The Crashworthiness Performance of Thin-Walled Energy Absorbing Devices: An Overview

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Over the past many decades, numerous research efforts have been directed to overcome the major challenge of automotive and aeronautical industries to design lightweight and crash-worthy vehicles that are subjected to impact loading. The energy absorbers are provided in automobiles and aircraft to minimize the damage to occupants and the main structural part of the vehicle itself. Many energy-absorbing devices could be appropriately designed for the transport vehicles, however, the thin-walled tubular structures have been widely employed to reduce the destructive effects of dynamic impact loading during a collision and thus increase the crash worthiness behavior of the structural frame. Comprehensive knowledge of the structural performance and material properties of various thin-walled structures under different dynamic loading conditions is important for designing a perfect energy-absorbing device. In this paper, based on a detailed literature survey, a comprehensive overview of the recent investigations in the area of crash worthiness behavior of thin-walled tubes is specified on the topics that appeared in the last decade such as optimization for crash worthiness and energy absorbing performance of unconventional thin-walled components including functionally graded thickness tubes and multi-cell tubes. Due to a large number of studies that analyzed and evaluated the energy absorption behavior of various thin wall structures, this paper presents only an overview of the crash worthiness response of the structural components that can be used in vehicular structures including multi-cell thin-walled tubes under axial, oblique and bending loading.

Keywords: Foam-filled thin-wall structure, Functionally Graded Tubes, Specific absorbed energy, Thin-walled tubes, Bi-tubular structures.

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1. Introduction

Modern cars and airplanes must be both durable and safe for the passengers that ride in them. There is a desire to increase vehicle safety, and many scientists and engineering researchers have attempted to do so. There is optimism that employing thin-walled tubes will help in this regard. Since the early 1980s, researchers have studied the effect and performance of thin-walled tubes made of various materials, cross-sectional geometry, foam-filled tubes, structure and texture, and even the application of load and its orientation in the automotive and aeronautical industries. To analyze the mean crushing force, energy absorption effectiveness, specific energy absorption, and crush force efficiency factors, a variety of procedures are used, including manual and mechanical testing and computer simulations using software such as ABAQUS, Ansys, Autodyn, and LS-DYNA through finite element analysis. Various sorts of buckling and deformations are being investigated, and the tubes are being designed to absorb as much energy as possible. Tapered tubes, functionally graded thickness tubes, adding windows [1] and grooves on the tube surface, bi-tubular structures, and multicellular design [2, 3] have all been used to improve energy absorption. Here we describe all of the tubular structural research that has been done, as well as the adjustments that have been made to improve the impact attenuation of the tubes. It will assist the reader in comprehending all elements of thin-walled energy absorbing devices.

The mechanical properties of the absorber's material, such as yield stress and strain hardening behavior, influence the crashworthiness behavior of the structure. The material's strain rate sensitivity is a property of the material that is unchanged by the thin-walled tube's geometrical features, it should be stressed. Material strain rate sensitivity is an advantageous situation because it permits the material to reach a higher energy absorption when dynamically loaded [4]. There are three types of loading that can be applied to tubes to understand their crushing behavior: static loading, dynamic loading, and quasi-static loading, which can be applied axially or obliquely. Concertina mode, diamond mode, and mixed modes are the most common deformities seen in tube crushing, and several failure modes have been reported, including catastrophic failure [5], unstable local buckling, progressive end compression, and gradual failure, and mid-length collapse. Many studies have been carried out to evaluate the behavior of these tubes under various loading circumstances, as well as changes in geometry, material, and shape. The load absorption properties of thin-walled tubes are highly influenced by their geometry, which varies from section to section. Rolling blank technology, bladder modeling approach, Johnson-Cook constitutive & fracture models, and tube tapering are some techniques by which these tubes can be made.

