre/PEEK thin-wall structure both have maximum Von Misses stress that is below their material yield stress value. This proves that there is no fracture or splaying occurrences on the origami pattern thin-walled structure. In addition, mild steel structure only has about 3.2 to 4.52% higher maximum stress compared to other materials which shows the capability of these two composite to withstand stresses using pattern structure. On the other hand, the high displacement experienced by glass fibre/PEEK thin-wall structure is probably due to the low value of its modulus of elasticity in comparison to the other materials used which lead to highest $E$ value.

Conclusion:
The analysis for the origami pattern thin-walled structure is performed using three types of materials and the mild steel material acts as the benchmark. Through the analysis, it is found that the origami pattern thin-
walled structure using carbon fibre/PEEK material and glass fiber/PEEK material are susceptible of being crushed along the origami pattern bending lines. This finding shows glass fiber/PEEK material proves that polymer composite material is able to replace mild steel as candidate for lightweight materials with the capability to absorbed more energy and withstand high impact load.

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