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An Investigation on Crashworthiness Design of Aluminium Columns with Damage Criteria

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Abstract

This paper presents a crashworthiness design of aluminium columns with damage criteria. A parametric study is performed to study the effect of loading and geometrical parameters. The effect of impact mass, impact velocity, side length, thickness and length of columns are investigated numerically. The numerical analysis carried out by Abaqus software and is compared by literature.

Key words: Crashworthiness, aluminium column, damage criteria, finite element.

Introduction

Various kinds of energy-absorbing systems are being extensively used in many engineering applications such as automobiles and other transport vehicles. Indeed, during an impact event, the energy of the crash and the manner in which the loads are transmitted through the system, are very important points. As a consequence, the axial crushing behavior of thin-walled structures, which are efficient energy absorbers, has been a topic of great interest for many researchers. In designing such structures, maximizing their energy-absorption capability should always be a major objective. As presented in previous researches, there are two approaches to enhance the performance of the multi-cell thin-walled columns: either using advanced materials with high mechanical properties[1,2] or designing optimized wall thickness and cross-sectional dimensions for such columns that can provide the best crash performances[3].

Experimental, theoretical and numerical studies on axial structural collapse have mainly focused on the mode of collapse, the peak force, the mean force and the energy-absorption characteristics[4].

The deformation and damage behaviors of aluminum under crash loading are not well known compared with steel. So in recent years a great amount of research has been performed on this object. Some studies[5] have been done on the crash behavior of circular aluminum tubes undergoing axial compressive loading. In this work, non-linear finite element analysis was carried out to predict the crushing force and fold formation. Meanwhile, some observations are made on the influence of geometrical imperfection and material strain rate. The behavior of thin-walled aluminum extrusions under axial loading conditions in detail, and the combined distortion of extrusions and aluminum foam filler have been done[6]. The failure behavior of transportation vehicles for advanced crashworthiness has been predicted[7]. A design of an aluminum intensive vehicle platform for front impact has been presented[8].

In this study the crashworthiness of aluminum extrusion damage under impact loading is investigated. The influence of geometrical and loading parameters on the impact response is investigated using validated numerical models and results are quantified in terms of important impact response parameters. The research information generated will be useful in developing guidance towards the design of these devices in impact applications.

Material and Methods

Numerical simulation: The numerical simulations were carried out using the finite element software ABAQUS/Explicit. In this simulation, a self-contact algorithm was used to prevent interpenetration during the folding of the columns. For this analysis, the linear four-node element S4R is suitable for an analysis of thin shells. No mesh refinement studies were conducted. In this paper has been used element elimination scheme. In this method elements are deleted by default upon reaching maximum degradation.In the axial crushing simulation, one end of the aluminum extrusion is supported by a fixed rigid base and the other end is subjected to an instantaneous velocity by a planar rigid impactor.

For apply the imperfection on the column, an initial eigenvalue analysis should be conducted for all specimens of a crushing analysis in order to find the mode shapes. For an eigenvalues analysis, the ‘‘frequency’’ step was completed by ABAQUS. For all specimens, three first-mode shapes and their corresponding displacements were obtained. The effects of these mode shapes must be considered in a crushing analysis (ABAQUS/Explicit step). Otherwise, the software may choose the buckling mode in an arbitrary manner and produce unrealistic results in nonlinear analyses.

Materials: Metal sheets and thin-walled extrusions made of aluminum alloys may fail due to one or a combination of the following failure mechanisms: ductile failure due to nucleation, growth, and coalescence of voids; shear failure due to fracture within shear bands and failure due to necking instabilities[9]. If the model consists of shell elements, a criterion for the last failure mechanism is necessary because the size of the localized neck is of the order of the sheet thickness and, hence, cannot be resolved with shell elements of dimensions one order of magnitude larger than the thickness.

Abaqus/Explicit offers a number of damage initiation criteria to model the onset of necking instabilities in sheet metals. These include the Forming Limit Diagram (FLD), Forming Limit Stress Diagram (FLSD), Müschenborn-Sonne Forming Limit Diagram (MSFLD), and Marciniak-Kuczynski (M-K) criteria. The first three criteria utilize the experimentally measured forming limit curves in the appropriate strain or stress spaces. The last criterion introduces virtual thickness imperfections in the sheet metal and analyzes the deformation in the imperfection zone to determine the onset of the instability.

