

Explicit Dynamic Analysis and Trigger-based Design of an Aluminum Crush Tube

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Abstract. Crush tubes are widely used as energy absorption devices in automobiles, racing cars and railway vehicles to maximize the protection of human life. Crash analysis is critical to ensure that crush tubes collapse in a controlled and sequential manner, absorbing as much energy as possible to protect the occupied space. Explicit dynamics is therefore well suited for capturing the initial response of crush tubes during collision. This study investigated the crushing performance of a 6061-T6 extruded aluminum crush tube through an explicit dynamic finite element analysis. A half-symmetry model was used to simulate axial impact against a rigid wall with an initial velocity of 7 m/s. The simulation results indicated that the crush tube absorbed approximately 22.6 kJ with a stroke of 35.1 mm within 5 ms. To improve the crush tube performance, we modified the design by reducing the wall thickness from 5 mm to 3 mm, removing internal stiffeners, and introducing sidewall dents to trigger sequential collapse. This approach is referred to as trigger-based design. The optimized design shows a more stable progressive collapse while maintaining the same stroke. These results demonstrate that trigger-based optimization is an effective strategy for improving the collapse behavior of extruded aluminum crush tubes.

Keywords: Aluminum crush tube, explicit dynamics, progressive collapse, trigger-based design

1. Introduction

Crush tubes have long been used as energy absorbing devices because they dissipate impact kinetic energy through plastic deformation while offering low weight and simple manufacturing [1-3]. In railway vehicles, these elements form part of a crash energy management (CEM) system intended to protect passenger's safety during collisions [4, 5].

The main challenge in crashworthiness design is not only to increase energy absorption and ensure a stable progressive collapse mode, but also limit the initial peak load, prevent global bending or local failure, and provide sufficient stroke under mass constraints [1, 2, 6, 7]. Common crashworthiness metrics include peak crush force, mean crush force, stroke, and specific energy absorption [1, 2, 6]. Since aluminum structures are relatively light, they are most commonly used in energy absorbing structures, yet the geometric details that improve energy absorption can also increase sensitivity to local instability and collapse mode changes [2, 6, 8].

The development of crashworthiness structures has progressed from classical studies of square and circular columns [2, 3] to trigger-based initiators [6, 7], extrusion-friendly aluminum front rails [8], and multi-cell aluminum tubes [9]. Recent work continued this trend through finite element-based parametric analysis and optimization of energy absorbers [5], as well as mass constrained optimization of multi-cell aluminum tubes [9]. Other reviews also focused on hierarchical and hybrid lightweight crashworthiness structures and integrated optimization methods [10, 11].

Explicit dynamic analysis is particularly appropriate for initial crush problems because the event occurs over milliseconds and is dominated by impact contact, large displacement, progressive collapse, material nonlinearity, and rapidly changing inertia effects [2, 3]. Early collapse formation is especially sensitive to these effects, and the initiation stage strongly influences the subsequent collapse path and peak load [6, 7]. Therefore, our paper focuses on a 3D explicit dynamic analysis of an extruded aluminum crush tube and a trigger-based redesign derived from the same overall geometry. This study aims to investigate the initial crushing response of the aluminum crush tube, identify the factors contributing to unstable deformation, and evaluate if the trigger-based design can improve collapse control.

2. Numerical methodology

2.1. Geometry and material model

The aluminum crush tube consists of an extruded 6061-T6 aluminum profile with internal stiffeners. Its material response was defined using the 6061-T6 material properties listed in Table 1. The aluminum tube was modeled using multilinear isotropic hardening. Because ANSYS Explicit Dynamics requires constitutive input in true stress-plastic strain form, an ANSYS compatible hardening curve was constructed from the published nominal tensile properties of 6061-T6 aluminum [12]. To improve crush performance, an optimized design was developed from the original geometry by reducing the wall thickness from 5 mm to 3 mm, removing the internal stiffeners, and introducing sidewall dents to trigger sequential collapse. The original and optimized geometries are shown in Fig. 1. Both designs have the same overall geometry, with a length of 539 mm and a height of 130.5 mm.

