Quasi-static and dynamic axial crushing of circular and square stainless steel tubes

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Abstract

Twenty-five quasi-static and forty-three dynamic axial crushing tests have been performed on square and circular stainless steel type 304 specimens in order to investigate the transitions between dynamic progressive buckling and global bending of thin-walled tubes. The columns consisted of three different circular (mean diameter/thickness, \(2R/H = 7.5, 22, 47\)) and three different square (mean width/thickness, \(C/H = 7.7, 24, 42\)) cross-sections, which are representative of ‘thick’, ‘intermediate’ and ‘thin’ shells, and have a range of different lengths, \(L\), \((3.38 \leq L/2R \leq 15.45\) and \(3.37 \leq L/C \leq 20.8\)) that encompass the two failure modes. Standard collapse modes were identified for the structures and the associated energy absorbing characteristics have been examined and compared with previous studies on mild steel tubes. Empirical formulae for the critical slenderness ratios for the transition between modes are suggested and the material properties of the stainless steels obtained by standard static and dynamic tensile tests are also reported.

1 Introduction

Thin-walled sections are often used as primary energy absorbing members for various transportation systems because of their efficiency and ease of manufacture [1]. The desirable mode of collapse for these tubes is a regular and
controlled manner of deformation, or progressive collapse, in which the material of the entire member is deformed plastically by absorbing a major part of the impact energy. The less efficient Euler mode, or a global or overall bending behaviour, on the other hand, can lead to large deformations with potentially catastrophic consequences. Therefore, it is vital to understand the basic mechanics of behaviour and the transitions between the various response modes in these systems in order to predict the correct response mode for a particular design.

Despite the importance of global buckling, very few systematic studies have been reported in the open literature. In one recent study, Abramowicz and Jones [2] reported on the axial crushing behaviour of thin-walled mild steel square and circular tubes struck by relatively heavy masses travelling up to 12 m/s. In spite of the complex behaviour of the specimens, some empirical relations were obtained for the mode transitions between dynamic progressive buckling and global buckling within the restricted range of the geometrical, material and loading parameters examined.

Despite the favourable mechanical properties of stainless steel, their practical applications in load-bearing structures are scarce [3] due possibly to the lack of test results. Nonetheless, it has been shown in one recent experimental study [4] that stainless steel top-hat sections, with appropriately sized and positioned spot-welds, can absorb significantly more energy than carbon steel structures. Type 304, also designated as 1.4301, belong to a group called ‘austenitic’ or ‘18-8’ steels and have reported mechanical properties similar to high-strength steels, such as a 0.2% proof stress of 310 – 470 MPa and an ultimate tensile stress of 620 – 820 MPa. This particular grade is one of the most familiar and most frequently used alloys in the stainless steel family.

Thus, the aim of this paper is to investigate the energy absorption properties of type 304 stainless steel tubing under both quasi-static and dynamic axial crushing loads and the role that geometrical parameters and impact velocities play on the transition from local, or progressive crushing, to an inelastic global buckling mode for this grade of stainless steel.

2 Experiments

Briefly, the quasi-static tests (≤ 2mm/min) were carried out on a Denison compression machine with a maximum rating of 500 kN and the impact tests were performed on two drop hammer rigs (main rig: tup mass, G < 250 kg, initial velocity, V₁ < 14 m/s and a large rig: G < 1400 kg, V₁ < 8 m/s). In all cases, the specimens were loaded axially by a travelling mass while sitting vertically on an anvil block. The velocity-time history was monitored by: (1) a Dantec Laser Doppler Anemometry (LDA) system and (2) a Kodak 4540 high-speed digital camera with a film speed of 18,000 frames per second (fps). To minimise the number of variable impact parameters, three input energies were selected namely, 4.5, 9 and 18 kJ, which were based on the quasi-static ‘bottoming out’ energies of the various cross-sections. These energies were attained by a combination of different striking masses and impact velocities.
Table 1: Circular tubes