The strain-based FLD criterion is limited to applications where the strain path is linear. On the other hand, the stress-based FLSD criterion is relatively insensitive to changes in the strain path. However, this apparent independence of the stress-based limit curve due to the strain path may simply reflect the small sensitivity of the yield stress to changes in the plastic deformation. The M-K criterion can capture the effects of nonlinear strain paths accurately; however, it is computationally expensive, especially if large numbers of imperfection orientations are introduced. It has been verified that the results obtained using the MSFLD criterion are similar to those obtained using the M-K criterion but with a much reduced computational expense. Therefore, in this paper we choose the MSFLD damage initiation criterion for necking instability. For specifying the MSFLD damage initiation criterion, the forming limit curve of the material is required. In Abaqus this criterion can be specified by converting the forming limit curve from the space of major versus minor strains to the space of equivalent plastic strain versus ratio of principal strain rates. Abaqus also allows direct specification of the forming limit curve for the MSFLD criterion. All models in this study are made of aluminum alloy (E = 70 GPa, ν = 0.3 and ρ = 2700 kg/m3). We use the forming limit curve based on the experimental work[10]. The stress curves for aluminium alloy EN AW-7108 T6 are shown in figure 1.

For validation of FEA, deformation mode and load-deformation curve are of interest[11-13]. Figure 2 shows the comparison of from the present simulations with experimental and theoretical results[10].

Results and Discussion

Parametric study: For comparison, the energy absorption capacity of specimens is a criterion that defines the mean collapse load and specific energy absorption SEA. Mean collapse load is calculated by dividing the area under the load–displacement curve by the deformation height and specific energy absorption SEA is calculated by dividing the area under the load–displacement curve by the column mass. It's shown in equations 1-2.

$$P_m = \frac{Total\ energy\ absorption\ E_A}{\delta} = \frac{\int P d\delta}{\delta} \qquad (1)$$

$$SEA = \frac{Total\ energy\ absorption\ E_A}{column\ mass\ M} = \frac{\int P d\delta}{M} \qquad (2)$$

Columns were nominated as follows: a100-t3-l750-m500-v10. The numbers following show the side length and the thickness of column are 100mm and 3mm and length of column is 750 mm, also impact mass and impact velocity are 500 kg and 10 m/s, respectively. The table1 listed the maximum crash distance, initial peak load, crush force efficiency ηc, mean load and SEA. Mean load and SEA have been introduced in equations 1 and 2. Normally, the crush force efficiency, ηc is defined as mean load to maximum load. The effects of loading parameter and geometrical parameter have been shown below:

Effect of impact mass: With increasing impact mass, the initial peak load remains constant and maximum crash distance and SEA are increased but mean load and crush force efficiency are decreased. These are shown in table 1 and figure 3.

Effect of impact velocity: With increasing impact velocity, the maximum crash distance and SEA are increased but peak load and mean load are decreased and also the crush force efficiency remain constant. These are shown in table 1 and figure 4.

Effect of thickness: With increasing thickness, peak load and mean load and crush force efficiency are increased but maximum crash distance and SEA are decreased. These are shown in table 1 and figure 5.

Effect of side length: With increasing side length, peak load and mean load are increased but maximum crash distance and SEA and crush force efficiency are decreased. These are shown in table 1 and figure 6.

Effect of column length: With increasing column length, peak load and maximum crash distance and SEA are decreased but crush force efficiency and SEA are increased. These are shown in table 1 and figure 7.

