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Influence of Apertures on Dynamic Energy Dissipation in Thin-Walled Tubular Structures Under Impact

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ABSTRACT

Thin-walled tubular structures are widely employed as energy-absorbing components in various engineering applications, particularly in crash protection systems.1 This study investigates the impact of introducing cutouts, or apertures, on the energy absorption capabilities of thin-walled tubes subjected to dynamic loading conditions. Computational simulations, validated against existing literature, were conducted to analyze the deformation modes, peak crushing force, mean crushing force, and specific energy absorption of tubular structures with varying cutout geometries (size, shape, and location). The results reveal a complex interplay between the presence of cutouts and the energy absorption characteristics, highlighting the potential for both enhancement and degradation of crashworthiness performance depending on the design parameters of the apertures. This research provides valuable insights for the tailored design of thin-walled tubes with cutouts to optimize their energy dissipation capacity under dynamic impact scenarios.

KEYWORDS

Cutouts, Energy Absorption, Thin-walled Tubes, Dynamic Loading, Crashworthiness, Impact Behavior, Finite Element Analysis (FEA), Structural Optimization, Tube Deformation, Lightweight Structures, Axial Compression, Material Failure, Energy Dissipation, Structural Integrity, Impact Resistance.

INTRODUCTION

The critical importance of mitigating the effects of dynamic impact in various engineering domains, including automotive, aerospace, and infrastructure, has driven extensive research into energy-absorbing structures [2, 4, 1]. Thin-walled tubular structures have emerged as highly efficient energy dissipaters due to their stable and progressive collapse mechanisms under axial or oblique impact, leading to significant deceleration of impacting masses over a controlled deformation distance [5, 16].2 Their lightweight nature and relatively high energy absorption-to-weight ratio make them particularly attractive for applications where structural efficiency is paramount [3, 8].

Numerous studies have explored various strategies to enhance the crashworthiness performance of thin-walled tubes, including the use of different cross-sectional shapes (e.g., square, hexagonal, multi-cell) [7, 17], material modifications (e.g., functionally graded materials) [6], and the incorporation of internal or external reinforcements [9].3 Another design feature that can significantly influence the buckling behavior and energy absorption characteristics of thin-walled structures is the introduction of cutouts or apertures in their walls [10, 12].4

The presence of cutouts can alter the stress distribution within the tube, potentially triggering different buckling modes and influencing the progressive folding mechanism under impact [11].5 Depending on their design, cutouts can act as stress concentrators, initiating buckling at specific locations and potentially leading to a more controlled and progressive collapse. Conversely, poorly designed cutouts might weaken the structure prematurely, leading to unstable buckling and a reduction in the overall energy absorption capacity [10, 12].

Previous research has investigated the effects of cutouts on the crashworthiness of thin-walled structures under quasi-static loading conditions [11, 12, 10].6 However, the dynamic response of these structures, where inertia effects and material strain rate sensitivity play a significant role, can differ substantially from their quasi-static behavior [16]. Understanding the influence of cutouts on the energy absorption characteristics of thin-walled tubes under dynamic impact is crucial for their effective application in real-world crash scenarios.

This study aims to address this gap by investigating the effects of cutouts on the dynamic energy dissipation of thin-walled tubular structures subjected to impact loading. Using validated computational models, we will analyze the influence of cutout geometry (size, shape, and location) on key crashworthiness parameters, including deformation modes, peak crushing force, mean crushing force, and specific energy absorption (SEA). The findings of this research will provide valuable insights for the design of thin-walled tubes with tailored cutout configurations to optimize their energy absorption performance under dynamic impact conditions, contributing to the development of more effective crash protection systems [2, 4].