Table 1. Material properties [12]

Material	Property	Simulation Input	Units
Aluminum 6061-T6	Density	2703	kg/m ³
	Young's Modulus	68300	MPa
	Poisson's Ratio	0.33	
	Bulk Modulus	66961	MPa
	Shear Modulus	25677	MPa
	Yield Strength	276	MPa
	Ultimate tensile strength	310	MPa
	Elongation	12%	

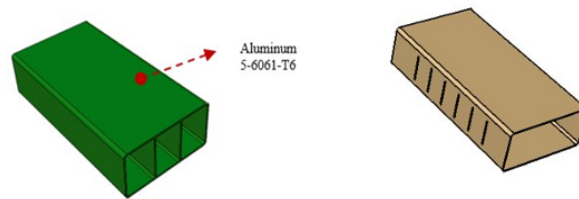


Figure 1. The aluminum crush tube (green) and the optimized design (yellow). The optimized design reduces wall thickness, removes internal stiffeners, and introduces sidewall dents to trigger a sequential collapse pattern

2.2. Explicit dynamic modeling and loading

Explicit dynamic analyses were performed in ANSYS to evaluate the initial crush performance of the crush tube. A total mass of 85,000 kg was assigned to represent the remainder of the vehicle structure. The rigid wall was fully fixed and modeled as a rigid body, while the mass block and crush tube was given an initial velocity of 7 m/s impacting the rigid wall. Crushing action was solely provided by the kinetic energy of the impacting mass, corresponding to an initial kinetic energy of 2083 kJ. The simulation time was set up to 5 ms, which was considered sufficient to capture the initial crush response and early-stage collapse. A Multizone meshing strategy was utilized for the aluminum crush assembly. The 3D CAD geometry and mesh model of the original crush tube are presented Fig. 2, while those for the optimized design are shown in Fig. 3. The mass block is not included in these two figures but is illustrated Fig. 4 and Fig. 6.

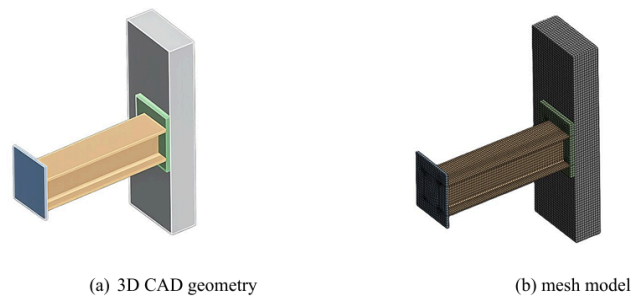


Figure 2. The original aluminum crush tube model: (a) 3D CAD model and (b) mesh model

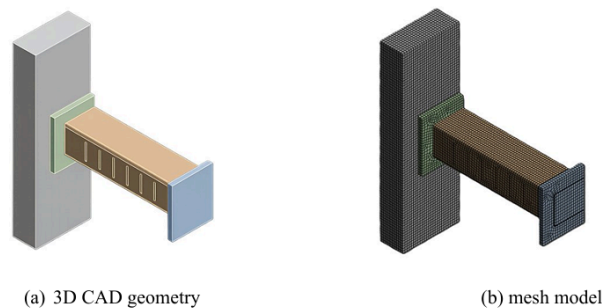


Figure 3. The optimized design model: (a) 3D CAD geometry and (b) mesh model

3. Results and Discussion

3.1. The original aluminum crush tube

The original crush tube deformed in the midsection and its collapse did not proceed in a sequential manner, as shown in *Fig. 4*. The maximum equivalent stress in the simulation was 328 MPa, while the maximum equivalent plastic strain reached about 0.287. It was observed that the maximum plastic strain exceeds the reported elongation at break of 12%, which indicated some elements have surpassed the material's failure limit. Since no damage or fracture model was included in the simulation, material separation or failure can't be determined. The displacement-time curve in *Fig. 4* shows a maximum stroke of 35.1 mm was obtained over the 5 ms simulation. The results indicate insufficient control over the early deformation path.

