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Energy Absorption Characteristics of Thin-Walled Tubes Filled with Rice Husk and Kenaf Fibers

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ABSTRACT

This study investigates the energy absorption characteristics of thin-walled tubes filled with rice husk and kenaf fibers when compressed under axial compression. The aim of this study is to evaluate the crashworthiness parameters such as energy absorption (EA), initial peak load (IPL), crush force efficiency (CFE) and specific energy absorption (SEA). Experimental results show that tubes filled with rice husk and kenaf exhibit significant improvements in overall energy absorption compared to empty tubes. However, while both fillers enhanced EA, the SEA values were lower than predicted. Thus, it is suggested that further optimization, such as adjusting filler density or exploring hybrid filler combinations, could improve crashworthiness. This study highlights the potential for rice husk and kenaf fibers as sustainable filler options for lightweight, impact-resistant designs in automotive, aerospace, and other engineering applications, with opportunities for improvement in future research.

Keywords: Energy absorption characteristics, Filled thin-walled tube, Rice husk, Kenaf fiber, Compression test.

1. INTRODUCTION

Crashworthiness refers to a structure's ability to protect occupants from injuries during an impact [1]. It is important in industries such as automotive, aerospace, marine and railway, where manufacturers aim to enhance crashworthy designs to increase occupant safety in the event of accidents or collisions [2]. An energy absorber is a crucial component in improving crashworthiness, as it dissipates the kinetic energy of the structure by converting it into other forms of energy, thereby reducing the impact experienced by occupants. The studies of crashworthiness have been at interest to many researchers in the past until this date [3]–[5].

The common energy-absorbing structures include thin-walled tubes [6]–[8], sandwich panels [9], egg-box materials [10], lattice frameworks [11], and cellular materials [12]. Thin-walled tubes have gained significant research interest due to their ease of manufacturing and their ability to absorb high levels of energy through extensive deformation.

Over the years, various approaches have been explored to enhance the energy absorption properties of thin-walled tubes. The approach involves using different cross-sectional shapes [13]–[15], groove application [16] and many more. Additionally, advancements in materials technology have introduced a broader range of materials for use in energy absorbers, enabling

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researchers to improve the energy absorption performance of these structures by optimizing material properties.

Besides that, another approach involves the use of various filler materials, which can improve the structural performance of thin-walled tubes by modifying their deformation modes and enhancing their energy-absorbing efficiency [4], [17], [18]. For example, filling thin-walled tubes with lattice structures has been shown to significantly enhance their energy absorption performance [19]. Another well-studied approach is the use of metallic foams such as aluminum foam, which can improve energy absorption capacity by developing progressive deformation modes such as concertina folding that optimize the dissipation of impact forces [20]. Another study conducted by [21] found that low-density foam fillers, particularly polyurethane, have also proven effective in increasing energy absorption, especially when combined with structural features like circumferential grooves. The structural effectiveness of the filled specimens is approximately double that of the empty tubes, averaging around an 88% improvement.

Until now, there has been limited research focused on utilizing low-cost, eco-friendly materials as fillers in thin-walled tubes. For example, Cheng et al. [22] investigated the application of paper scraps as a biomass filler. They found that using paper scraps as the filler have successfully improved the energy absorption and increased 11.35% of specific energy absorption. This study seeks to expand on this work by exploring the effectiveness of rice husk and kenaf as sustainable fillers in thin-walled tubes and aiming to assess their potential for enhancing energy absorption in a cost-effective and environmentally friendly manner.

2. MATERIAL AND METHODS

2.1 Material preparation

In this study, stainless-steel thin-walled tubes are selected as the primary structure for evaluating energy absorption characteristics with and without fillers. The fillers chosen are rice husk and kenaf fibers, which are low-cost, eco-friendly, and readily available biomass materials. The rice husks or kenaf fibers are compacted within the tubes to achieve uniform distribution, ensuring consistent deformation behavior during the experiment, as shown in Figure 1.

