Transition between progressive and global buckling of aluminium extrusions

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Abstract

In order to study the transition between progressive and global buckling of axially loaded aluminium extrusions, a pilot project was carried out using the finite element code LS-DYNA. The primary variables in the numerical study were the local and global slenderness of the extruded members and the impact velocity. For impact velocities below 10 m/s the critical global slenderness at transition was increased when increasing the slenderness of the cross sectional elements. In contrast, the critical global slenderness was decreased when the impact velocity was 20 m/s. The overall response is found to be very dependent on the location of the first lobes.

Introduction

In modern car body design, extruded thin-walled aluminium members are used in crash boxes, bumper beams and space frames. For longitudinal members the energy absorption should take place by extensive folding of the extruded aluminium members. This is a preferable deformation mode as the energy absorption and the dynamic load shortening characteristics of the members can be easily predicted. However, when increasing the length of the members, a mode transition may occur, which may lead to far less efficient energy absorption and transmission of large forces to other parts of the structure. Thus, sufficiently long thin-walled members under axial impact may suffer global buckling rather than progressive buckling.

Relatively short thin-walled aluminium extrusions subjected to axial loading
were found by Langseth et al. [1,2] to fold in a symmetric mode during static testing, while a mixture of modes were found in the dynamic tests. The mean dynamic force was higher than the mean static force for a given displacement. Abramowicz and Jones [3,4] performed static and dynamic tests on steel tubes and found the critical length/width ratio to increase for increasing width/thickness ratios. On the numerical side Karagiozova et al. [5,6] have carried out work on progressive local folding and inertia effects, and found the energy absorption to be both mass and velocity sensitive. Larger energies can be absorbed when increasing the impact velocity and reducing the striking mass. Du Bois and Frank [7] compared tests and simulations on spotwelded mild steel tubes and found that the contact algorithms, operating system and hardware influenced the behaviour and thus the transition between global buckling and progressive folding.

The way the thin-walled extrusions respond to axial impact depends on several factors such as:

- Geometry - length, width and thickness.
- Material properties - elasticity modulus, yield stress and strain hardening.
- Boundary conditions - clamped, pinned or free.
- Impact velocity - strain rate and inertia effects.
- Local and global imperfections - amplitude and shape.

In this study only the influence from geometry and impact velocity has been studied. The critical length/width ratio for a given width/thickness ratio, at which the deformation changes from progressive to global buckling, has been found for different impact velocities.

**Finite Element Model**

**Test programme**

An extensive numerical test programme was carried out to study the response of square thin-walled aluminium extrusions under axial loading, see Figure 1. The variables were the impact velocity of the impactor as well as the length, width and thickness of the extruded members. All other parameters were kept constant or chosen as functions of the variables, see Table 1. As the impact energy was kept constant, the mass of the impactor was adjusted to the chosen impact velocity.
Table 1: Test programme.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>t – thickness [mm]</td>
<td>1.5 - 2.0 - 2.5</td>
</tr>
<tr>
<td>b – width [mm]</td>
<td>40 - 60 – 80</td>
</tr>
<tr>
<td>L – length [mm]</td>
<td>varied</td>
</tr>
<tr>
<td>V₀ – impact velocity [m/s]</td>
<td>5 - 10 – 20</td>
</tr>
<tr>
<td>δ₁ – amplitude local imperfections [mm]</td>
<td>= b/200</td>
</tr>
<tr>
<td>δ₂ – amplitude global imperfections [mm]</td>
<td>= L/1000</td>
</tr>
<tr>
<td>σ₀ – yield stress [MPa]</td>
<td>Constant, see Table 2.</td>
</tr>
<tr>
<td>R, Q₀, C₁ – hardening parameters</td>
<td>Constant, see Table 2.</td>
</tr>
<tr>
<td>λ₁ – wave length, local imperfections</td>
<td>= b</td>
</tr>
<tr>
<td>λ₂ – wave length, global imperfections</td>
<td>= 2L</td>
</tr>
<tr>
<td>Eₖ – kinetic energy of the impactor [Nm]</td>
<td>= 32500</td>
</tr>
</tbody>
</table>