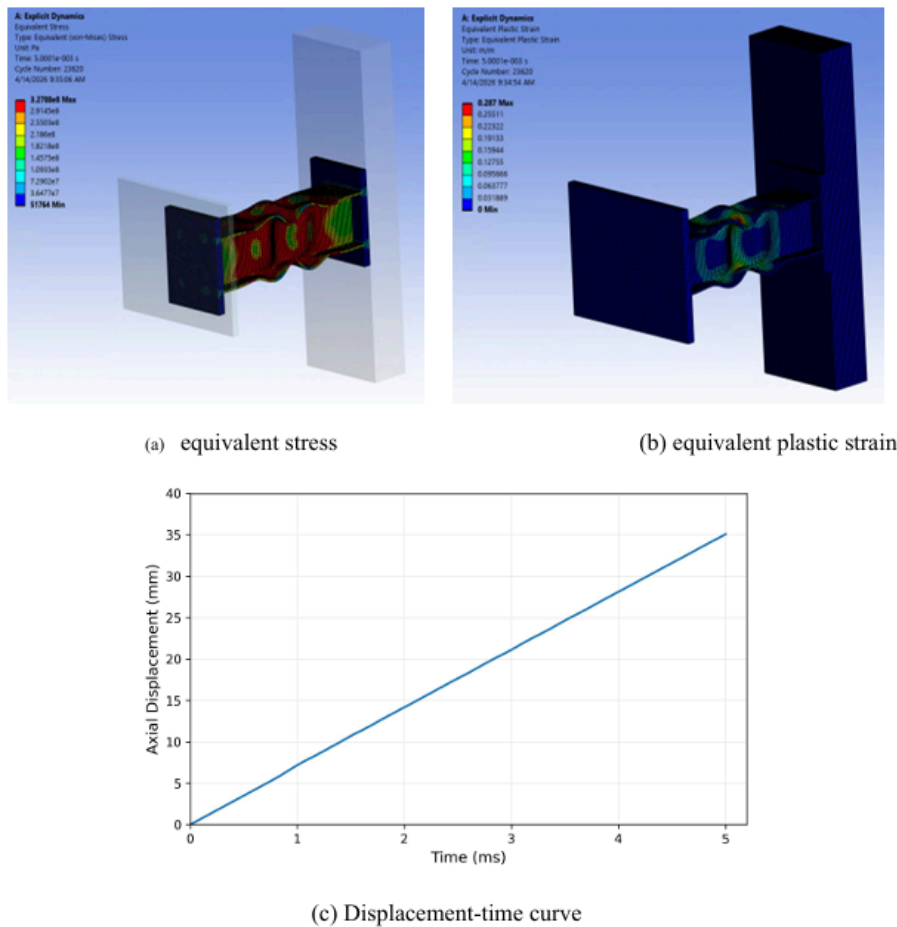


Figure 4. Initial crush response of Tthe original crush tube: (a) equivalent stress, (b) equivalentplastic strain, and (c) axial displacement-time curve

The energy curve in *Fig. 5* further clarifies the original crush tube performance. Internal energy rose to 22.6 kJ by the end of the analysis, but the hourglass energy also became significant, reaching approximately 26% of the internal energy. The high hourglass ratio indicates that a notable portion of deformation energy is going into non-physical modes, which is a limitation discussed further in Section 4. The mean crush force was approximately 656 kN. The simulation shows the general instability and undesirable deformation characteristics of the design. To improve the crush

performance, an optimized crush tube was therefore developed based on the trigger-based modifications described in Section 2.1.