Table 1
Summary of numerical analysis for energy absorption

Specimens specification	Peak load (kN)	d_{max} (mm)	SEA (kJ/kg)	Mean load (kN)	η_c
a100-t3-l750-m500-v10	406	145	10.1	169	0.41
a100-t3-l750-m750-v10	406	242	15.3	153	0.37
a100-t2.5-l750-m750-v10	313	347	18.4	107	0.34
a100-t3-l750-m500-v12.5	392	246	16.1	159	0.41
a100-t3-l500-m500-v10	408	158	15.4	158	0.38
a125-t3-l750-m500-v10	500	136	7.9	178	0.35

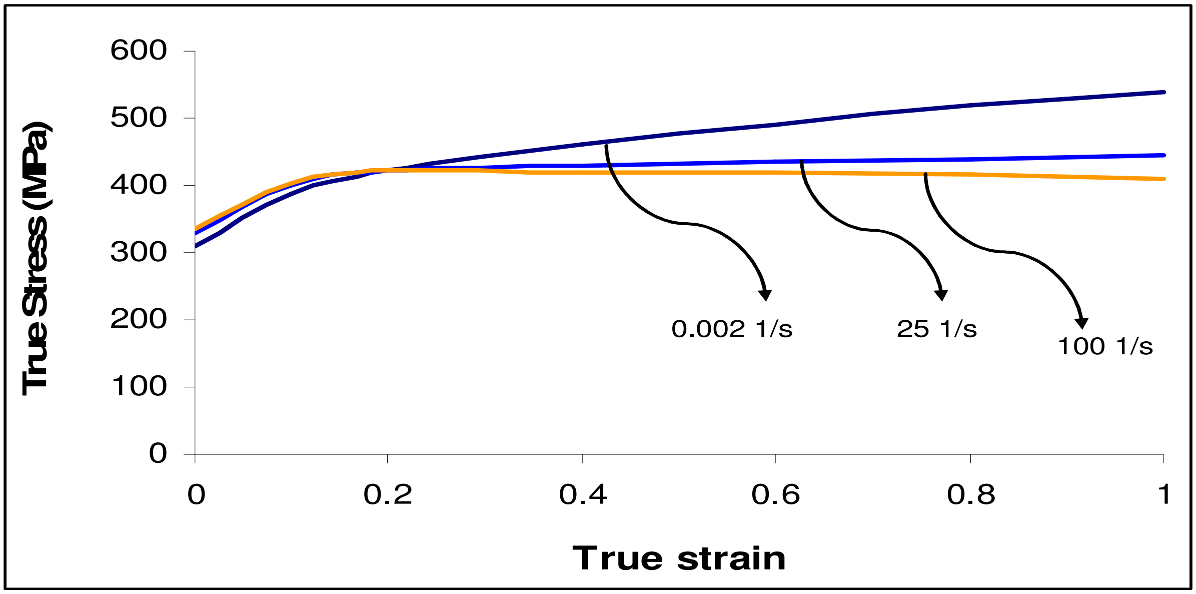


Figure 1
Stress vs. strain for different strain rates for EN AW-7108 T6 specimens cut in extrusion direction