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>2R (mm)</th>
<th>H (mm)</th>
<th>2R/H</th>
<th>ϕ</th>
<th>η</th>
<th>P_{mx} (kN)</th>
<th>P_{ps} (kN)</th>
<th>P_{md} (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QC</td>
<td>22.4</td>
<td>3.00</td>
<td>7.5</td>
<td>0.54</td>
<td>0.70</td>
<td>101.03</td>
<td>129.2</td>
<td>133.4</td>
</tr>
<tr>
<td>SC</td>
<td>49.0</td>
<td>2.19</td>
<td>22.4</td>
<td>0.18</td>
<td>0.40</td>
<td>100.86</td>
<td>177.28</td>
<td>110.2</td>
</tr>
<tr>
<td>RC</td>
<td>75.0</td>
<td>1.60</td>
<td>46.9</td>
<td>0.09</td>
<td>0.28</td>
<td>57.01</td>
<td>137.12</td>
<td>64.0</td>
</tr>
</tbody>
</table>

ϕ – solidity ratio, η – structural effectiveness (Equation 9.21 [1], Alexander solution), P_{mx} – average mean static load, P_{ps} – average peak static load, P_{md} – dynamic mean load

Table 2: Square tubes

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>C (mm)</th>
<th>H (mm)</th>
<th>C/H</th>
<th>ϕ</th>
<th>η</th>
<th>P_{mx} (kN)</th>
<th>P_{ps} (kN)</th>
<th>P_{md} (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QS</td>
<td>22.3</td>
<td>2.90</td>
<td>7.7</td>
<td>0.52</td>
<td>0.84</td>
<td>229.68</td>
<td>273.9</td>
<td>271.9</td>
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<tr>
<td>SS</td>
<td>48.0</td>
<td>2.02</td>
<td>23.8</td>
<td>0.17</td>
<td>0.39</td>
<td>94.10</td>
<td>218.5</td>
<td>104.9</td>
</tr>
<tr>
<td>RS</td>
<td>78.4</td>
<td>1.85</td>
<td>42.4</td>
<td>0.09</td>
<td>0.27</td>
<td>77.82</td>
<td>197.8</td>
<td>84.6</td>
</tr>
</tbody>
</table>

η – structural effectiveness (Equation 9.44 [1], Wierzbicki and Abramowicz solution)

The specimens are seam-welded austenite stainless steel tubes (grade 304) with circular and square cross-sections, 2R/H = 7.5, 22, 47, and C/H = 7.7, 24, 42 as shown in Tables 1 and 2, respectively. For comparison purposes, the various cross-sections were chosen for their similar 2R/H and C/H ratios.

3 Material properties

The tensile stress-strain relations for three thicknesses of type 304 stainless steel have been determined experimentally over a range of strain rates from $4.7 \times 10^{-4}$ s^{-1} to 144 s^{-1}. The results are consistent for all three thicknesses and Figure 1 shows the engineering stress-strain curves for the 2 mm thick specimens tested at six different strain rates.

The average quasi-static 0.1% and 0.2% proof stresses are 473 MPa and 484 MPa, respectively, when assuming a Young’s modulus, E, of 197 GPa, and the static ultimate tensile strength is 745 MPa. The material exhibits a typical increase in yield stress with strain rate, albeit a very mild one, but a less straightforward strain rate dependency of the ultimate tensile strength (UTS) and the rupture strain. The UTS displays a minimum at a strain rate of approximately 0.047 s^{-1} before increasing and exceeding the quasi-static value at 144 s^{-1}. This dip is approximately 9.6%. Despite being highly ductile at low strain rates (>55%), the ductility of the material also reveals a minimum at the critical strain rate of 0.047s^{-1} (35% - 45%) with the eventual value at 144 s^{-1} not exceeding the quasi-static one. It is thought that the main strengthening mechanism of Type 304 stainless steel at low speed testing at room temperature is the strong strain hardening effect which is due to slippage in the lattice structure of austenite (face-centred cubic), which increases lattice resistance [5].
In conclusion, the current batch of 304 stainless steel has a mild negative strain rate effect on the UTS at low strain rates and a positive effect between 0.047 and 144 s\(^{-1}\), which has the material constants \(D = 6.14 \times 10^5\) s\(^{-1}\) and \(q = 4.077\).