2. Tapered tubes

Tapered tubes are preferred over non-tapered tubes in general because they absorb oblique impact loads in a better way and are less prone to buckle generally. Tapered tubes also have a more balanced plastic behavior and a lower initial peak force than straight tubes under axial stress. On investigating the tapered circular tubes it was discovered that the majority of the specimens were distorted in concertina mode [6] as shown in figure 1 [4], with the strain rate effect having a significant impact on dynamic force response and the inertia effect having a minor impact. Fengxiang Xu discovered a gradient exponent that has a significant impact on crashworthiness, and understanding its impact is critical [7]. For optimum crashworthiness, multiple surrogate models were determined to have linear thickness distribution and small diameters. The study suggests that lightweight and high-energy absorbing tubes with variable thickness structures may prove to be appropriate structures. In another research, it was discovered that axial crushing and radial displacement are easier to perform in smaller sections. It has been found that changing the distribution pattern of the wall thickness of the tube can vary the buckling pattern from buckling with minor folds to progressive large buckling and vice versa. The researchers concluded that stepped and functionally graded thickness (FGT) tubes perform better than uniform tubes [8]. Conical tubes which show similar behavior to tapered tubes have also been studied by Zhang and Zhang [9] who observed the compression behavior of conical tubes with varied thickness distribution tested under the axial crushing. The most critical aspect that leads to a dramatic increase in crashworthiness performance was material hardening during shrinkage. The tube with a nonlinear thickness distribution was discovered to have the highest efficiency.

Fig. 1: Deformed TCTGT and circular specimens [4]

3. Grooved Circular tubes

The issue of long circular energy absorbers' poor performance due to Euler's buckling has been recognized, and it has been attempted to be addressed by putting grooves and stiffeners on the body of the tube's surface. The experimental investigations were carried out to resolve this problem by incorporating circumferential grooves into the material [10]. This aids in the transformation of Euler's buckling to plastic deformation. Axisymmetric bending of the long tube was also prevented by introducing grooves in the tubes and controlling the sudden force among the tubes. The external grooves control and stabilize the collapse of tubes [11]. Finally, it was discovered that grooves cause the production of concertina mode, which is followed by diamond mode following the construction of two rings, and that grooved specimens are significantly superior to groove-less ones. The tube collapse modes are not symmetrical across the tube, according to Mohammed and Kumar [12], who stiffened the tubes and compared them to non-stiffened tubes. Adding stiffeners also causes a concertina mode with two folds to appear, followed by a diamond mode. Experiments have demonstrated that adding stiffeners enhances the energy absorption of the devices, which may be controlled by varying the location of the stiffeners. It was suggested that stiffeners may be used as a tunable energy absorption element in various architectures. It was discovered that adding them to the long tubes makes the energy absorbers more adjustable.

4. Bi-tubular structure

Many researchers have investigated the bi-tubular structure to analyze the effects it has on tube performance and crashworthiness. Under quasi-static axial compression, the crushing behavior of bi-tubular thin-walled devices made of stainless-steel sheets with inner tubes of various cross-sections and external circular tubes was examined [13]. Experiments have shown that as the number of corners grows, the amount of energy absorption increases. As the number of edges of the polygon grows, the pattern of folding of polygonal sides and external tubes may change. It was found that in all three inscribed diameters of the polygonal section, bi-tubes with hexagonal inner tube arrangements exhibited more specific energy absorption (SEA) than single and other sections. During the inversion process, the inner tube and polyurethane foam shrank, signaling the start of the deformation. The process of external and internal inversion is important in terms of energy absorption and specific energy absorption. When different geometries are assumed in a bi-tubular system, the internal tube is pressed through the inner folds of the square cross-section by the external [11]. In the axial deformation of internal tubes, this is a critical factor. The energy absorption capacity was found to be higher when the outer tube had a circular cross-section, and it was even better when an end cap was attached to the bi-tubular structure. Even though the energy absorption of bi-tubes was higher than the sum of individual tube crushing, there was a transition from global bucking to non-symmetric collapse in diamond pattern from single tube to bi-tubes [14].

5. Foam-filled thin-walled Structures

In tubular structures, foam-filled hollow thin-wall tubes are used to increase crashworthiness while keeping them lightweight. These foam materials absorb energy and increase the structure's energy-absorbing capability. Foam-filled thin wall structures have a larger mean crush force because both the foam and the wall absorb energy, enhancing the energy-absorbing efficiency. The inclusion of foam has been discovered to have a significant role in reducing local tube deformation by offering support within the tube [15]. Figure 2 depicts the deformation modes of foam-filled circular tubes [15]. The most important component that controls energy absorption, is the density of the material which infills the tubes. It has been demonstrated that a structure with a higher foam density will have a larger energy absorption capacity [16]. Metal foams absorb the impact energy in form of plastic deformation, converting that to heat, but polymeric foams behave as elastoplastic material, returning a significant amount of kinetic energy to the impacting system. The experimental and simulation results were closely correlated, demonstrating that the analytical model accurately predicted the collapsed shell's energy-absorbing capability [17].

