Energy absorption in axially loaded square thin-walled aluminium extrusions

M. Langseth, T. Berstad, O.S. Hopperstad & A.H. Clausen

Department of Structural Engineering, The Norwegian Institute of Technology, N-7034 Trondheim, Norway

ABSTRACT

The energy absorption in axially loaded square thin-walled aluminium extrusions in alloy AA6060 tempers T4 and T6 has been studied experimentally. Both static and dynamic tests have been carried out and the primary variables were the wall thickness and impact velocity. In addition, numerical simulations have been done with LS-DYNA3D and reasonable agreement has been found between the analyses and tests.

INTRODUCTION

One of the main questions which arises when using aluminium in the body structure of a vehicle is its capability to absorb energy during a crash situation. Two types of aluminium body structures are of interest: a sheet unit body and a space frame construction. The sheet concept is based essentially on the same technology as that employed in steel bodies, while the space frame version has extrusions for the main structural members. In the space frame concept, the energy absorption during a crash will normally take place by extensive folding and bending collapse of the extruded members. Compared with commonly used steel qualities, aluminium alloys have reduced yield strength which implies that an aluminium component must be thicker to absorb as much energy as steel. This increased thickness combined with a lower ductility of aluminium compared with steel may increase the risk of material failure during deformation.

Extensive experimental work has been carried out to study the crashworthiness of steel vehicles, and a large amount of data are available in the literature regarding energy absorption in axially loaded square and circular tubes. However, there is only a limited amount of experimental data available for the performance of thin-walled aluminium extrusions. Most of the published work is related to circular tubes and spot- and weld-bonded box sections [1-3].
An experimental study has been completed to increase understanding of the mechanisms controlling the energy absorption in impacted thin-walled aluminium extrusions. Two different tempers of alloy AA6060 have been tested and the primary variables were the wall thickness and impact velocity. Furthermore, numerical simulations have been done with LS-DYNA3D [4] to extend the parameter range.

A summary of the most important findings from the experimental study is given together with a comparison between the analyses and tests.

TEST PROGRAMME AND EXPERIMENTAL SET-UP

The objective of the investigation was to study the energy absorption of square thin-walled aluminium extrusions of alloy AA6060 tempers T4 and T6 subjected to an axial impact, Table 1. Quasi-static tests were also carried out to study the relationship between the dynamic and static behaviour. The specimens were initially assumed to be straight as the out-of-plane deformations of the sidewalls were less than 0.4 mm. However, to study the effect of initial geometrical deformations, some test specimens were prebuckled statically prior to impact testing. The following test identification system was used: T4-h-nX means temper T4, nominal plate thickness h, test No. n, X=S(static) and X=D(dynamic).

As shown in Table 1, the test specimens were clamped at the lower end and were free at the top. The impact tests were carried out by means of a pneumatic accelerator consisting of a reservoir of compressed air and an accelerator tube. During testing a rigid projectile with a mass of 56 kg was fired against an aluminium cover resting on the top of the test specimens. The cover, which had a mass of 0.74 kg, was used to ensure a central impact.
The clamping support was obtained by means of two plates 1 and 2 (Table 1) fixed to a rigid support, and a wooden piece 3 adjusted to the inside periphery of the test specimens.

The projectile was instrumented by strain gauges that were used to measure the interface force between projectile and test specimen. Assuming the projectile and cover as rigid bodies, the displacement of the specimens was calculated by means of double integration of the force-time history after filtering out the high frequency elastic vibrations set up in the projectile and cover during impact. It should be noted that the filtering might reduce the measured peak load somewhat depending on the filter cut-off frequency. Comparing the calculated permanent displacement of the test specimens with that measured on the test specimens after impact, the accuracy of the measurements was estimated to ± 5 %. A more detailed description of the test rig and instrumentation system is given in Ref. [5].

MATERIAL PROPERTIES

The test specimens were made of aluminium alloy AA6060 tempers T4 and T6 which is an Al-Mg-Si-alloy with the following chemical composition (in weight %): Si: 0.44, Fe: 0.22, Cu: 0.003, Mn: 0.16, Mg: 0.48, Cr: 0.02, Zn: 0.01, Ti: 0.007. The profiles were air cooled and stretched to an elongation of 1-2 % after extrusion. Temper T4 was naturally aged at room temperature, whereas temper T6 was aged for 2 hours at 195 °C.

Fig 1 shows typical engineering stress-strain curves for tempers T4 and T6 obtained from tensile tests at a strain rate of approximately 7-10^4 s^-1 together with the most relevant mechanical data. Here: \( \sigma_{0.2} \) is the proof stress, \( \sigma_u \) is the ultimate stress, \( \varepsilon_u \) is the rupture strain obtained using a gauge length of 50 mm and \( E \) is the elastic modulus. In addition, material strain rate testing in tension and torsion were carried out [6], and the effect of strain rate was found to be small (on the order of 5-10%) in the strain rate range tested (10^4 - 300 s^-1).

