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Araştırma Makalesi / Research Article

A Numerical Study About the Effects of Design and Test Parameters on the Crushing Behavior of a Truncated Cone

Ali İmran AYTEN[1]

[1] *Yalova Üniversitesi, Mühendislik Fakültesi, Polimer Malzeme Mühendisliği Bölümü, Yalova.*

e-mail: aiayten@yalova.edu.tr. ORCID ID: https://orcid.org/0000-0002-3948-3690

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Keywords
Crushing behavior; Truncated cone; Numerical simulation; Ls-Dyna; Aluminum

Abstract

A numerical study was performed on the crushing behavior of an aluminum truncated cone structure for different design parameters and test speeds. Numerical models were prepared in the Ls-Prepost v4.7.1 software, and simulations were run in the Ls-Dyna solver. The Mat_18 power law plasticity and Mat_20 rigid material models were used for mimicking the behaviors of the aluminum tube and rigid plate, respectively. The effects of three different parameters as the ratio of the bottom and top diameters, contact angle of the rigid plate and test speed were investigated. Force-displacement curves for each case were obtained and evaluated to understand the crushing behaviors of the geometries with the aforementioned parameters. The geometry which had the 2.5 bottom/top diameter ratio performed the highest energy absorption among all geometries.

Kesik Bir Koninin Ezilme Davranışı Hakkında Tasarım ve Test Parametrelerinin Etkileri Üzerine Nümerik Bir Çalışma

Anahtar Kelimeler
Ezilme davranışı; Kesilmiş koni; Nümerik simülasyon; Ls-Dyna; Alüminyum

Öz

Farklı tasarım parametreleri ve test hızları için alüminyum kesik bir konik yapının ezilme davranışı ile ilgili nümerik bir çalışma gerçekleştirilmiştir. Nümerik modeller Ls-Prepost v4.7.1 yazılımında hazırlandı ve simülasyonlar Ls-Dyna çözücüsünde gerçekleştirildi. Alüminyum tüp ve rijit plakanın davranışlarını taklit etmek için sırasıyla Mat_18 plastisite ve Mat_20 rijit malzeme modelleri kullanıldı. Alt ve üst çap oranı, rijit plakanın temas açısı ve test hızı gibi üç farklı parametrenin etkileri araştırıldı. Her durum için kuvvet-yer değiştirme eğrileri elde edildi ve yukarıda bahsedilen parametrelere sahip geometrilerin ezme davranışlarını anlamak için değerlendirildi. 2.5 alt/üst çap oranına sahip olan geometrinin, tüm geometriler arasında en yüksek enerji sönümlemesi gerçekleştirdiği belirlendi.

1. Introduction

Thin-walled structures have a common application area in the aircraft and automotive industries due to their lightweight and energy absorption capabilities. The axial compression behavior of these types of structures is important in terms of understanding their crushing behavior and energy absorption capability. There have been many studies in the literature about the crushing behavior of different materials such composite and metallic materials (Guillow *et al*. 2001, Ochelski and Gotowicki 2009, Boria *et al*. 2015, Chiu *et al*. 2015, Kathiresan and Manisekar 2016, Haolei *et al*. 2020, Lykakos *et al*. 2020). Lu *et al*. (2020) investigated the axial compression behavior of thin-walled circular tubes with different diameter to thickness ratios. They observed that the collapse mode can only be seen in the case that the length to diameter ratio is smaller than 10. They also found that the maximum force to average crush force ratio increased considerably with an increase in the diameter to thickness ratio.

Increasing the energy absorption capability of structures has been one of the primary aims in crush box design studies. To achieve this purpose, different designs have been considered to include kirigami structures (Li *et al*. 2018, Li *et al*. 2018), origami structures (Ma *et al*. 2019), bio-inspired structures (Liu *et al*. 2017, Tasdemirci *et al*. 2017) and truncated structures (Boria *et al*. 2015,

Kathiresan and Manisekar 2016, Lykakos *et al*. 2020, Jiang *et al*. 2018, Li *et al*. 2018, Li *et al*. 2019).