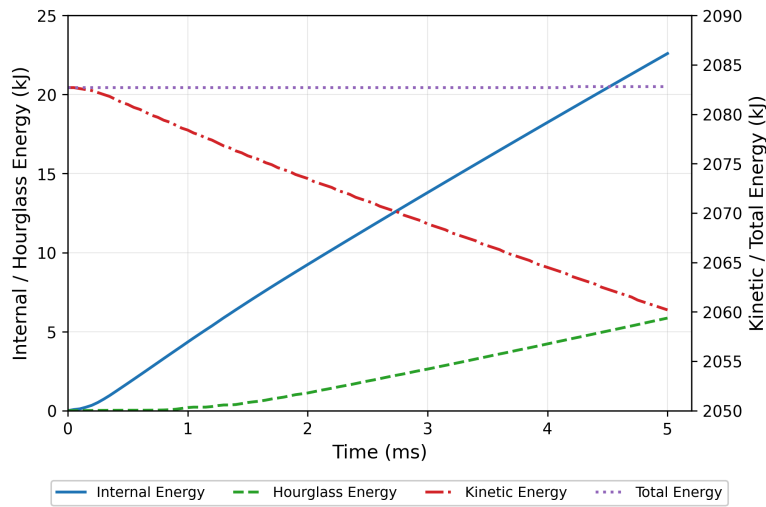


Figure 5. Energy-time curve for the original crush tube

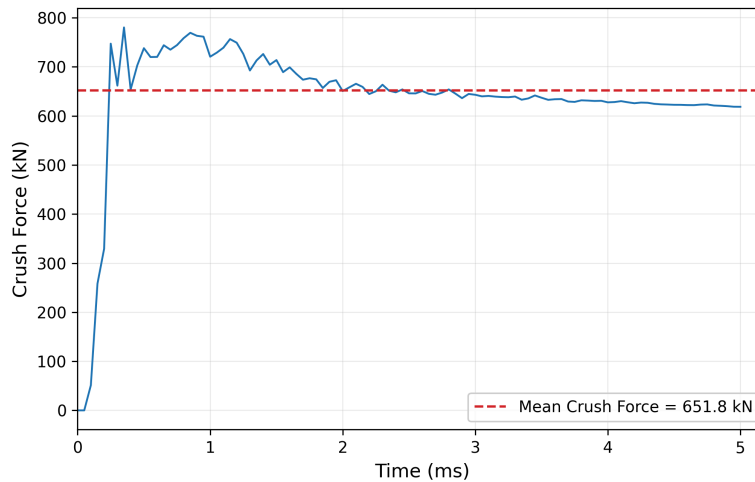


Figure 6. Crush force-time curve for the original crush tube

3.2. Optimized aluminum crush tube

The optimized design produced a more stable collapse pattern than the original crush tube. The added dents helped initiate the collapse sequence and promoted progressive crush behavior along the tube length, which is shown in *Fig. 6 (a)*, rather than the non-sequential collapse observed in the original design. However, the full collapse sequence is not captured due to the 5 ms simulation duration. In addition, the dent positions and spacing require further optimization to achieve stable, controlled collapse while preventing material peeling.

It was also found that the maximum equivalent stress was 328 MPa which is shown in *Fig. 6*. This value is same as the original crush tube. The maximum equivalent plastic strain reached 0.4195, which is higher than the original value of 0.287. This strain was localized in a small region near the trigger dents, while the rest of the tube remained at lower strain levels. The overall collapse pattern improved, and the stroke of the optimized crush tube reached 35.0 mm as shown in *Fig. 7*.

The internal energy reached 5.0 kJ, while the hourglass energy was only 12.6 J, representing 0.25% of the internal energy. Fig. 8 presents energy evolution with time. Fig. 9 shows that the peak crush force was 336 kN and the mean crush force was 146 kN.