![Figure 1 Typical stress-strain curves and mechanical properties](image-url)
EXPERIMENTAL RESULTS AND DISCUSSION

Deformation modes
Fig 2a shows typical deformation modes from the static tests carried out. A progressive symmetric deformation mode was observed to be independent of wall thickness and temper. However, the number of lobes formed during deformation was different. Six lobes were found for temper T4 while seven were found for temper T6. This means that the effective crushing distance to form a complete lobe is a function of the hardening properties of the material.

Fig 2b shows typical deformation modes from the dynamic tests. For both tempers buckles could be seen over the entire length of the test specimens with a mode number that was higher than the corresponding static one. However, compared with temper T4, the buckles of temper T6 were hardly visible. For temper T4 the buckles were localized at arbitrary positions and only symmetric modes were found for the 2.5 mm thick tubes, while either symmetric or a combination of symmetric and asymmetric modes were found for the thinner specimens. For temper T6, however, the buckles were always localized at the impacted end of the specimens and symmetric, asymmetric and extensional collapse modes were observed. The extensional deformation modes were always limited to either the first lobe or the first and second lobes from the impacted end.

Fig 3 illustrates the effect of axial impact loading on the prebuckled test specimens. The mode of failure for both tempers tested was symmetric and the axial deformation was increased compared to a test performed on an initially straight tube, Figs 3b and 3c. Furthermore, the number of lobes was the same as for the static tests.

Based on a visual inspection of the static and dynamic test specimens after testing, incipient fracture was observed in the corners of some tubes of
temper T6, while no such behaviour was found for temper T4. However, the incipient fracture seemed to have no influence on the global response.

Static and impact loads

Figs 4 and 5 depict typical measured force-displacement curves for tempers T4 and T6 respectively. The corresponding static curves are plotted for comparison. As seen, the static loading curves are characterized by a high initial peak load followed by an almost repeated pattern, where each peak is associated with the development of a buckle. The dynamic curves have a similar shape to those measured statically. The main difference is related to the first part of the impact where the dynamic load level is significantly higher.

Fig 6 illustrates the effect of prebuckling on the dynamic force-displacement curve. The peak load is reduced and the total axial deformation is increased compared to an initially straight tube. It was found that the magnitude of the peak load could be controlled by varying the amplitude of the initial buckle.

Fig 7 shows a typical ratio between the dynamic and static mean loads $P_{md}$ and $P_{ms}$ as a function of the displacement, impact velocity and initial geometry of the test specimens. For the initially straight specimens, the ratio
is a decaying function with respect to the axial displacement, and when reducing
the impact velocity both the axial displacement and dynamic mean load are
reduced. For the prebuckled specimens (impact velocity $v_i = 16.1$ m/s) an
almost constant ratio with respect to the axial displacement is found and the
mean load is reduced compared with an initially straight tube (impact velocity
$v_i = 15.6$ m/s).

**Energy absorption**
The variation of the impact energy $T$ with respect to the permanent axial
displacement $w_p$ for all test specimens is shown in Fig 8. An almost linear
relationship is found between energy and displacement for temper T4, Fig 8a,
and tests performed with the same impact energy give approximately the
same permanent axial displacement. The latter implies that the difference in
energy absorption between a symmetric and a mixed (sym. and asym.) mode
within the parametric range studied is indistinguishable from a practical point
of view, which is also shown analytically by Abramowicz and Jones [7]. For
temper T6, however, scatter in the measured permanent displacement is found
for parallel tests, especially for the 2.5 mm thick tubes. The reason for this
scatter is assumed to be related to the appearance of extensional modes in
combination with symmetric and asymmetric modes.
Structures under Shock and Impact 407

Discussion

When the projectile impacts the end of an initially straight extrusion, a complex process takes place due to the transfer of kinetic energy from the projectile to the specimen. As long as strain rate effects are of minor importance, the difference between a static and a dynamic test is related to the inertia forces set up at the instant of impact, leading to a quite different deformation behaviour. Looking at the measured force-displacement curves, Figs 4 and 5, the main difference takes place in the beginning of the impact which implies a decaying ratio between the measured dynamic and static mean loads. For axial displacements beyond approximately 150 mm, Fig. 7, the mean load ratio seems to approach a level ranging between 1.3 - 1.6 for the parametric range studied. Winter et al. [2] found approximately the same when impacting close hat-shape die castings (v_i = 8 m/s), while McGregor et al. [1] found that the ratio was less than 1.1 when impacting spot-welded double hat sections (v_i = 12 m/s, M = 69 kg) in alloy AA5754-0.