Ochelski and Gotowicki (2009) studied the crushing behaviors of carbon and glass fiber composite tubes for different geometries and test parameters. They found that the specific energy absorption value of the carbon-epoxy composites was 20% greater than the glass-epoxy composites in both the cone and tube geometries. Boria *et al*. (2015) investigated the effects of parameters of conical structures in terms of their energy absorption capability under static and dynamic loadings. They concluded that the energy absorption capabilities of the samples under the dynamic loadings were lower than those under the static loadings. Kathiresan and Manisekar (2016) investigated the axial crushing behaviors of aluminum truncated cone and glass/epoxy wrapped aluminum truncated cone shells at different strain rates numerically and experimentally. They found that the composite wrapped aluminum cones showed a higher initial crush force than the neat form of aluminum conical shell.

In this study, the crushing behaviors of aluminum truncated cone shell structures which had different bottom/top diameter ratios were numerically investigated. Force-displacement curves were obtained, and the energy absorption characteristics of all structures were determined for different angles of loading and test speeds.

2. Materials and Method

The numerical study was conducted to investigate the crushing behavior of a truncated cone structure. The Ls-Prepost pre-processor and the Ls-Dyna R10.1 solver were used for the preparation of a numerical model and solve it, respectively. 2 mm of thickness was defined in the *SECTION_SHELL card, and this value was kept constant throughout all steps. The samples were 200-mm-long in all numerical studies. A fully integrated shell element (ELFORM=16) was used in the numerical studies. The Mat_18 and Mat_20 material models were used for the aluminum cone and rigid plate, respectively. Mat_18 is an isotropic plasticity material model which includes strain rate effects and uses the power law hardening rule. Yield stress (σ_y) is calculated for this material model by using equation 1,

$$\sigma_y = k\epsilon^n \tag{1}$$

where k is the strength coefficient, and n is the hardening exponent. The effects of two test parameters and one design parameter on the crushing behavior of the aluminum tube were investigated. Table 2 shows the values of the test and design parameters.

Table 1. Material properties used in numerical experiments (Int.sour.1)

Property	Aluminum tube	Steel plate
ρ (ton/mm^3)	2.713e-9	7.8e-9
E (MPa)	70000	200000
ν	0.33	0.3
k (MPa)	378.82	
n	0.050692	

Table 2. Simulation parameters

r_b/r_t	Contact angle of plate [°]	Test speed [mm/s]
1.5	0	20
2.5	15	200
4	30	
	45	

Fig. 1 shows the design parameters used in this study. Nodes at the bottom of the geometry were fixed by the *BOUNDARY_SPC_SET card. Automatic surface to surface type of contact was defined for the rigid plate and aluminum truncated cone. A nodal force group was created for the bottom nodes to obtain a reaction force during the crushing process. Rigid body displacement was plotted by the reaction force of the bottom nodes, and force-displacement curves for each of the cases were obtained. Fig. 2 shows the numerical model of all geometries with different r_b/r_t ratios. Contact angles of 0, 15, 30 and 45 degrees between the rigid plate and aluminum sample are demonstrated in Fig. 2.

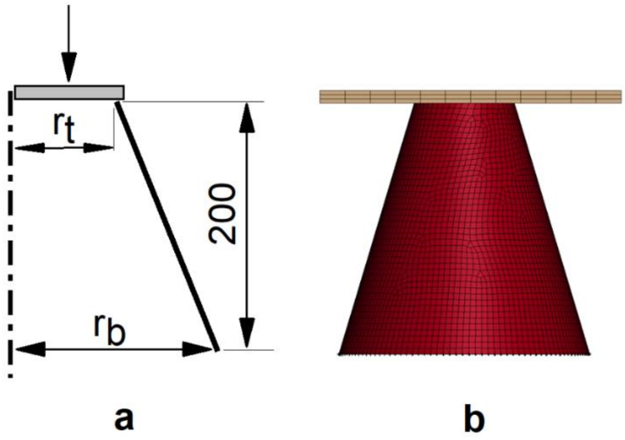

Figure 1. Design parameters of a truncated cone geometry. a) sketch for cone geometry, b) meshed geometry and boundary condition for one of cases