METHODS

To investigate the effects of cutouts on the energy absorption characteristics of thin-walled tubes under dynamic loading, a series of computational simulations were conducted using a finite element analysis (FEA) software capable of handling dynamic impact events [15]. The methodology comprised the following key steps:

1. Model Geometry: A baseline model of a thin-walled circular tube with specific dimensions (diameter, thickness, and length) was created. Subsequently, variations of this model were generated by introducing cutouts of different geometries. The parameters varied included:

* Cutout Size: The area or characteristic dimension (e.g., diameter for circular cutouts, side length for square cutouts) of the cutouts was varied as a percentage of the tube's surface area.

* Cutout Shape: Different cutout shapes, such as circular, square, rectangular, and elliptical, were considered to assess the influence of geometric discontinuity.

* Cutout Location: The axial and circumferential placement of single and multiple cutouts along the tube's length was varied to examine the effect of their positioning on the buckling behavior and progressive collapse.

2. Material Model: The material properties of a typical metallic material used in energy absorption applications (e.g., aluminum alloy) were defined. A rate-dependent material model, such as the Johnson-Cook model, was employed to account for the influence of strain rate on the material's yield strength and flow stress under dynamic impact conditions [16]. Material parameters were obtained from literature for the selected alloy.

3. Finite Element Mesh: The tubular structures were discretized using a fine mesh of shell elements to accurately capture the buckling and folding behavior. Mesh sensitivity studies were performed on the baseline model to ensure that the results were independent of the mesh size, balancing accuracy and computational cost [14].

4. Dynamic Impact Simulation: A dynamic explicit finite element solver was used to simulate the impact event. One end of the tube was fixed, while the other end was subjected to an impact by a rigid mass with a defined initial velocity. The impact energy was controlled by varying the mass and velocity to represent typical dynamic loading scenarios. Contact algorithms were defined to model the self-contact of the tube walls during the crushing process.

5. Boundary Conditions and Constraints: Appropriate boundary conditions were applied to simulate the impact scenario. The fixed end of the tube was constrained in all translational and rotational degrees of freedom. The rigid impactor was constrained to move only in the axial direction.

6. Data Acquisition and Analysis: During the simulations, key parameters were recorded as a function of time and displacement, including:

* Deformation Modes: The progressive buckling and folding patterns of the tubes with and without cutouts were visually analyzed.

* Crushing Force-Displacement History: The axial force experienced by the tube during the impact was recorded as a function of the axial deformation.

* Peak Crushing Force (PCF): The maximum force experienced during the initial stage of crushing.

* Mean Crushing Force (MCF): The average crushing force over the effective deformation distance, calculated by integrating the crushing force-displacement curve.7

* Energy Absorption (EA): The total energy dissipated by the tube during the crushing process, calculated as the area under the crushing force-displacement curve.

* Specific Energy Absorption (SEA): The energy absorbed per unit mass of the deformed tube, calculated

by dividing the total energy absorbed by the mass of the tube.8

7. Validation: The computational model for the baseline tube without cutouts was validated by comparing the simulation results (deformation modes, PCF, and MCF) with experimental data or numerical results available in the literature for similar thin-walled tubes under dynamic axial impact [5, 13]. This validation step ensured the accuracy and reliability of the simulation methodology.

8. Parametric Study: Once the model was validated, a systematic parametric study was conducted by varying the size, shape, and location of the cutouts in the thin-walled tubes. The influence of each cutout parameter on the deformation modes and the energy absorption characteristics (PCF, MCF, and SEA) was analyzed and compared to the baseline tube without cutouts.

RESULTS

The computational simulations revealed a significant influence of cutouts on the dynamic energy absorption characteristics of the thin-walled tubes. The specific effects observed varied depending on the size, shape, and location of the apertures.9

1. Deformation Modes: The presence of cutouts significantly altered the buckling and folding patterns of the tubes under dynamic impact. In tubes without cutouts, a relatively uniform and progressive axisymmetric or diamond-shaped folding pattern was typically observed. However, the introduction of cutouts often initiated buckling at or near the edges of the apertures.