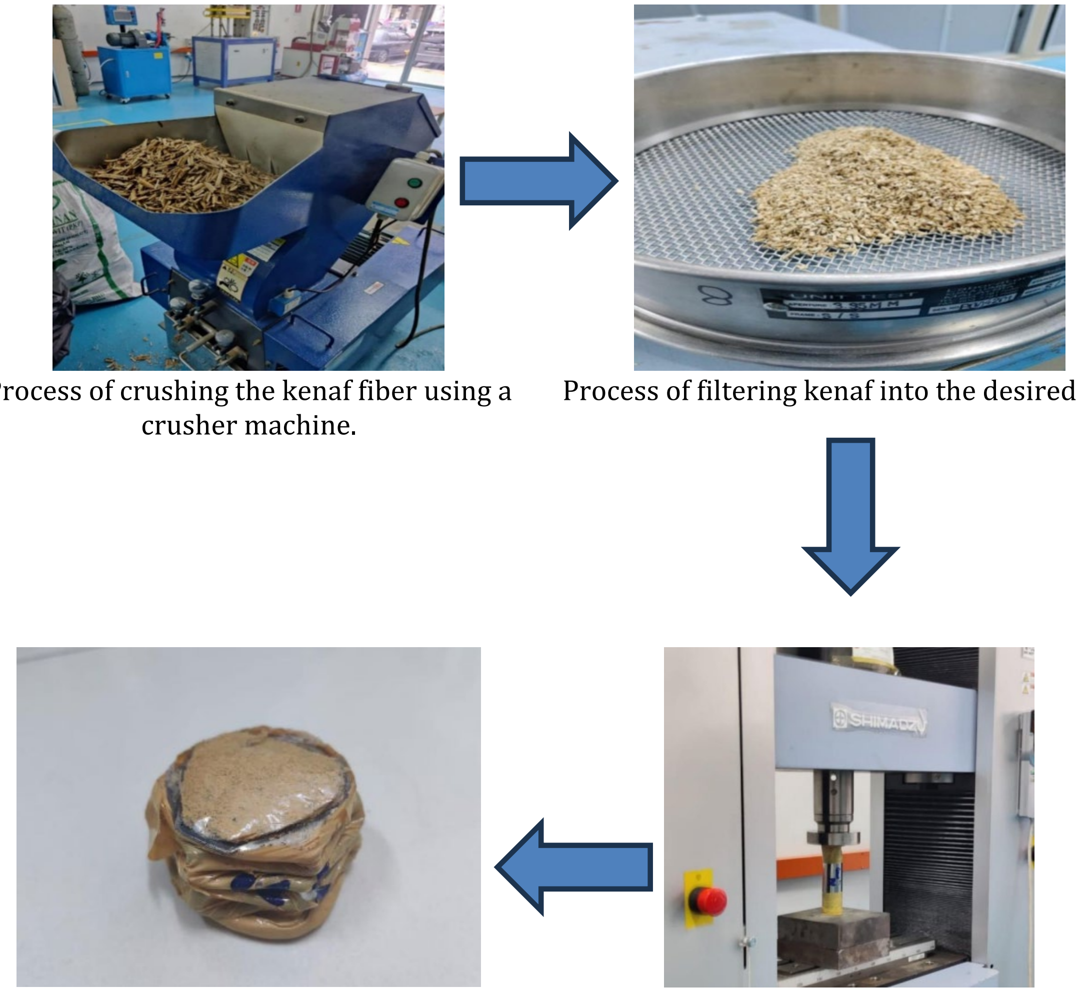
Figure 1: Stainless steel tubes filled with rice husk.

Table 1 shows the specification of the thin-walled tubes used in this study. Two different tube lengths, 100 mm and 160 mm were selected, and both have similar inner diameter and wall thickness. The tubes were filled with rice husk or kenaf fibers to achieve filler densities ranging from 130 to 390 kg/m^3 for rice husk and 60 to 140 kg/m^3 for kenaf. Each filler was carefully measured and packed within the internal volume of the tubes.

Table 1: Parameters of the stainless steel tube used in the experiment.

<table>
<tr><th>Tube length (mm)</th><th>Inner Diameter (mm)</th><th>Tube Thickness (mm)</th><th>Tube mass (kg)</th></tr>
<tr><td>100</td><td rowspan="2">35.0</td><td rowspan="2">1.0</td><td>0.086</td></tr>
<tr><td>160</td><td>0.134</td></tr>
</table>

Figure 2 shows a process for preparing and compressing the rice husk and kenaf fibers as fillers in thin-walled tubes. First, the rice husk and kenaf fibers are crushed into smaller particles using a crusher machine and filtered to achieve a specific particle size. Once prepared, the fillers are carefully packed and compacted into the tubes. These filled tubes are then subjected to compression testing by using a Universal Testing Machine (UTM) at a speed of 5mm/min to obtain the force-deformation curve.