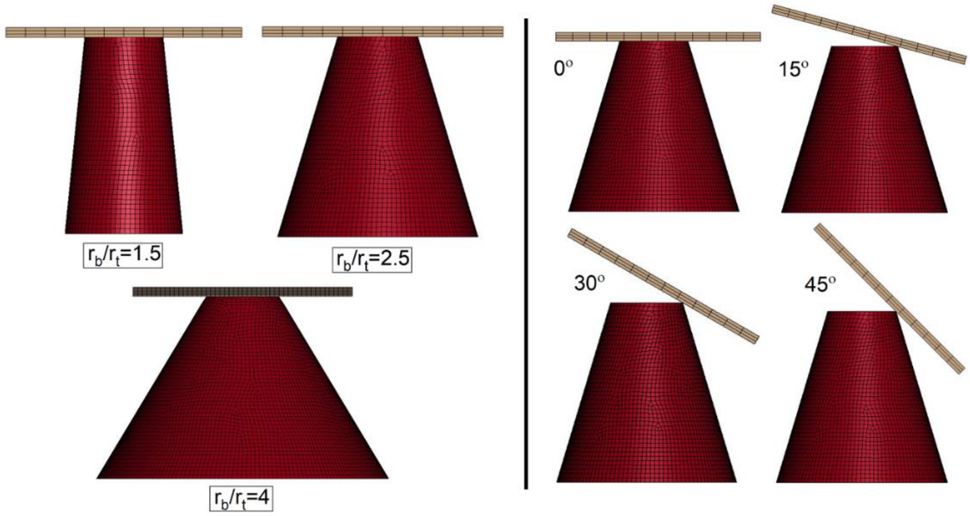

Figure 2. All geometry types (left) and contact angles of plates for one of the geometries (right)

3. Results and Discussions

The energy absorbed by structures can be found by calculating the area under the force-displacement curve. In all numerical simulations, the rigid plate crushed the whole sample and returned back to its initial point. The effect of the bottom/top diameter ratio is presented in Fig. 3. Firstly, the initial trends of all curves were generally similar to each other until their densification stage as the same material properties were used in all simulations. In the case of 0°, r_b/r_t=2.5 performed the highest contact force value. It is clear that the ratio of 2.5 showed a more stable behavior than the other ratio values at all contact angles. This may be understood from the fact that it performed a similar closed curve behavior. On the contrary to the 2.5 ratio, the r_b/r_t=4 sample exhibited the minimum energy absorption on all contact angle levels. This behavior may have originated from the fact that the sample was tending towards an unstable behavior under loading when it reached a critical bottom/top diameter ratio.

As the contact angle increases, the axial force in the *y* direction decreases. Thus, the reaction force applied to the plate by the truncated cone decreases, and the absorbed energy value drops. The effect of the contact angle between the plate and the cone may be seen in Fig. 4. It was remarkable that the structure which had the ratio of r_b/r_t=4 was not affected by changing the contact angle. Contact force did not change by increasing the angle after the level of 15°.

Fig. 5 exhibits the effects of test speed on the crushing behavior of the aluminum truncated cone samples. It is clearly seen that the higher test speed caused a higher reaction force at all bottom/top diameter ratios. The structure with the 2.5 diameter ratio performed the highest energy absorption among all other cases.

Fig. 6 presents a comparison of the folding behavior of the samples which were compressed with the 20 mm/s deformation speed and 0° contact angle at different times. Symmetrical folding patterns were observed in three samples, especially until the 0.4th sec. Then, densification of the samples was observed. This case caused a sudden increase in the reaction force in the sample. If Fig. 3 and Fig. 6 are discussed together, the folding mechanism could be more comprehensible. The reaction forces in the samples abruptly increased after the 150-mm displacement value. This situation was consistent with the samples shown in Fig. 3.