* Cutout Size: Larger cutouts tended to promote localized buckling and the formation of fewer, larger folds compared to tubes without cutouts or with smaller apertures. In some cases, excessively large cutouts led to premature failure and a less progressive collapse.

* Cutout Shape: The shape of the cutout influenced the stress concentration at its edges, thereby affecting the initiation and propagation of buckling. Sharp corners, such as those in square or rectangular cutouts, often acted as more pronounced stress concentrators compared to the smoother edges of circular or elliptical cutouts, leading to earlier buckling initiation at these locations.

* Cutout Location: The axial and circumferential placement of cutouts had a substantial impact on the sequence of fold formation. Strategically placed cutouts could promote the formation of more uniform and stable folds along the tube's length, while poorly positioned cutouts could lead to asymmetric deformation and inefficient energy absorption. Multiple cutouts, depending on their spacing and alignment, could either enhance progressive buckling or lead to localized crushing between the apertures.

2. Crushing Force-Displacement History: The crushing force-displacement curves for tubes with cutouts exhibited variations compared to the baseline tube.

* Peak Crushing Force (PCF): The PCF was generally reduced with the introduction of cutouts, particularly for larger apertures. This reduction is attributed to the weakened structural integrity at the cutout locations, leading to earlier buckling initiation at a lower force level. However, in some specific configurations with strategically placed small cutouts, a slight increase in PCF was observed due to a modified initial buckling mode.

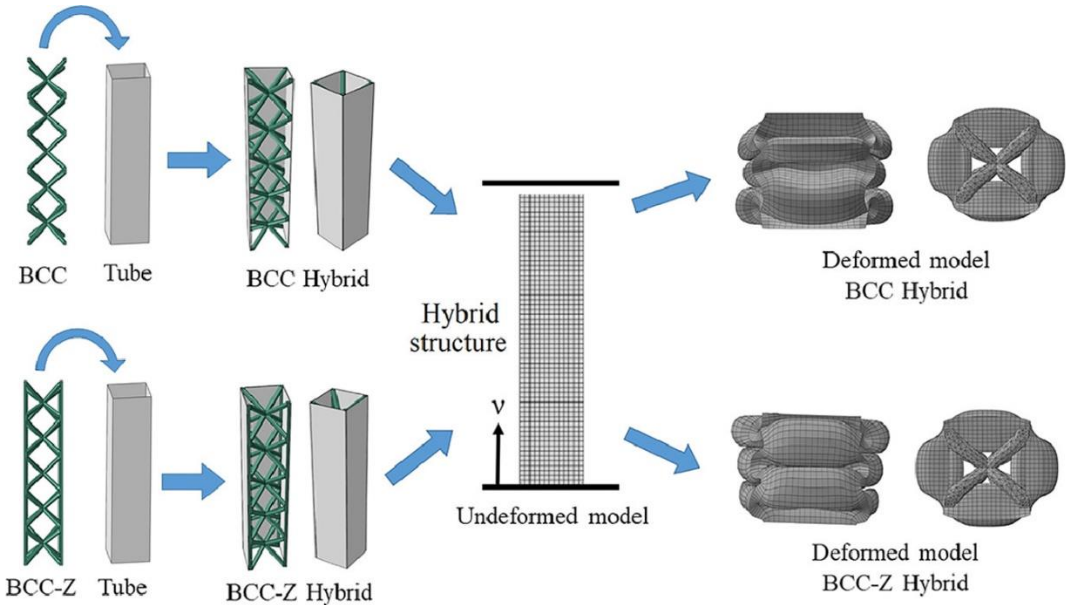
* Mean Crushing Force (MCF): The effect of cutouts on the MCF was more complex. In some cases, the MCF was reduced due to a less stable and progressive collapse mode induced by the cutouts. However, specific cutout designs (e.g., certain sizes, shapes, and arrangements) promoted a more controlled and sustained crushing process, resulting in a comparable or even slightly higher MCF compared to the baseline tube.

