Analysis of the energy absorption of aluminium tubes for crash boxes

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Objectives

- Introduction to light weight energy absorbers
- Aluminum 6060 metallic tubes as energy absorbers
- Experimental setup
  - Quasi-Static tests
  - Dynamic impact tests
- Identifying crashworthiness parameters
- Experimental observations
- Plastic collapse mechanism and mathematical modeling (Literature)
- Comparison of experimental results with literature
- Conclusion and future prospects
Light weight energy absorbers

In the recent years, much importance was given to light weight vehicle design to improve environment-friendliness and fuel efficiency.

Apart from this, it is also important for the vehicles to meet the collision safety requirements.

Most of vehicle accidents were the front end collisions due to driver inattention care should be taken in designing (crash box) energy absorbers.

An energy absorber is a system which absorbs impact kinetic energy totally or partially by its deformation.
Light weight energy absorbers

- Alexander in 1960 was the first person who conducted the axial crushing on circular metallic shells.

- In our research,
  - The tube cross-section is fixed to circular.
  - Initially ‘Aluminum 6060-T66’ material was chosen, later its hardness was increased with ‘T6’ solution heat treatment.
  - Experiments was conducted on over 70 tubes with different dimensions, where different failure mechanism’s are plotted.
  - A lot of theoretical study was done on failure mechanism’s of axially crushed tubes.
  - At the end the experimental results are compared with theoretical results.
Aluminum 6060 (AlMgSi0.5 alloy)

- The Aluminum 6060 tubes are received in T66 state, with Vickers hardness of 77.74 (kg/mm$^2$).
- In order to investigate the higher hardness, the received tubes are solution heat treated under 490°C for 2 hours and artificially aged from 2 to 25 hours under 160°C.

Variations of Vickers hardness in Al-6060 with respect to time

<table>
<thead>
<tr>
<th>Hours (h)</th>
<th>Vickers hardness (kg/mm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>52.98</td>
</tr>
<tr>
<td>4</td>
<td>63.92</td>
</tr>
<tr>
<td>5.5</td>
<td>73.2</td>
</tr>
<tr>
<td>7</td>
<td>77.76</td>
</tr>
<tr>
<td>8</td>
<td>78.78</td>
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<tr>
<td>9</td>
<td>82.34</td>
</tr>
<tr>
<td>10</td>
<td>86.04</td>
</tr>
<tr>
<td>12</td>
<td>87.34</td>
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<tr>
<td>14</td>
<td>88.78</td>
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<tr>
<td>16</td>
<td>96.66</td>
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<td>18</td>
<td>95.54</td>
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<td>19.5</td>
<td>90.28</td>
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<tr>
<td>21</td>
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<td>22</td>
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<tr>
<td>24</td>
<td>88.16</td>
</tr>
<tr>
<td>25</td>
<td>86.98</td>
</tr>
</tbody>
</table>
Experimental Setup

**Quasi-Static**
- Moving plate
- Sample
- Fixed plate

- Capacity - 250 kN
- Velocity - 10 mm/min

**Dynamic-Impact**
- Concrete block
- Sample
- Sled with accelerometer

- Velocity - 20 m/sec
Crashworthiness parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{max}}$</td>
<td>Maximum force</td>
</tr>
<tr>
<td>$F_{\text{avg}}$</td>
<td>Average force</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Initial Displacement</td>
</tr>
<tr>
<td>$D_f$</td>
<td>Final Displacement</td>
</tr>
<tr>
<td>$L$</td>
<td>Total length of the tube</td>
</tr>
<tr>
<td>$m$</td>
<td>Total mass of the tube</td>
</tr>
</tbody>
</table>

**Force-Displacement graph of crushed tubes**

- **Energy absorption**, $E_A = \int_{D_i}^{D_f} F_{\text{avg}} \, dD = F_{\text{avg}} (D_f - D_i)$ in ‘Joule’

- **Crush Strain**, $CS = \frac{D_f - D_i}{L}$

- **Specific energy absorption**, $SE_A = \frac{E_A}{m \times CS}$ in ‘Joule/gram’

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Quasi-static experimental observations
Plastic collapse mechanism

2-D view of tube collapse

\[ P = \text{Loading} \]
\[ D = \text{Mean diameter of tube} \]
\[ t_0 = \text{Thickness of tube} \]
\[ \alpha = \text{Arm bending angle} \]

Collapse mechanism of Axi-symmetric folded tubes under quasi-static testing
Mathematical modeling

\[ b \]

\[ (1-m)h \]

\[ mh \]

\[ a \]

\[ c \]

\[ b \]

\[ h \]

‘\( h \)’ is half the fold length

‘\( m \)’ is eccentricity factor, equal to ratio of outside fold length to the total fold length

2-D view of tube collapse

**Work done in plastic bending**

Is equal to area covered by the arm ‘ab’, ‘bc’ (fig.) during 0° to 90° rotation which is given by,

\[
W_b = 2\pi M_p \int_0^{\pi/2} \left( D + 2mh \sin \theta \right) d\theta + 2\pi M_p \int_0^{\pi/2} \left( D - 2(1-m)h \sin \theta \right) d\theta
\]

\[
W_b = 2\pi M_p (\pi D + 2h - 4mh)
\]