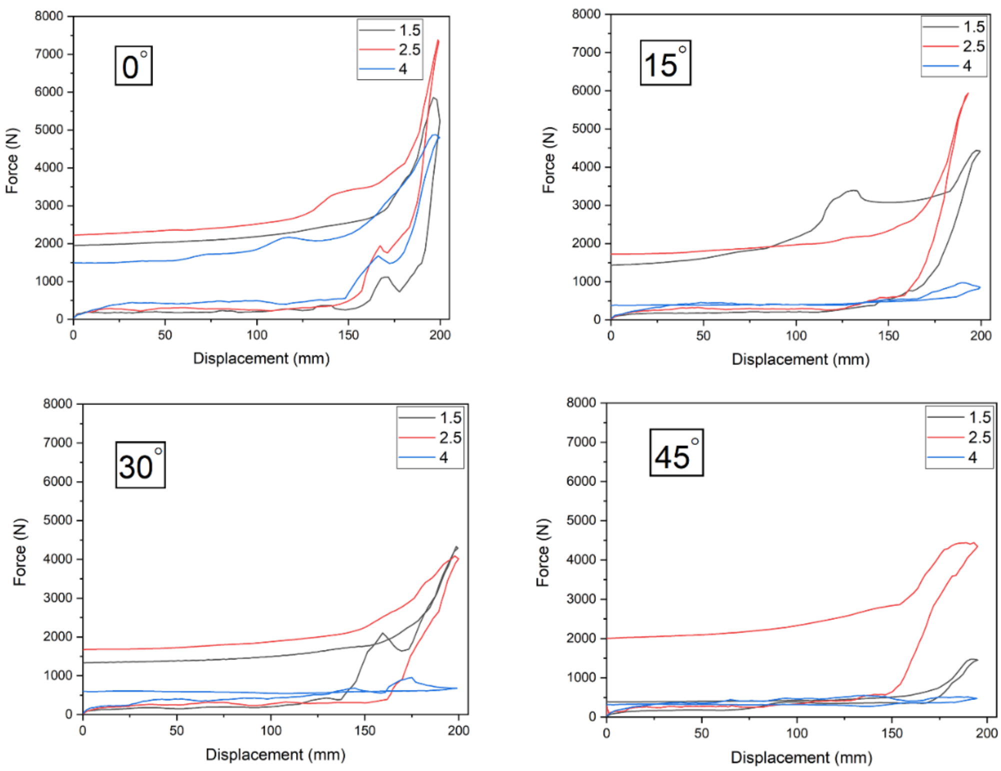

Figure 3. Force-Displacement curves for all radius ratios at different contact angles