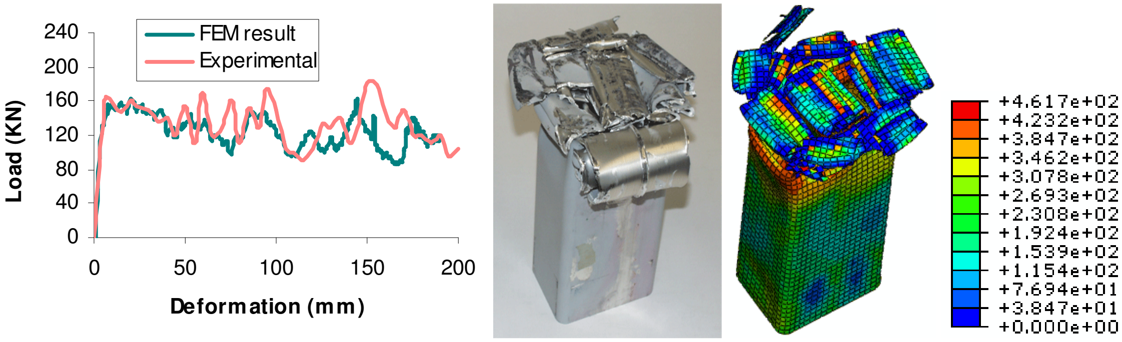
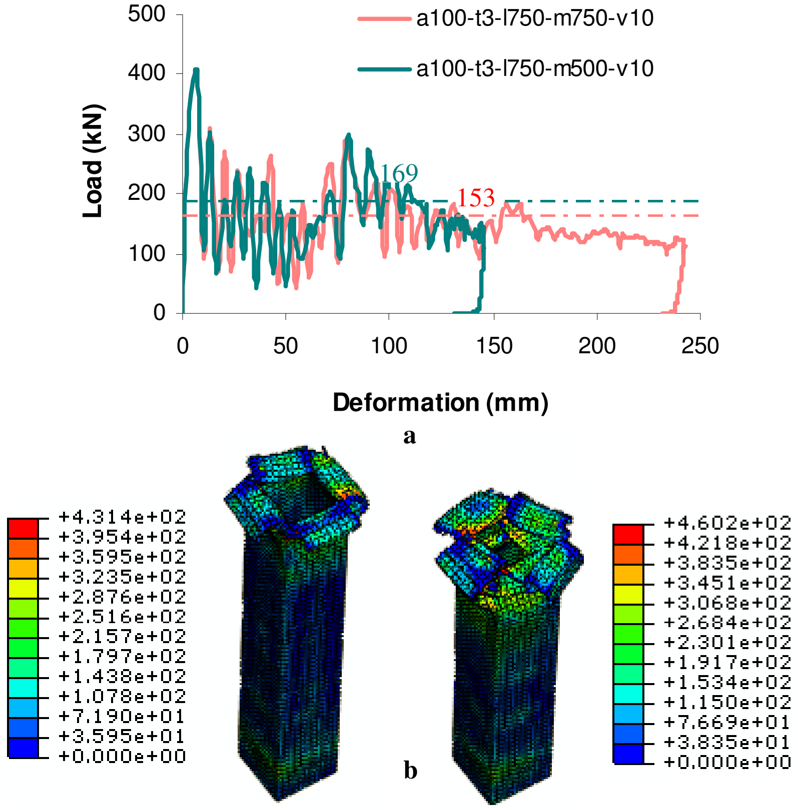


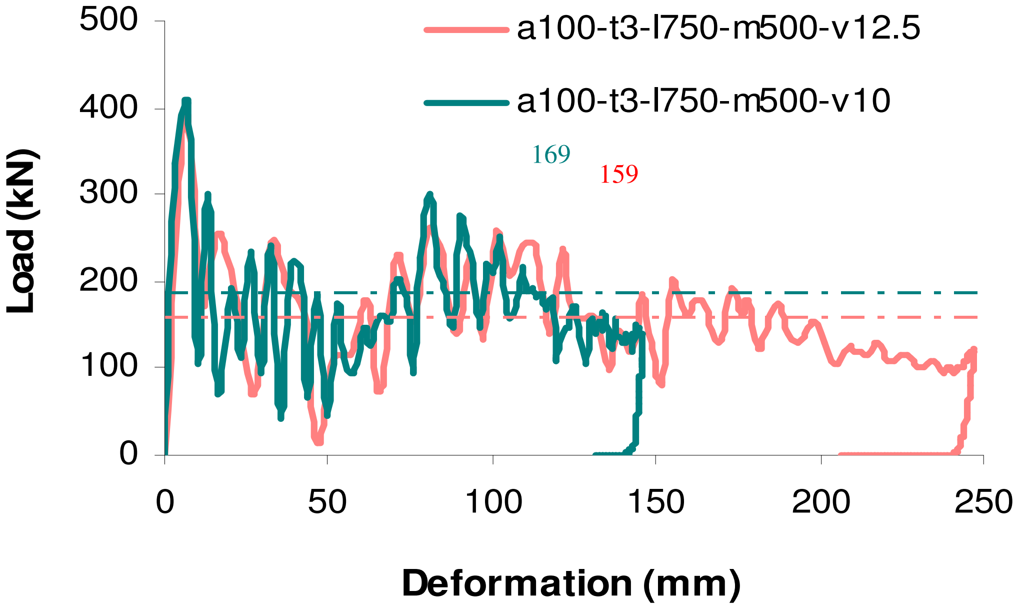
Figure-2
Comparison load-deformation curve and deformation mode (von mises contour) in experimental and numerical