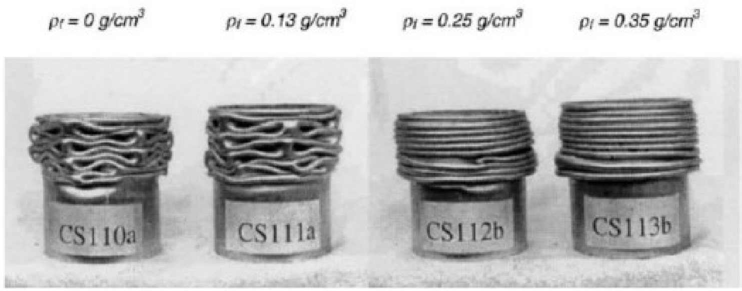

Fig. 2: Deformation modes of foam-filled circular tubes [15]

Reid et al. used polyurethane foam to fill tubes in early investigations under axial loading [18], which increased the mean crushing load. Following that, extensive research was carried out on tubes of various forms, including square, hexagonal and octagonal tubes [20], conical tubes [21], circular tubes [19, 22], and tapered rectangular tubes [23]. All of these investigations suggest that thin-wall tubes have improved energy absorption qualities. Overall, foam-filled tubes give greater suppress response, weight competence, energy absorption efficiency, and reduced risks of global buckling as compared to hollow thin wall tubes. S Asavavisithchai et al. discovered that foam-filled thin wall tubes display a higher number of folds during deformation under axial loading [24].

6. Different Metallic tubes

There has been a wide study on the material of energy absorbers which includes mild steel [25], aluminum alloys (AA6061-T5 [7], AA6061-T6 [26], AA6060-T4 [3]), stainless steel [13], glass fabric reinforced epoxy polymer composite [27], carbon fiber reinforced [28] and ultralight braided lattice composites [29]. Ernesto Guades et al. were the first to explore the behavior of fiber-reinforced composite tubes when they were subjected to axial impact [30]. Damage parameters such as applied load's mass, incident energy, and the frequency of blows were studied to see how they affected impact behavior. The number of hits had a significant impact on peak load evolution in the pre-collapse zone, while it had a much less impact in the post-collapse zone. When the number of hits is minimal, the impact energy is the primary cause of tube collapse; however, when the value of impact energy drops, the number of hits becomes the primary cause. In the case of carbon fiber reinforced tubes, the results of the research revealed that the length-diameter curve in the test followed a variation pattern characterized by a single peak load in the pre-crushing zone. The force decreases dramatically after the initial pre-crushing zone, approaching zero, implying that the tube entirely broke at the incident end, leaving no wall to physically withstand compressive loading. While the results of the double section triangular tubes revealed the benefits of using eight layered glass fabric composite tubes in the aircraft manufacturing industries to produce a suitable crash safety system for absorption of energy during accidents. Mohammad Mahdi Abedi et al. experimentally and numerically investigated the crashworthiness of thin-walled ultralight braided lattice composites (UBLCs) against quasi-static compressive loading [29]. A variety of geometries i.e., circular, rectangular, octagonal, and hexagonal samples were tested, with the square-shaped sample demonstrating the maximum specific absorbed energy (SAE) and energy absorption per length.

7. Natural materials

Nature has a depth of information to share, and it does so by attentively examining natural structure patterns, strengths, and behaviors. Meng Zou et al. [31] used the design technique that is bionic to introduce the bamboo structure to boost thin-walled tubes' axial and lateral energy absorption. Figure 3 shows different samples of bamboo and its failure modes [31]. Drop weight trials demonstrated good energy absorption due to the gradient distribution of nodes, vascular bundles, and density. The intended bionic structure is made up of bionic terminals, bionic units, and internal tubes, which perform the same functions as bamboo joints, vascular bundles, and matrices. The optimal tube shapes to maximize specific energy absorption (SEA) value and reduce maximum impact forces (MIF) value are numerically investigated, revealing that bionic structures have advantageous energy-absorbing properties under bending, axial and lateral loading conditions.