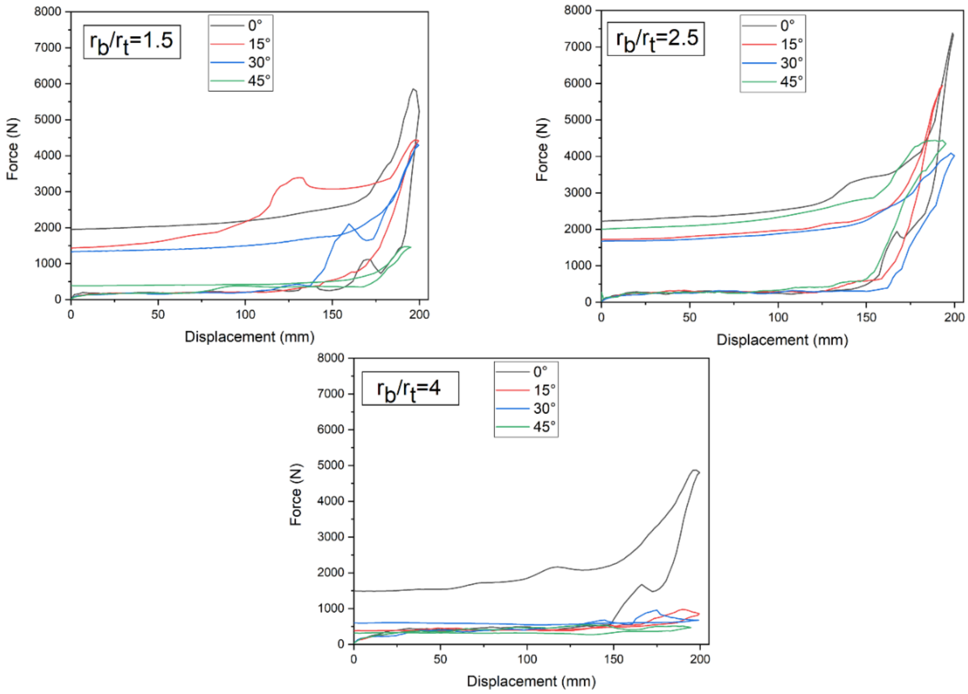

Figure 4. Force-Displacement curves for different contact angles at different radius ratios

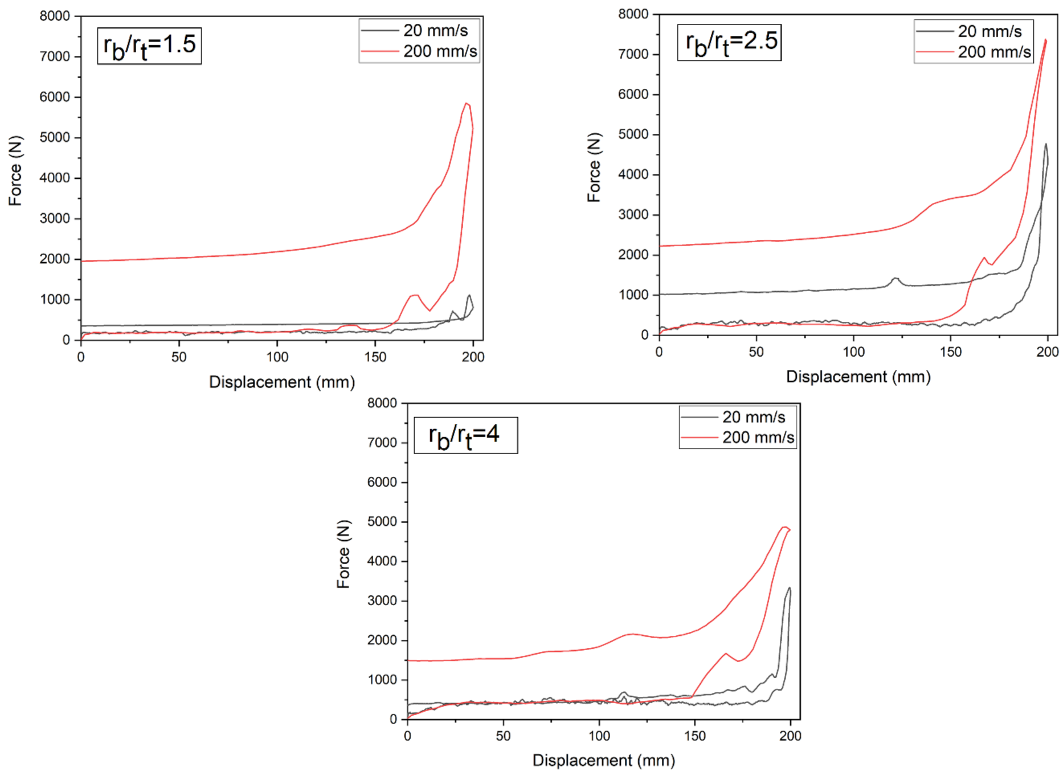

Figure 5. Force-Displacement curves for different radius ratios at different test speeds