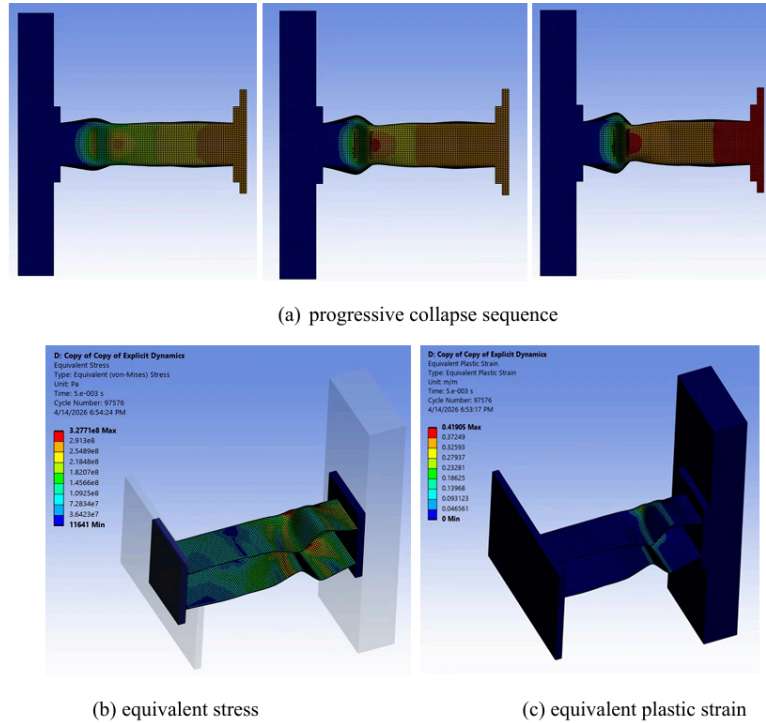


Figure 6. Initial Crush response of the optimized aluminum crush tube: (a) progressive collapse sequence, (b) equivalent stress, and (c) equivalent plastic strain. The trigger dents initiate a more progressive collapse path than in the original crush tube

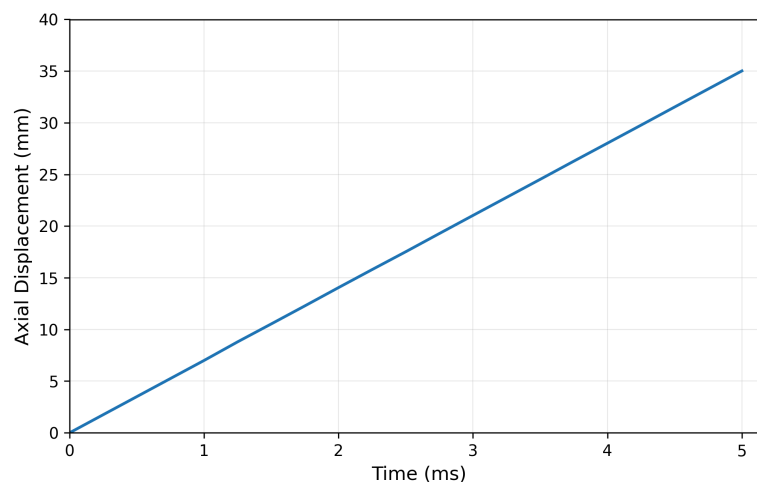


Figure 7. Displacement-time curve for the optimized crush tube

We made comparison between the two crush tube designs mainly on collapse stability, deformation uniformity, and mass reduction. Reducing the wall thickness, removing the internal stiffeners, and introducing trigger dents achieved a lighter structure with a more progressive collapse pattern. The mean crush force decreased from 656 kN to 146 kN, corresponding to a reduction by a

factor of approximately 4.5. Because the absorbed energy is equal to the crush force integrated over displacement, and both tubes underwent nearly the same crushing stroke of 35 mm, the absorbed energy decreased by the same proportion.

The lower crush force can be attributed to the design modifications. Reducing the wall thickness from 5 mm to 3 mm removed about 40% of the material. And the removal of the internal stiffeners reduced the structural resistance to plastic deformation. This finding highlights a common trade-off in crashworthiness design, where improved collapse stability is often achieved at the expense of energy absorption capacity. Future designs should therefore preserve the trigger dents while exploring intermediate wall thicknesses or alternative cross-sectional profiles to regain the lost energy absorption. The main properties of the two crush tubes are summarized in Table 2.

Table 2. Comparison between the original crush tube and the optimized design

Metric	The original crush tube	The optimized crush tube
Wall thickness	5 mm	3 mm
Internal stiffeners	Present	Removed
Trigger	None	Sidewall dents
Maximum equivalent stress	328 MPa	328 MPa
Maximum equivalent plastic strain	0.287	0.419
Crush stroke	35.1 mm	35.0 mm
Peak crush force	780 kN	336 kN
Mean crush force	656 kN	146 kN
Absorbed Energy	22.6 kJ	5.0 kJ
Hourglass/Internal energy ratio	26%	0.25%
Crush pattern	Non-sequential	Progressive, more distributed