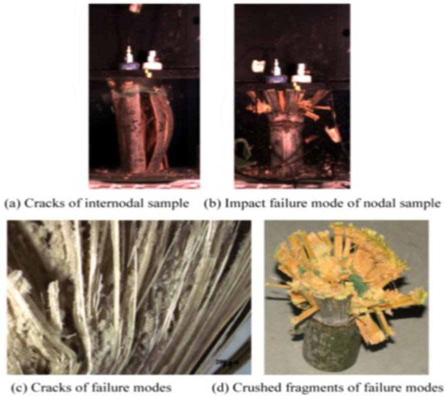

Fig. 3: Failure modes in bamboo under impact [31]

Jinwu Xiang et al. [32] investigated the internal structure of the lady beetle elytron to develop a bionic bi-tubular thin-walled structure (BBTS). Using the nonlinear finite element code LS DYNA, BBTSs with six distinct cross-sectional shapes of external tubes and five distinct inner tube sizes were numerically examined under axial loads. The energy absorption qualities of regular hexagonal BBTS units are superior to those of their uneven distribution counterparts. The optimized regular BBTS unit structure can absorb more energy than the original bionic structure, as seen by this feature. Future research in this area may provide results.

8. Conclusions

Road accidents are one of the major causes of fatalities and injuries annually. So the crashworthiness of vehicle structures is essential. Designers are required to design a structure that dissipates kinetic energy into vehicle deformation but away from occupants. It has been discovered that changing the thickness distribution of the tube can change the buckling pattern from buckling with minor folds to progressive buckling. The study concluded by noting that stepped and FGT tubes have better performance than uniform tubes. Among all cross-sections, a square-shaped sample had the maximum specific absorbed energy (SAE) and absorbed energy per length. Also, the total energy absorbing capacity is enhanced by increasing the edge number of the cross-sectional profile. It was also found that the energy absorption capacity of thin-wall tubes can be increased by filling foam materials. These stuffed tubes absorb more energy than hollow tubes due to the absorption of energy by filler material along with the interaction effects of filler material and the tube itself. It should also be noted that the functionally graded foam material shows better results. A new type of filler material was recently developed in which density varies along the length. Because of their potential to boost specific energy absorption (SEA) without raising maximum crush force. The serviceably graded filler materials showed higher crashworthiness responses than traditional filler materials with better specific energy absorption (SEA) without improving maximum crush force.

References

[1] Nikkhah, Hamid, Ahmad Baroutaji, and Abdul Ghani Olabi. "Crashworthiness design and optimisation of windowed tubes under axial impact loading." *Thin-Walled Structures* 142 (2019): 132-148.

[2] Xie S, Yang W, Li H, Wang N. Impact characteristics and crashworthiness of multi-cell, square, thin-walled, structures under axial loads. International journal of crashworthiness. 2017 Sep 3;22(5):503-17.

[3] Tran, TrongNhan. "Crushing analysis under multiple impact loading cases for multi-cell triangular tubes." *Thin-Walled Structures* 113 (2017): 262-272.

[4] Baroutaji, Ahmad, Mustafa Sajjia, and Abdul-Ghani Olabi. "On the crashworthiness performance of thin-walled energy absorbers: recent advances and future developments." *Thin-Walled Structures* 118 (2017): 137-163.

[5] Alkhatib, F., E. Mahdi, and A. Dean. "Crushing response of CFRP and KFRP composite corrugated tubes to quasi-static slipping axial loading: experimental investigation and numerical simulation." *Composite Structures* 246 (2020): 112370.

[6] Zhang, Xiong, Hui Zhang, and Zhuzhu Wen. "Axial crushing of tapered circular tubes with graded thickness." *International Journal of Mechanical Sciences* 92 (2015): 12-23.

[7] Xu, Fengxiang. "Enhancing material efficiency of energy absorbers through graded thickness structures." *Thin-Walled Structures* 97 (2015): 250-265.

[8] Rajabiehfard, R., et al. "Experimental and numerical investigation of dynamic plastic behavior of tube with different thickness distribution under axial impact." *Thin-Walled Structures* 109 (2016): 174-184.

[9] Zhang, Hui, and Xiong Zhang. "Crashworthiness performance of conical tubes with nonlinear thickness distribution." *Thin-Walled Structures* 99 (2016): 35-44.

[10] Nalla Mohamed, M., P. Yuvarajan, and M. Umasankar. "Energy enhancement of long cylindrical tubes with grooves subjected to axial impact." *Applied Mechanics and Materials*. Vol. 787. Trans Tech Publications Ltd, 2015.

[11] Jafarian, Behnam, and Mohammad Javad Rezvani. "An experimental investigation on energy absorption of thin-walled bitubal structures by inversion and axial collapse." *International Journal of Mechanical Sciences* 126 (2017): 270-280.

[12] Mohamed, M. Nalla, and A. Praveen Kumar. "New Insight to Improve Energy Absorption Characteristics of Long Circular Tubes With Stiffeners as Controllable Energy-Dissipating Devices." *Procedia engineering* 173 (2017): 1399-1406.