In the field of structural crashworthiness, it is of interest to control the mean dynamic crushing force to estimate the overall characteristics of the energy absorber (for example decelerations etc.). An initially straight tube in temper T6 shows different permanent axial displacements for the same impact energy, Fig 8b. However, when introducing geometrical imperfections obtained from a static buckling test, Figs 3 and 6, the deformation mode and peak load were controlled as was the energy absorption.

From an energy absorption point of view, a high proof stress \( \sigma_{0.2} \) is preferable. However, by increasing \( \sigma_{0.2} \) the strain hardening will normally be reduced and fracture may take place in the severely strained regions. In the present study, incipient fracture was observed in some of the test specimens of temper T6, while no such behaviour was seen for temper T4.

The static buckling of the tubes takes place at a stress level that corresponds to the inelastic part of the stress-strain curve of the material (assuming a proportionality limit of 0.8\( \sigma_{0.2} \)). The peak load has been calculated using the Stowell theory [8] for plates and compared with the test data results.

Figure 8 Impact energy vs permanent displacement

![Graph showing impact energy vs permanent displacement for Temers T4 and T6.](image-url)
within ± 5% are obtained. Furthermore, the mean static crushing force has been calculated using the model proposed by Abramowicz and Jones [7] for a rigid perfect-plastic material. Using σ₀.2 as yield stress, less than ± 5% difference is achieved between the model and test for temper T6 due to the low hardening modulus. However, the model underestimates the mean crushing force with a factor of 1.6 compared with the test data for temper T4.

NUMERICAL ANALYSIS

The numerical simulations have been carried out using the LS-DYNA3D code. The specimens are modelled using the Belytschko-Lin-Tsay shell element, while the projectile and cover are modelled as rigid bodies. A single surface contact algorithm is employed to take into account the contact between the different lobes during deformation and the contact between the specimen and the rigid cover. No friction is used in the contact. The comparison is shown for a 2.5 mm thick tube of temper T4, which means that only one quarter of the extrusion is modelled due to the symmetric deformation modes observed during testing. No initial geometrical imperfections are modelled. However, to initiate the required deformation mode, a local geometric perturbation is introduced in the sidewalls.

Due to the nonlinear stress-strain curve of aluminium, Fig. 1, a proper description of the strain hardening properties is necessary for a good correlation with test data. In the present analysis a material model is used [9] that takes into account a combination of nonlinear isotropic and kinematic hardening. Using two sets of isotropic and kinematic hardening variables, the material model has the flexibility to both represent the initial buckling phase as well as the phase with large strains during localization of the buckles. The material model seems suitable for large scale finite element analyses and will be vectorized. The input to the material model is the true stress-strain curve obtained from tensile material tests. This means that the data for large strains are extrapolated.

Fig 9a shows a comparison of the computed and measured interface-force between projectile and specimen as a function of the axial displacement. Considering the complexity of the problem, reasonable agreement is found, with the analysis somewhat underpredicting the measured force level. This means, as shown in Fig 9b, that the mean load is underpredicted by approximately 20%. The measured static curve is also plotted, and as expected, the dynamic analysis predicts a mean load that is higher than the measured static one. The reason for the difference between the analysis and test is not quite clear, and is at present subject to further studies. However, it may be due to insufficient modelling of the geometry and material. Geometrical imperfections such as initial out-of-plane deformations as well as variations in the sidewall thickness may influence the behaviour. Furthermore, a proper description of the strain hardening properties at large strains is necessary. At the moment no such material data are available.
CONCLUSIONS

The energy absorption in axially loaded square thin-walled aluminium extrusions in alloy AA6060 tempers T4 and T6 has been studied experimentally and the results can be summarized as follows:

- An almost linear relationship is found between the impact energy and the permanent axial displacement for temper T4 as only symmetric and asymmetric deformation modes are observed. For temper T6, however, scatter in the measured permanent displacement is found for parallel tests due to the appearance of extensional modes in combination with symmetric and asymmetric modes.

- A reduced energy absorption is found when introducing geometrical imperfections obtained from static buckling tests. The peak load is reduced and an almost constant mean load is found with respect to the axial displacement.

- For the same axial displacement a reduced energy absorption is found when reducing the impact velocity.

- For the same axial displacement an impact test absorbs more energy than a corresponding static one. As strain rate effects are of minor importance this is due to inertia effects.

- Only symmetric deformation modes are observed for the static tests, and the number of lobes is a function of the strain hardening.

- The numerical analyses carried with LS-DYNA3D show reasonable agreement with test data.
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REFERENCES