Process of crushing the kenaf fiber using a crusher machine.

Process of filtering kenaf into the desired size.

Compressed filled tube.

Conduct compression test using UTM Machine.

Figure 2: Process of preparing and testing rice husk and kenaf fiber-filled thin-walled tubes.

2.2 Energy absorption characteristics

Energy absorption characteristics determine the efficiency level of the thin-walled structure during the crushing. The common terms used to characterize the energy absorption of a structure are energy absorption (EA), initial peak load (IPL), Crush force efficiency (CFE) and Specific energy absorption (SEA).

2.2.1 Energy absorption (EA)

The energy absorption capacity of the tube at a specified deformation length is determined by calculating the area under the load-displacement curve (Figure 3) using the integration method. This calculation is represented mathematically in Eq. 1:

$$EA = \int_0^{\delta} P \, d\delta \tag{1}$$

where δ is the deformation length, and P is the crushing load applied in the axial direction. A thin-walled tube that maximizes energy absorption at a given deformation length is considered more efficient and is preferred as an energy-absorbing device.

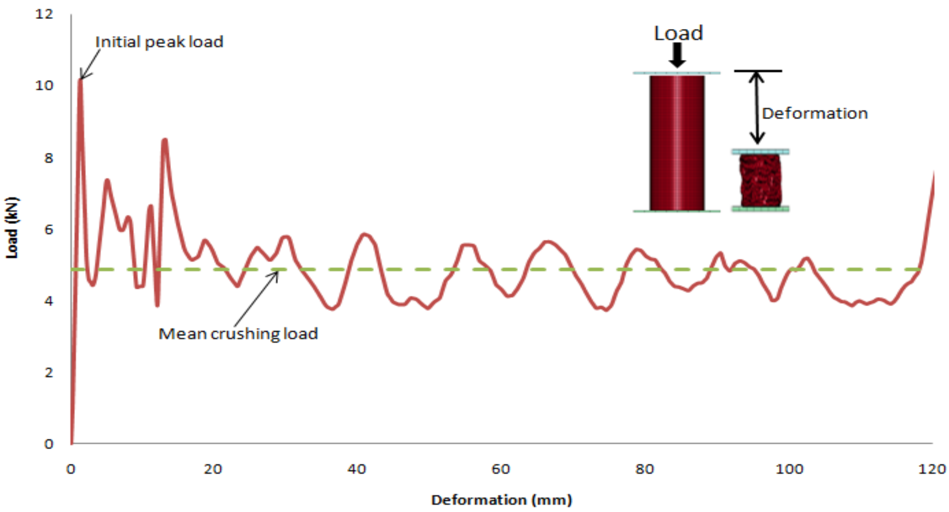


Figure 3: Load-deformation curve for axial loading of thin-walled tube.

2.2.2 Initial peak load (IPL)

In the event of an impact situation, a thin-walled tube receives forces or loads from the moving body. The initial peak load is reached when the force applied exceeds the yield strength in the elastic region and initiates the collapse of the tube. During collision in the axial direction, the first peak load commonly results in the highest value, as indicated in Figure 3. In designing the thin-walled tube, it is important to reduce the value of the initial peak load, especially when the application involves humans or passengers.

2.2.3 Crush force efficiency (CFE)

Crush force efficiency is calculated by the ratio of mean crushing force, F_{mean} to the peak load as shown in Eq. 2:

$$CFE = \frac{F_{mean}}{IPL} \tag{2}$$

An ideal thin-walled tube should have a minimal difference between the IPL and the mean crushing force during impact. In other words, a tube with a CFE value close to 1 is more efficient.

2.2.4 Specific energy absorption (SEA)

Specific energy absorption (SEA) is also known as the energy absorption capacity per unit mass. This value is obtained by Eq. 3, where m is the mass of the tube:

$$SEA = \frac{E_a}{m} \tag{3}$$

The SEA characteristic is used to get the efficiency of energy absorbed by considering the mass of the tube. It also contributes as the main parameter when attempts to achieve weight reduction are important, especially in aerospace, automotive and other lightweight engineering applications. In these sectors, the energy-absorbing component with a larger SEA indicates a more efficient structure.