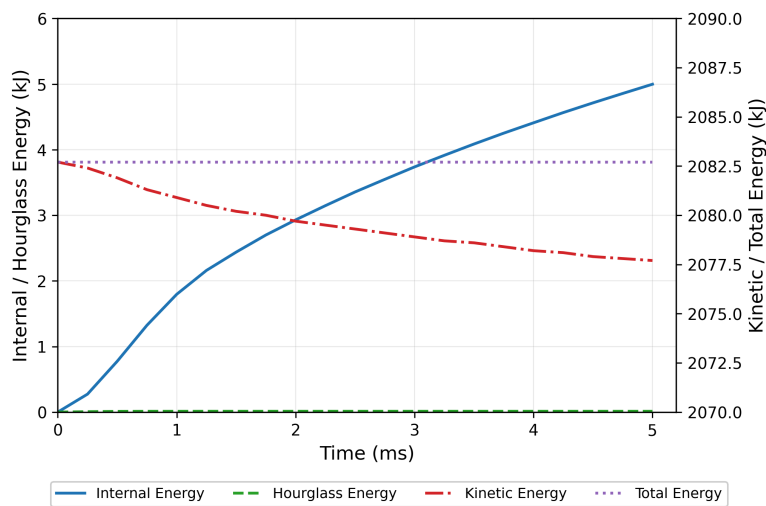


Figure 8. Energy-time curve for the optimized aluminum crush tube

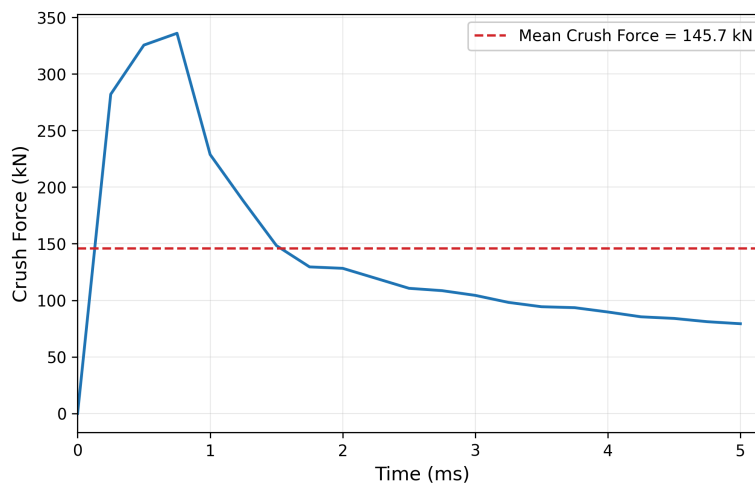


Figure 9. Crush force-time curve for the optimized aluminum crush tube

4. Future work and limitations

Several limitations still exist in our study. The trigger geometry and positions need further refinement for better collapse control, and other aluminum alloys or cross-sectional shapes can also be explored. Full stroke crush analysis is necessary for the validation of the crush tube design.

On the modeling side, the hourglass energy in the original crush tube reached 26% of the absorbed energy. Future work should address this through mesh refinement, or improved hourglass control settings. The current model uses published nominal material properties, however, experimentally measured stress-strain data should be used to ensure reliability. Moreover, the maximum plastic strains in the original and optimized crush tubes were 0.287 and 0.415, respectively, both of which exceed the material's elongation at break of 12%; however, no fracture model was considered. Incorporating a damage or failure criterion is therefore necessary to enable the model to capture local material separation and failure in the final results.

5. Conclusions

This study used an explicit dynamic finite element model to examine the initial impact response of an extruded 6061-T6 aluminum crush tube and a redesigned tube with trigger features. The original tube showed an unstable, non-sequential collapse mode, with a stroke of 35.1 mm and an energy absorption of about 22.6 kJ within 5 ms. In the redesigned model, the thickness of the wall was reduced from 5 mm to 3 mm, the internal stiffeners were removed, and trigger dents were added to the sidewalls. A more progressive and controlled collapse pattern was obtained by these changes. The hourglass energy ratio decreased from 26% to 0.25%, indicating better numerical reliability. However, the absorbed energy also decreased from 22.6 kJ to 5.0 kJ because of the thinner walls and the removal of the stiffeners. These results highlight the trade-off between collapse stability and energy absorption capacity. Overall, this study provides useful insight into the design of aluminum crush tubes for energy absorption applications. Although the trigger-based modification improved the collapse behavior, further work is needed to achieve a better balance between collapse stability and energy absorption capacity.

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