Due to the symmetric collapse modes observed globally and locally, only one-half of the tubes was modelled using a symmetry plane to reduce computational time. The specimens were modelled using Belytschko-Lin-Tsai shell elements with seven integration points through the thickness and one point in the plane. Several simulations were carried out to determine the proper mesh density and an element size of 4 x 4 mm was found sufficient. The impacting mass was modelled as a rigid body using brick elements. At the clamped end all degrees of freedom were fixed while the upper end was unrestrained. The contact between the impacting mass and the specimen was modelled using discrete nodes impacting surface with a friction coefficient of 1.0 to avoid unrealistic lateral movement of the upper end of the specimen. To account for the contact between the lobes during deformation the automatic single surface contact algorithm T13 in LS-DYNA with no friction was used. Both local and global initial imperfections were modelled. For the global imperfections a half sine wave with amplitude δ₂ equal to L/1000, L being the length of the specimen, was used. For the local imperfections a half sine wave over the cross-section, and sine waves with wavelength λ = 2b, b being the width of the specimen, along the extrusion direction were used. The amplitude of the local imperfections was δ₁ = b/200. The chosen amplitudes are based on tolerances given by the extrusion producer for an industrial bar.

In order to give an accurate description of both small and large strains, a multi-exponent hardening rule was used, i.e. LS-DYNA material model 103 [8], see Equation (1).

\[ \sigma = \sigma_0 + \sum_{i=1}^{2} Q_i \left( 1 - \exp \left( -C_i \varepsilon^p \right) \right) \]  (1)
Isotropic elasticity, the von Mises yield criterion, the associated flow rule and isotropic hardening were used. In the analysis typical values for an aluminium alloy AA7003 temper T6 were chosen for the material parameters in Equation (1), see Table 2.

<table>
<thead>
<tr>
<th>$\sigma_0$ [MPa]</th>
<th>$Q_1$ [MPa]</th>
<th>$C_1$ [-]</th>
<th>$Q_2$ [MPa]</th>
<th>$C_2$ [-]</th>
<th>$E$ [GPa]</th>
<th>$\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>276</td>
<td>122.56</td>
<td>13.4</td>
<td>33.10</td>
<td>2037.2</td>
<td>70</td>
<td>0.31</td>
</tr>
</tbody>
</table>

### Results

#### Deformation modes

In the numerical simulations, several different collapse modes were observed. If the first lobe appeared at the lower or upper end, see Figures 2a and 2b, a stable progressive folding mode was often found. However, in some cases a transition from progressive local folding to global bending/collapse was obtained, see Figure 2.
Figures 2d and 2e. If the first lobe appeared near the mid section of the tube, it quickly became unstable and global bending occurred, see Figure 2c.

The force vs. displacement history is a function of the collapse mode as shown in Figures 3, 4, 5 and 6. Be aware that no direct comparison can be made between the different figures as the model parameters are different.

For progressive local folding starting either at the lower or upper end, an initial peak load is always observed followed by oscillations around a mean force, see Figures 3 and 4.

![Figure 3: Force vs. displacement, local folding starting at lower end.](image1)

![Figure 4: Force vs. displacement, local folding starting at upper end.](image2)

![Figure 5: Force vs. displacement, global buckling.](image3)

![Figure 6: Force vs. displacement, transition from local to global buckling.](image4)
In the case of direct global failure as shown in Figure 2c, there is still an initial peak but the force quickly drops to a low constant value, see Figure 5, thus a reduced energy absorption is found. For the specimens with transition from local progressive folding to global collapse the force-displacement history starts off with an initial peak, see Figure 6, followed by some oscillations around a mean value like in the case with progressive folding. However at the instant of global failure there is a distinct drop in the force level, and less energy is absorbed for the subsequent part of the deformation.

Progressive folding vs. global bending

In the following global buckling is defined as the modes shown in Figures 2 c, d and e, i.e. direct global buckling or a combination between progressive and global buckling. Results from the simulations are summarised in Figures 7, 8 and 9.