3. Energy Absorption (EA): The total energy absorbed by the tubes with cutouts was influenced by the combined effects on the PCF and the MCF, as well as the effective crushing distance. Generally, excessively large or poorly designed cutouts led to a reduction in the total energy absorbed due to premature failure or unstable buckling. However, optimized cutout configurations could potentially maintain or even slightly enhance the total energy absorption by promoting a more stable and progressive deformation mechanism over a longer crushing distance.

4. Specific Energy Absorption (SEA): The SEA, which considers the mass of the structure, is a crucial parameter for evaluating the efficiency of energy absorbers. The introduction of cutouts reduces the mass of the tube. Therefore, even if the total energy absorbed is slightly reduced, the SEA could potentially increase if the mass reduction is proportionally larger than the reduction in energy absorption. The results indicated that the effect of cutouts on SEA was highly dependent on the specific cutout design. Optimized cutout configurations that promoted stable progressive buckling with a significant reduction in mass often resulted in a higher SEA compared to the baseline tube. Conversely, cutouts that led to premature failure or inefficient crushing typically resulted in a lower SEA.

DISCUSSION

The findings of this study demonstrate the significant and complex influence of cutouts on the dynamic energy absorption characteristics of thin-walled tubular structures. The alteration of deformation modes, the reduction in peak crushing force, the variable impact on mean crushing force, and the subsequent effects on total energy absorption and specific energy absorption highlight the critical role of cutout design parameters.



The initiation of buckling at the edges of cutouts, particularly those with sharp corners, underscores the importance of stress concentration in dictating the initial collapse mechanism [11, 12]. The size and location of cutouts further influence the subsequent fold formation and the overall stability of the progressive crushing process. Strategically placed cutouts can act as "triggers" for controlled buckling, potentially leading to a more predictable and sustained energy absorption [10]. This controlled buckling can help to avoid the high initial peak force often associated with the buckling of intact thin-walled tubes, which is beneficial for reducing the impact load transmitted to the protected structure or occupants [16].

The reduction in PCF observed with larger cutouts is generally advantageous from a crashworthiness perspective, as it lowers the initial impact force. However, this reduction should not be accompanied by a significant decrease in MCF or the effective crushing distance, as this would compromise the total energy absorption capacity. The results suggest that there exists an optimal range of cutout sizes and configurations that can balance the reduction in PCF with the maintenance or even enhancement of MCF and SEA.

The potential for increased SEA in tubes with optimized cutouts is particularly noteworthy for lightweight design considerations [12]. By strategically removing material in the form of cutouts, the mass of the energy absorber is reduced.10 If this mass reduction is achieved without a proportional decrease in the total energy absorbed (or even with a slight increase due to a more controlled crushing mechanism), the SEA can be improved, leading to more efficient crash protection systems.

The comparison with existing literature on quasi-static loading [11, 12, 10] suggests that the effects of cutouts can differ under dynamic impact conditions. Inertia effects and material strain rate sensitivity, which are significant under dynamic loading [16], can influence the buckling behavior and the propagation of deformation in ways that are not captured in quasi-static analyses.11 Therefore, it is crucial to conduct dynamic analyses to accurately assess the crashworthiness performance of thin-walled structures with cutouts for impact applications.

Further research could explore a wider range of cutout geometries, including more complex shapes and patterns. Additionally, investigating the interaction effects of multiple cutouts with varying spacing and alignment would be valuable for optimizing energy absorption. Experimental validation of the computational results across different impact velocities and cutout configurations is also essential to build confidence in the numerical predictions and to provide a more comprehensive understanding of the dynamic crushing behavior of thin-walled tubes with apertures.