3. RESULTS AND DISCUSSION

The effect of filler density on the energy absorption characteristics of thin-walled tubes filled with kenaf and rice husk are evaluated for two different tube lengths which are 100 mm and 160 mm. The measured characteristics in this result are energy absorption (EA), specific energy absorption (SEA), initial peak load (IPL) and crush force efficiency (CFE). All the results are compared at a similar compression length of 80 mm.

3.1 Energy absorption capacity (EA)

Figure 4 shows the results of energy absorption capacity for empty tube, tube filled with rice husk (rice husk filled) and tube filled with kenaf (kenaf filled) at different tube lengths. The results indicate that both types of fillers enhance the energy absorption capacity compared to empty tubes. Moreover, filled tubes exhibit an increase in EA as filler density increases. It shows that both kenaf and rice husk contribute positively to structural reinforcement under compressive loads.

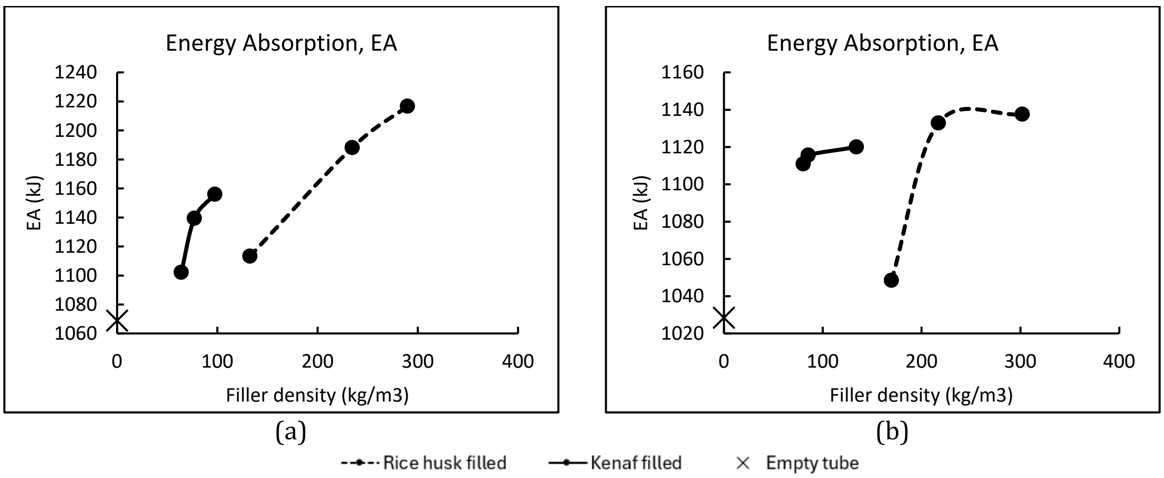


Figure 4: Effect of filler density on the energy absorption, EA of filled tubes with different tube lengths: (a) L=100mm and (b) L=160mm.

For the 100 mm tube length (Figure 4(a)), the energy absorption improves with an increase in filler density for both kenaf and rice husk. The rice husk-filled tube shows slightly higher EA values at certain filler densities, indicating that the rice husk provides better energy absorption compared to the kenaf. This finding aligns with prior studies that have demonstrated the effectiveness of natural fillers, such as paper scrap, in enhancing energy absorption capacity [22]. Besides that, for the 160 mm tube length (Figure 4(b)), the pattern varies slightly when filler densities increase. This observation is due to the structural instability or buckling in longer tubes.

3.2 Initial Peak Load

Figure 5 shows the effect of filler density on the initial peak load (IPL) for both tube lengths. The IPL generally increases with filler density, which indicates that fillers strengthen the structural resistance to initial compressive load. Kenaf-filled tubes show a rapid increase in IPL, especially for 100 mm length, while rice husk filled tubes exhibit a small increment with increasing filler densities, followed by a plateau. This behavior suggests that rice husk may contribute to load stabilization at higher densities.

