The thin-walled tubes with origami pattern under axial loading

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Abstract
Thin-walled tubular structures are widely used as energy absorbing devices. However, when they are subjected to axial crushing, they usually exhibit a high initial peak force and large fluctuation in the load-displacement curve. Introducing patterns to the tubes can improve their energy absorption characteristics. In the present study, a new origami pattern is proposed and introduced to the thin-walled tubes to minimize the initial peak and the subsequent fluctuation. Tubes the origami pattern are investigated by finite element analysis. Numerical results show that compared with the conventional tube, the patterned tubes have a lower initial peak force and more uniform crushing load.

Keywords - energy absorption, axial crushing, patterned tubes, numerical simulation

1 Introduction
Tubular structures are widely used as energy absorbing devices, which dissipate kinetic energy through plastic deformation. Among all the forms of deformation, the progressive collapse of tubes under axial loading has been studied extensively. Because of its long stroke distance and high material utilization, this deformation form is favorable for energy absorption. One disadvantage of progressive collapse is that its crushing force is not uniform, especially the existence of a high initial peak force.

Introducing patterns to the tube can effectively improve its energy absorption characteristics. Singace and El-Sobky [1] experimentally studied the axial crushing of circular tube with patterned corrugations. Song et al. [2] proposed an origami pattern for tubes under axial loading. Recently, tubes with topological pattern have been investigated [3, 4]. It was shown that such pattern could significantly reduce the tube’s weight while retaining its energy absorption capacity, therefore higher specific energy absorption could be achieved.

To make the pattern effective, its depth must be large enough so that the tube will collapse in the mode prescribed by the pattern [5]. There was a critical dihedral angle for the origami pattern [2]. If the patterned tube had a dihedral angle larger than the critical value, its collapse did not follow the pattern. In the present study, a new origami pattern for thin-walled square tubes under axial loading is proposed.

2 Pattern Description
The pattern consists of basic folding element shown in Fig. 1(a), in which the solid line represents the hill fold and the dash line presents the valley fold, and the parallelograms in the element are identical. A multi-layered square patterned tube is shown in Fig. 1.

The patterned tubes and the corresponding conventional square tube considered in the present study are listed in Table 1. All the tubes have $L=120\text{mm}$, $s=42\text{mm}$, and wall thickness $t=2.1\text{mm}$. For the patterned tube, the number of layers, $N$ ranges from 3 to 5, and the dihedral angle, $\theta$ ranges from $160^\circ$ to $120^\circ$. The notation SQU-$N-\theta$ is adopted for the patterned tube. For the conventional tube, notation SQU-180 is used.

Table 1 Initial peak force and mean crushing force of the conventional tube and the patterned tubes

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N$</th>
<th>$\theta$ (°)</th>
<th>Initial peak force (kN)</th>
<th>Mean crushing force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SQU-180</td>
<td>-</td>
<td>180</td>
<td>116.97</td>
<td>55.78</td>
</tr>
<tr>
<td>SQU-150-3</td>
<td>3</td>
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<td>41.88</td>
<td>22.00</td>
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<tr>
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<td>3</td>
<td>120</td>
<td>17.83</td>
<td>13.23</td>
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<td>160</td>
<td>57.63</td>
<td>45.67</td>
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<td>4</td>
<td>150</td>
<td>45.27</td>
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<td>140</td>
<td>35.09</td>
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<td>130</td>
<td>27.68</td>
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<tr>
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</tr>
<tr>
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<td>120</td>
<td>26.37</td>
<td>25.43</td>
</tr>
</tbody>
</table>

3 FE modelling
Abaqus/Explicit 6.10 was adopted for the simulation. Figure 2 shows the sketch of a tube under axial crushing. The tube was meshed with 3-node shell element, S3R with 7 integration points through the thickness. The global element size was 1mm. No imperfection was introduced to the patterned tube. Both the top plate and the bottom plate were modelled as rigid body.

The tube was put on a bottom plate, and a top plate, initially contacted with the tube, moved downward to crush the tube. No extra clamping or holding apparatus was used to constrain the tube’s ends. Quasi-static crushing process was assumed.

The material of tube was annealed mild steel, with the mechanical properties as follows: density $\rho=7332.3\text{kg/m}^3$, Young’s modulus $E=190.5\text{GPa}$, Poisson’s ratio $\nu=0.3$, yield
stress $\sigma_y=287.9\text{MPa}$ and ultimate stress $\sigma_u=506.9\text{MPa}$. The strain hardening effect was approximated by using power law hardening model with the strain hardening exponent being 0.22. No strain rate effect was considered.

4 Results and discussion

All the patterned tubes followed the pattern. Figure 3 shows the load-displacement ($P-\delta$) curve of conventional tube and patterned tubes SQU-160-4 to SQU-120-4. Figure 4 shows the deformed profiles of conventional tube and patterned tube SQU-160 at different stages of crushing process. Table 1 shows the initial peak force and mean crushing force of each tube. The mean crushing force is calculated as

$$P_m = E_a \int_0^{\delta_e} \frac{Pd\delta}{\delta_e}$$

in which $\delta_e$ is 90mm for each tube, and $E_a$ is the energy absorption of the tube up to $\delta_e$.

Figure 5 shows load-displacement curves of patterned tubes: (a) SQU-150-3, SQU-150-4 and SQU-150-5, (b) SQU-120-3, SQU-120-4 and SQU-120-5.

From Fig. 3 and Table 1, it is concluded that the pattern tube has much lower initial peak force than the conventional tube, and the initial peak force decreases as $\theta$ decreases. The mean crushing force of the patterned tube also decreases with the decrease of $\theta$, and it is lower than that of the conventional tube. However, the crushing force of the patterned tube is more stable during the crushing process.

5 Conclusions

An origami pattern has been proposed to tubes under axial loading. Numerical results showed that the initial peak force and make the crushing process more stable has been reduced.

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References