**Eq. 1**

\( M_p \) is plastic moment of bending given by, \( M_p = k\sigma_{0.2} t_0^2 \)

\( \sigma_{0.2} \) is yield stress of the tube

Where \( k \) is a constant whose value is in the analysis taken as \( \frac{1}{2\sqrt{3}} \) for Von-Mises criterion
Mathematical modeling

'\( \epsilon_1 \)' is strain caused in the outside fold

'\( \epsilon_2 \)' is strain caused in the inside fold

Work done during circumference deformation
Is the work done by the strains in the arm's 'ab', 'bc' (fig.) during 0° to 90° rotation.

\[
W_c = \int \overline{W_c} \, dt = \int_0^{mh} 2\pi \sigma_{0.2} \, t_0 \epsilon_1 \, dA_1 + \int_0^{(1-m)h} 2\pi \sigma_{0.2} \, t_0 \epsilon_2 \, dA_2
\]

\[
dA_1 = \pi(D - 2y_1 \sin \theta) \, dy_1, \quad \overline{\epsilon_1} = \frac{d\epsilon_1}{dt} = \frac{d}{dt} \left( \frac{\pi(D-2y_1 \sin \theta) - \pi D}{\pi D} \right)
\]

\[
dA_2 = \pi(D - 2y_2 \sin \theta) \, dy_2, \quad \overline{\epsilon_2} = \frac{d\epsilon_2}{dt} = \frac{d}{dt} \left( \frac{\pi(D-2y_2 \sin \theta) - \pi D}{\pi D} \right)
\]

\[
W_c = \int \overline{W_c} \, dt = 2\pi \sigma_{0.2} \, t_0 h^2 \left[ m^2 \left( 1 - \frac{2mh}{3D} \right) + (1 - m)^2 \left( 1 + \frac{2(1-m)h}{3D} \right) \right]
\]

Eq. 2
Comparison of experimental results with theory

- Total energy absorbed during one full fold formation = $W_t = 2 \times (W_b + W_c)$  
  \[ \text{Eq. 3} \]

- Average force = $F_{avg} = \frac{W_t}{2h}$  
  \[ \text{Eq. 4} \]

- Eccentricity factor 'm' can be obtained by, $\frac{\partial F_{avg}}{\partial m} = 0; \ 0.5 + \frac{k_{t_0}}{h}$  
  \[ \text{Eq. 5} \]

- Length of the arm 'h' can be obtained by, $\frac{\partial F_{avg}}{\partial h} = 0; \ \sqrt{\pi kD t_0} \approx 0.952 \sqrt{D t_0}$  
  \[ \text{Eq. 6} \]

### Average forces of axi-symmetric folded tubes from Equations vs. Experiments

<table>
<thead>
<tr>
<th>Type</th>
<th>D (mm)</th>
<th>$t_0$ (mm)</th>
<th>$D/t_0$</th>
<th>m (Eq 6)</th>
<th>h (Eq 5)</th>
<th>$W_b$ (Eq 2) (J)</th>
<th>$W_c$ (Eq 3) (J)</th>
<th>$W_t$ (Eq 1) (J)</th>
<th>$F_{avg}$ (Eq 4) (KN)</th>
<th>$F_{avg}$ (exp.) (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T66</td>
<td>60</td>
<td>2</td>
<td>30</td>
<td>0.555</td>
<td>10.42</td>
<td>269</td>
<td>135</td>
<td>404</td>
<td>38.8</td>
<td>39.4</td>
</tr>
<tr>
<td>T6</td>
<td>60</td>
<td>2</td>
<td>30</td>
<td>0.555</td>
<td>10.42</td>
<td>302</td>
<td>151</td>
<td>453</td>
<td>43.4</td>
<td>43.3</td>
</tr>
<tr>
<td>T66</td>
<td>40</td>
<td>1.5</td>
<td>26.66</td>
<td>0.558</td>
<td>7.37</td>
<td>101</td>
<td>50</td>
<td>151</td>
<td>20.4</td>
<td>19.3</td>
</tr>
<tr>
<td>T6</td>
<td>40</td>
<td>1.5</td>
<td>26.66</td>
<td>0.558</td>
<td>7.37</td>
<td>113</td>
<td>57</td>
<td>170</td>
<td>23</td>
<td>20.2</td>
</tr>
</tbody>
</table>

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Conclusion

- Like T66 tubes, the hardened T6 tubes also crushed and received high energy absorption.
- Axi-symmetric mode of crushing is considered to be the best stable crushing mode.
- In order to design a good crash box, ‘failure mechanism chart’ is helpful in predicting the length, diameter, and thickness of the tube.
- As the theoretical results are in good agreement with experimental results, it is possible to calculate the ‘mean force’ by substituting tube’s diameter and thickness in the theoretical equations.

Future Prospects

- In order to increase crashworthiness in term of Energy absorption per unit mass, tubes with materials like fibre reinforced plastic’s (FRP’s) or compound(FRP wrapped metallic) tubes has to be studied extensively for their capabilities due to the fact that they are lighter and stronger.
- There is also a necessity for Finite Element (FE) simulation’s, as they reduce the time and cost of experiments, materials etc.,
Thank you for your attention