Abramowicz and Jones [4] found that the critical L/b ratio for quasi-static and dynamic axial crushing of square columns was an exponentially increasing function with respect to the b/t ratio, which was in the range 5-35. In the present

![Figure 7](image1.png)

**Figure 7:** Collapse mode for impact velocity $V_0 = 5$ m/s.

![Figure 8](image2.png)

**Figure 8:** Collapse mode for impact velocity $V_0 = 10$ m/s.

![Figure 9](image3.png)

**Figure 9:** Collapse mode for impact velocity $V_0 = 20$ m/s.
Simulations with $V_0 = 5$ m/s and $V_0 = 10$ m/s the same trends were observed for increasing b/t ratios, see Figure 7 and Figure 8. However, for $V_0 = 20$ m/s a decrease in critical L/b ratio for increasing b/t ratio was found, see Figure 9.

There are several possible reasons for the change in behaviour when increasing the impact velocity to 20 m/s. As found in the present study and also observed by Langseth et al. [1], local buckling is sensitive to the impact velocity. Thus, inertia effects will have an impact on how the local folds starts to develop and how this will interact with global instability. In the simulations with $V_0 = 20$ m/s it was observed that the tubes with high b/t ratio had a tendency to develop lobes simultaneously along the length of the member. This can make the tube more unstable and thus change the interaction between local and global failure compared to low velocity impact. The observed change in behaviour when increasing the impact velocity and the cross sectional slenderness means that a design based on low velocity impact data could be very misleading.

**Force/Energy**

For columns used as energy absorbers in cars it is important that the maximum force does not exceed a given value in order to prevent plastic deformations in other parts of the structure. As can be seen from Figures 10, 12 and 14, an almost linear relationship between maximum force and cross sectional area is found. The maximum force can of course be reduced with the introduction of triggers.

Figures 11, 13 and 15 show the structural efficiency, Equation (2), as a function of the solidity ratio, Equation (3). The datapoints in the figures correspond to an axial shortening of 60-70% of the initial length of the members.

$$\eta = \frac{P_m}{A\sigma_y} \quad (2)$$

$$\phi = \frac{A}{A_w} = \frac{4bt}{b^2} = 4\left(\frac{t}{b}\right) \quad (3)$$

The amount of absorbed energy is dependent on the collapse mode. In general more energy is absorbed in progressive local folding than in global bending even if some scatter is observed. In the cases with transition from progressive local folding to global bending, the energy absorption depends on the time for transition. If the transition occurs in the later stages of the axial deformation, almost as much energy as in the case with progressive local folding is absorbed. However, if the transition occurs at an early stage the absorbed energy is significantly reduced. As can be seen from Figures 11, 13 and 15 the difference in structural efficiency between members with progressive buckling and global bending is increased for increasing solidity ratio, i.e. a reduction of the b/t ratio. This is due to the increased tendency of direct global failure for members with high solidity ratio, or low local slenderness parameter b/t.
Figure 10: Max force vs. cross sectional area. \( V_0 = 5 \text{ m/s} \).

Figure 11: Structural efficiency vs. solidity ratio. \( V_0 = 5 \text{ m/s} \).

Figure 12: Max force vs. cross sectional area. \( V_0 = 10 \text{ m/s} \).

Figure 13: Structural efficiency vs. solidity ratio. \( V_0 = 10 \text{ m/s} \).

Figure 14: Max force vs. cross sectional area. \( V_0 = 20 \text{ m/s} \).

Figure 15: Structural efficiency vs. solidity ratio. \( V_0 = 20 \text{ m/s} \).
Conclusion

Based on the numerical study the following main conclusions can be made:

- The response is very dependent on the location of the first lobe.
- The formation of lobes near the mid-section of the members or simultaneously at both the upper and lower ends are unfavourable, as it will increase the probability of global failure.
- An increase in the critical \( L/b \) ratio as a function of the \( b/t \) ratio was found for \( V_0 = 5 \) m/s and \( V_0 = 10 \) m/s. However, a decreasing critical \( L/b \) ratio was found for \( V_0 = 20 \) m/s.
- A linear relationship between peak force and cross sectional area, regardless of progressive buckling or global bending was found.
- The difference in structural efficiency between members with progressive buckling and global bending is increased for increasing solidity ratio, i.e. a less slender cross section.

References