[13] Vinayagar, K., and A. Senthil Kumar. "Crashworthiness analysis of double section bi-tubular thin-walled structures." *Thin-Walled Structures* 112 (2017): 184-193.

[14] Rahi, Abbas. "Controlling energy absorption capacity of combined bitubular tubes under axial loading." *Thin-Walled Structures* 123 (2018): 222-231.

[15] Z. Li, Z. Zheng, J. Yu, L. Guo, Crashworthiness of foam-filled thin-walled circular tubes under dynamic bending, Mater. Des. 52 (2013) 1058–1064.

[16] Onsalung, N., Thinvongpituk, C. and Painthong, K., 2010. The influence of foam density on specific energy absorption of rectangular steel tubes. Energy Research Journal, 1(2), pp.135-140.

[17] Mamalis, A. G., et al. "On the crashworthiness of composite rectangular thin-walled tubes internally reinforced with aluminum or polymeric foams: Experimental and numerical simulation." Composite Structures 89.3 (2009): 416-423.

[18] Reid, S.R., Reddy, T.Y. and Gray, M.D., 1986. Static and dynamic axial crushing of foam-filled sheet metal tubes. International Journal of Mechanical Sciences, 28(5), pp.295-322.

[19] Hanssen, A.G., Langseth, M. and Hopperstad, O.S., 2000. Static and dynamic crushing of circular aluminium extrusions with aluminium foam filler. International journal of impact engineering, 24(5), pp.475-507.

[20] Seitzberger, M., Rammerstorfer, F.G., Gradinger, R., Degischer, H.P., Blaimschein, M. and Walch, C., 2000. Experimental studies on the quasi-static axial crushing of steel columns filled with aluminium foam. International Journal of Solids and Structures, 37(30), pp.4125-4147.

[21] Ahmad, Zaini, and David P. Thambiratnam. "Dynamic computer simulation and energy absorption of foam-filled conical tubes under axial impact loading." Computers & Structures 87, no. 3-4 (2009): 186-197.

[22] W. Yan, E. Durif, Y. Yamada, C. Wen, Crushing simulation of foam-filled aluminium tubes, Mater. Trans. 48 (7) (2007) 1901–1906.

[23] Mirfendereski, L., Salimi, M. and Ziaei-Rad, S., 2008. Parametric study and numerical analysis of empty and foam-filled thin-walled tubes under static and dynamic loadings. International Journal of Mechanical Sciences, 50(6), pp.1042-1057.

[24] Asavavisithchai, S., D. Slater, and A. R. Kennedy. "Effect of tube length on the bucking mode and energy absorption of Al foam-filled tubes." Journal of materials science 39, no. 24 (2004): 7395-7396.

[25] Tak, S. K., and M. A. Iqbal. "Axial compression behaviour of thin-walled metallic tubes under quasi-static and dynamic loading." *Thin-Walled Structures* 159 (2021): 107261.

[26] Manaf, E. H. A., et al. "Crashworthiness analysis of empty singular aluminium tubes with varying shapes in LS-Dyna." *AIP Conference Proceedings*. Vol. 2030. No. 1. AIP Publishing LLC, 2018.

[27] Kumar, A. Praveen, M. Yadi Reddy, and M. Shunmugasundaram. "Energy absorption analysis of novel double section triangular tubes subjected to axial impact loading." *Materials Today: Proceedings* (2021).

[28] Liu, Qiang, et al. "Experimental investigation into dynamic axial impact responses of double hat shaped CFRP tubes." *Composites Part B: Engineering* 79 (2015): 494-504.

[29] Abedi MM, Nedoushan RJ, Sheikhzadeh M, Yu WR. The crashworthiness performance of thin-walled ultralight braided lattice composite columns: experimental and finite element study. Composites Part B: Engineering. 2020 Dec 1;202:108413.

[30] Guades, Ernesto, et al. "Experimental investigation on the behaviour of square FRP composite tubes under repeated axial impact." *Composite Structures* 97 (2013): 211-221.

[31] Zou M, Xu S, Wei C, Wang H, Liu Z. A bionic method for the crashworthiness design of thin-walled structures inspired by bamboo. Thin-Walled Structures. 2016 Apr 1;101:222-30.

[32] Xiang J, Du J, Li D, Scarpa F. Numerical analysis of the impact resistance in aluminum alloy bi-tubular thin-walled structures designs inspired by beetle elytra. Journal of Materials Science. 2017 Nov;52(22):13247-60.