4 Results

In total, 25 quasi-static crushing and 43 axial impact tests have been carried out. The basic collapse mechanism and the principal modes of failure of the stainless steel columns under both loading conditions are typical of these cross-sections, i.e. the columns failed by either global bending or systematic progressive folding with a few specimens exhibiting a mixed local-global mode. The results compare favourably with the experimental observations of Abramowicz and Jones [2, 6-8] on mild steel columns. Tearing is detected in most square sections and the specimens appear to be more prone to tearing for dynamic loads, which is consistent with the tensile test findings that ductility tends to decrease with increasing strain rate [9]. The collapse profiles of selected circular and square tubes are shown in Figures 2 and 3, with increasing pre-test lengths from left to right.

4.1 Failure modes

Three principal modes of failure are distinguished for the circular columns: axisymmetric (A), also known as concertina or extensional, diamond mode (D) and overall bending (OB). The majority of the globally bent specimens failed at the middle with three specimens collapsing in a location slightly above the middle region. Regular progressive collapse, on the other hand, was initiated at either end with the formation of an axisymmetric wrinkle followed by the diamond pattern of which the number of corners, \(N\), appears to be dictated by the \(2R/H\) ratio: two for \(2R/H = 7.5\) and 22 and three for \(2R/H = 47\). No tearing was
observed in the circular tubes, which suggests that the welding during manufacture of the columns was sound and that the material is ductile even when loaded dynamically. Three modes of failure are also identified for the square tubes: symmetric (S), extensional (E) and overall bending (OB). Despite having similar aspect ratios to the circular tubes, the square tubes tended to collapse progressively with the exception of three specimens which responded globally.

As with the circular tubes, the fold pattern is dictated by the size of the cross-section: regular symmetric lobes for the ‘thin’ and ‘intermediate’ tubes and an extensional mode for the ‘thick’ boxes. By contrast, the first lobes, however, are initiated at different positions along the length, including the ends, the middle or 2 inches (50.8 mm) above the bottom. Scattered tearing was observed at the corners of many of the square columns, although, elsewhere along the tube, the material is sufficiently ductile to allow for the formation of the folds without any tearing.

Figure 2: Quasi-static collapse profiles of circular stainless steel sections

Figure 3: Quasi-static collapse profiles of square stainless steel sections
4.2 Transition from progressive buckling to global bending

The effect of specimen length on the modes of deformation for the circular and square tubes subjected to quasi-static and dynamic axial loadings is summarised in Figures 4 (a) and (b), respectively. As anticipated, the longer the length, the more susceptible is a tube to global bending due to the inability of the lateral inertia to stabilise the crushing process [2]. One transition line separates the region of progressive collapse from the overall bending region in each graph as the tubes collapse mainly in these two modes.

The best-fit curves for the critical length-to-width aspect ratio resulting in overall bending for the present set of quasi-static test results are

\[ \left( \frac{L}{2R} \right)_{cr} = 4e^{0.0138(2R/H)} \]

for the circular columns and

\[ \left( \frac{L}{C} \right)_{cr} = 3.5e^{0.0399(C/H)} \]

for the square columns.