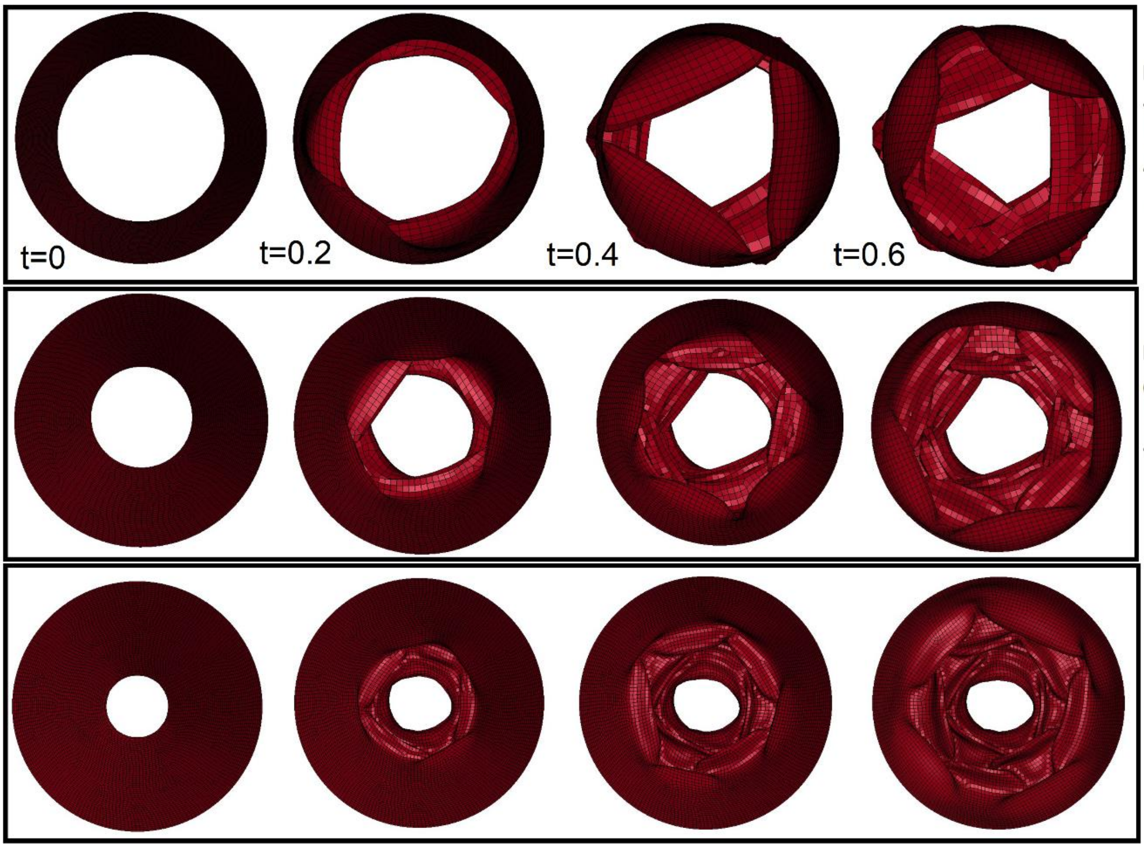

Figure 6. Comparison of folding behaviors at different times.

4. Conclusions

The crushing behavior of aluminum truncated cones at different bottom/top diameter ratios, contact angles and test speeds were numerically investigated in this study. Force-deflection curves for all cases were obtained and are presented throughout this paper. The results may be summarized as follows:

- The geometry which had the diameter ratio of r_b/r_t=2.5 showed the highest reaction force and absorbed the most energy among all designs.
- All samples performed strain hardening behavior beyond a certain level of deformation.
- The reaction force which was applied to the rigid plate by the aluminum cone dramatically increased with the increasing test speed.
- The proposed geometry may be used in a crush box design in the automotive industry or different applications which require high energy absorption.

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