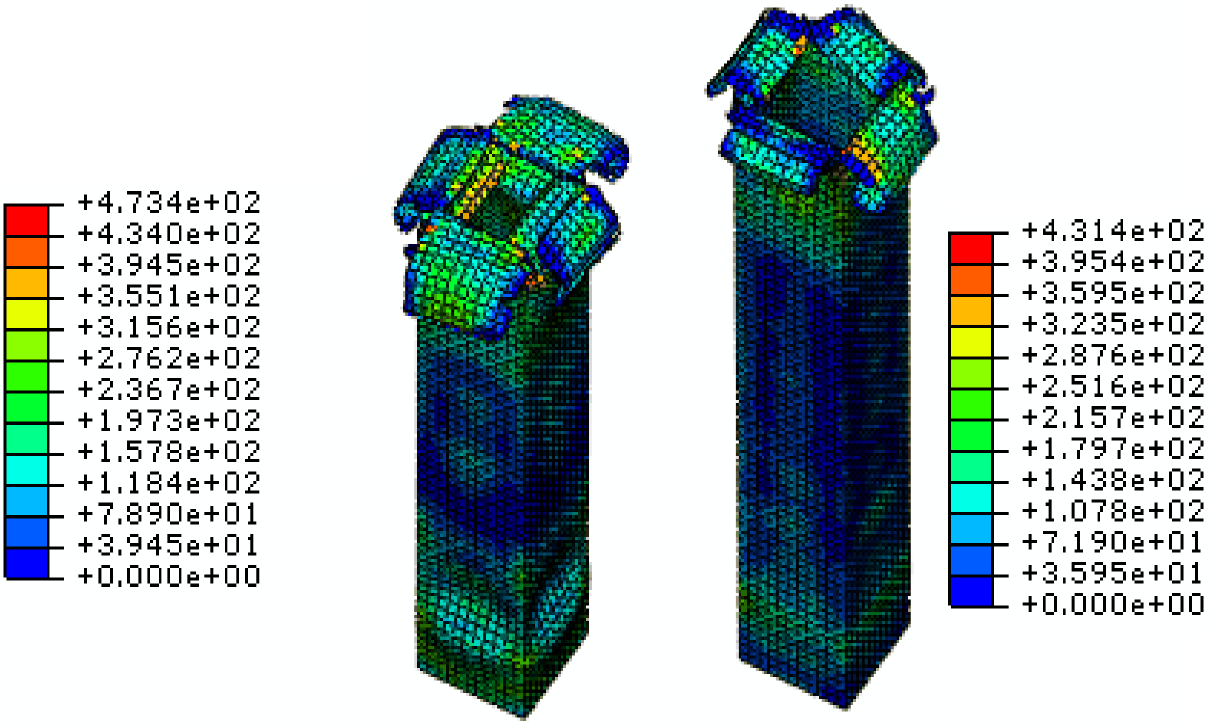
a

b

Figure-3
Plots of load-deformation and shell deformations and the von mises stress states for two specimens, a)a100-b100-t3-l750-m750-v10 and b) a100-b100-t3-l750-m500-v10