CONCLUSION

This computational study has demonstrated the significant influence of cutouts on the dynamic energy absorption characteristics of thin-walled tubular structures subjected to impact loading. The size, shape, and location of cutouts were found to affect the deformation modes, peak crushing force, mean crushing force, and specific energy absorption in complex ways. While poorly designed cutouts can degrade crashworthiness performance, optimized cutout configurations have the potential to reduce peak crushing force and enhance specific energy absorption by promoting controlled buckling and reducing the overall mass of the structure. These findings provide valuable guidance for the tailored design of thin-walled tubes with cutouts for improved energy dissipation in dynamic impact scenarios. Future research should focus on exploring a broader range of cutout designs and conducting experimental validation to further refine and validate these computational insights.

REFERENCES

World Health Organization & United Nations Regional Commissions. Global Plan Decade of Action for Road Safety 2021–2030 (2021).

Magliaro, J., Altenhof, W., & Alpas, A. T. (2022). A review of advanced materials, structures and deformation modes for adaptive energy dissipation and structural crashworthiness. Thin-Walled Structures, 180, 109808.

San Ha, N., & Lu, G. (2020). A review of recent research on bio-inspired structures and materials for energy absorption applications. Composites Part B: Engineering, 181, 107496.

Baroutaji, A., Sajjia, M., & Olabi, A. G. (2017). On the crashworthiness performance of thin-walled energy absorbers: recent advances and future developments. Thin-Walled Structures, 118, 137–163.

Luo, X., Xu, J., Zhu, J., Gao, Y., Nie, L., & Li, W. (2015). A new method to investigate the energy absorption characteristics of thin-walled metal circular tube using finite element analysis. Thin-Walled Structures, 95, 24–30.

Fang, J., Gao, Y., Sun, G., Zheng, G., & Li, Q. (2015). Dynamic crashing behavior of new extrudable multi-cell tubes with a functionally graded thickness. International Journal of Mechanical Sciences, 103, 63–73.

Nia, A. A., & Parsapour, M. (2014). Comparative analysis of energy absorption capacity of simple and multi-cell thin-walled tubes with triangular, square, hexagonal and octagonal sections. Thin-Walled Structures, 74, 155–165.

San Ha, N., & Lu, G. (2020). Thin-walled corrugated structures: A review of crashworthiness designs and energy absorption characteristics. Thin-Walled Structures, 157, 106995.

Barzigar, S. S., Ahmadi, H., & Liaghat, G. (2023). An analytical investigation on the crushing behavior of thin-walled tubes filled with a foam with strain hardening region. Thin-Walled Structures, 182, 110169.

Taştan, A., Acar, E., Güler, M. A., & Kılınçkaya, Ü. (2016). Optimum crashworthiness design of tapered thin-walled tubes with lateral circular cutouts. Thin-Walled Structures, 107, 543–553.

Kathiresan, M. (2020). Influence of shape, size and location of cutouts on crashworthiness performance of aluminium conical frusta under quasi-static axial compression. Thin-Walled Structures, 154, 106793.

Song, J., Chen, Y., & Lu, G. (2013). Light-weight thin-walled structures with patterned windows under axial crushing. International Journal of Mechanical Sciences, 66, 239–248.

Ahmad, M., Ismail, K. A., Hanid, M. H. M., Mat, F., & Roslan, A. M. (2020). Modification of the design of circular thin-walled tubes to enhance dynamic energy absorption characteristics: Experimental and finite element analysis. IOP Conference Series: Materials Science and Engineering, 917(1), 012027.

Ahmad, M., Ismail, K. A., & Mat, F. (2013). Convergence of finite element model for crushing of a conical thin-walled tube. Procedia Engineering, 53, 586–593.

Hallquist, J. (2006). LS-DYNA® theory manual. No. March.

Jones, N. (1989). Structural Impact. Australia: Cambridge University Press.

Tang, Z., Liu, S., & Zhang, Z. (2013). Analysis of energy absorption characteristics of cylindrical multi-cell columns. Thin-Walled Structures, 62, 75–84.