The two proposed equations give significantly higher critical values of L/2R or L/C, particularly in the case of the square columns, than those established by Abramowicz and Jones [2], due mainly to the significantly higher yield and ultimate tensile stresses of the stainless steel [10]. For example, when \( 2R/H = 10 \), \( (L/2R)_{cr} = 3.65 \) in ref [2] for static loading, while here \( (L/2R)_{cr} = 4.59 \); when \( C/H = 10 \), \( (L/C)_{cr} = 3.74 \) in ref [2], while Equation (2) here predicts \( (L/C)_{cr} = 5.22 \). However, the empirical equation proposed by Abramowicz and Jones [2] for the mild steel circular tubes would intersect the present empirical results for stainless steel at \( 2R/H = 45 \).

For the dynamic loading case, these equations are

\[ \left( \frac{L}{2R} \right)_{cr} = 4e^{0.0266(2R/H)} \]

for the circular columns and

\[ \left( \frac{L}{C} \right)_{cr} = 4e^{0.0631(C/H)} \]

for the square columns.

In the case of the widest square tubes, no transition from progressive buckling to overall bending has been observed for lengths up to \( L/C = 20.4 \). When comparing these curves, the critical L/2R or L/C ratio for both the circular and square cross-sections is much higher than in the quasi-static loading condition. For example, at \( 2R/H = 25 \), \( (L/2R)_{cr,a} = 5.65 \), while \( (L/2R)_{cr,d} = 7.78 \), a 38% increase, and at \( C/H = 25 \), \( (L/C)_{cr,a} = 9.49 \) while \( (L/2R)_{cr,d} = 19.37 \), a 104% increase.
4.3 Mean crushing loads

The variations of dynamic to static mean crushing force ratios with impact velocity for the circular and square columns are shown in Figure 5. The mean load, \( \bar{P}_m \), is defined as the total input energy, i.e. area under the load-displacement curve obtained by differentiating and integrating the LDA’s velocity with time respectively, divided by the permanent crushing distance of the specimen. Only progressively collapsed specimens are considered and it
must be noted that the majority of the circular tubes deformed in a mixed mode of an axisymmetric wrinkle followed by the diamond pattern. Despite the scatter, the dynamic mean load appears to increase with increasing initial velocity for a given kinetic energy. The increase in mean loads for the circular and square columns is between 9 and 32%, which is partly due to the strain rate effect and partly due to the inertia effect.

For comparison, the theoretical predictions from Reference [1] are also plotted. The strain-rate parameters at the ultimate tensile stress of $D = 6.14 \times 10^5$ s$^{-1}$ and $q = 4.077$ are quoted since the average strain experienced by the circular shell is 12% which has an associated plastic flow stress similar to the UTS.

Figure 5: Variation of mean dynamic to static crushing force ratios with impact velocity for (a) circular and (b) square stainless steel columns
Despite being developed for the axisymmetric mode of crushing, Equation (9.36) from Reference [1] gives good agreement with the present mixed-mode experimental results in Figure 5(a), in particular for the two larger cross-sections. The theoretical predictions from Reference [1] (Equation (9.50)) for the mean axial crushing loads of the square tubes agree reasonably well with the corresponding dynamic test results as shown in Figure 5 (b). Significantly more scatter is observed in this group, although the comparatively larger number of tests performed on square tubes compared to circular tubes may have exaggerated this effect.

5 Conclusions

Preliminary experimental results on stainless steel thin-walled sections crushed axially with impact velocities up to 13.5 m/s are reported. The circular and square sections responded by either stable progressive buckling that is typical of these sections and/ or global bending. Deformation maps have been constructed and critical length-to-width ratios have been proposed to allow the prediction of the collapse type for the static and dynamic axial loading of these sections. It transpires that the higher critical transition lengths of the stainless steel tubes for the range of the velocities are due to the considerably higher yield and ultimate tensile stress of the material compared with mild steel, which has similar material hardening characteristics. It was also found that the mean load of the sections increases with impact velocity.

In terms of structural crashworthiness, the stainless steel tubes, particularly the square ones, are found to be good energy absorbers in view of their consistent regular progressive manner of collapse despite the presence of tearing at the corners of most specimens.

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References