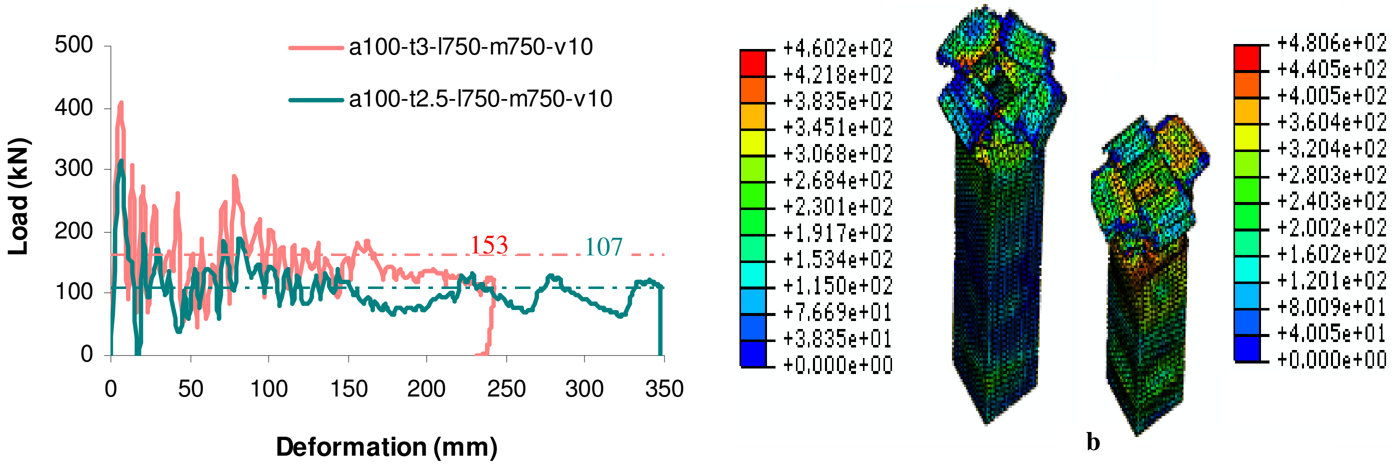


a



b

Figure-4
Plots of load-deformation and shell deformations and the von mises stress states for two specimens, a) a100-b100-t3-l750-m500-v12.5 and b) a100-b100-t3-l750-m500-v10



a **b**

Figure-5
Plots of load –deformation and shell deformations and the von mises stress states for two specimens, a) a100-b100-t3-l750-m750-v10 and b) a100-b100-t2.5-l750-m750-v10

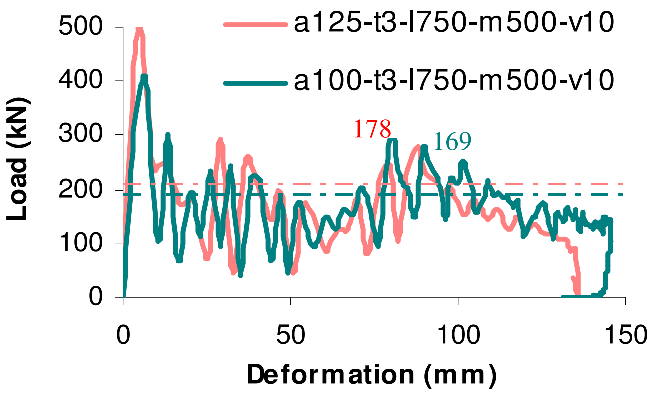


Figure-6
Plots of load–deformation and effect of side length

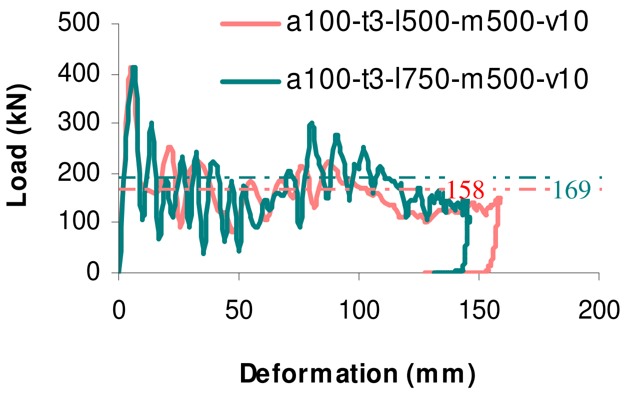


Figure-7
Plots of load–deformation and effect of column length

Conclusion

This paper presents the crashworthiness design for thin-walled aluminum columns. This paper shows that the selected model for prediction of damage behavior is suitable. The parametric study was done and gives suitable information for design of this type of column and the following results were found in this study: SEA and maximum crash distance is increased by increasing impact velocity and impact mass and decreasing in side length, column length and thickness. Initial peak load is increased by increasing thickness and side length and decreasing impact velocity and column length. Mean load is increased by increasing column length, thickness and side length and decreasing impact velocity and impact mass. Crush force efficiency is increased by increasing column length and thickness and decreasing impact mass and side length.

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