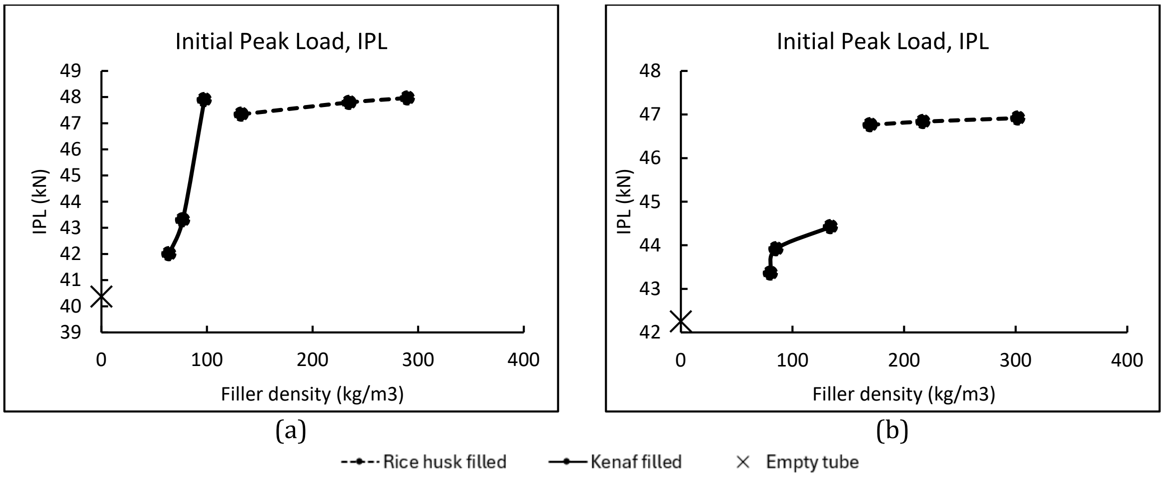


Figure 5: Effect of filler density on the initial peak load, IPL of filled tubes with different tube lengths: (a) L=100mm and (b) L=160mm.

3.3 Crush Force Efficiency (CFE)

As shown in Figure 6, the pattern of crush force efficiency (CFE) is contradicted between kenaf and rice husk filled. The CFE increases with the increasing rice husk density in both lengths' tubes. However, the CFE decreases for kenaf filled tube with an increase of filler density. In the longer tube (160 mm), CFE reaches an optimum density for rice husk, after which performance decreases, possibly due to filler density-induced brittleness and increased risk of buckling. On the other hand, it should be noted that empty tubes perform better CFE compared to the filled tubes for longer tubes.

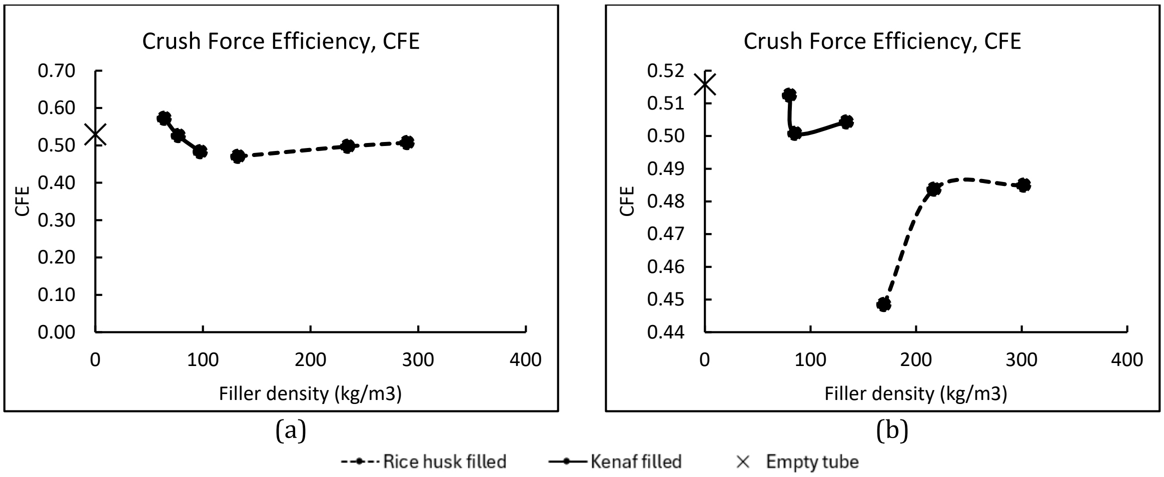


Figure 6: Effect of filler density on the crush force efficiency, CFE of filled tubes with different tube lengths: (a) L=100mm and (b) L=160mm.

3.4 Specific Energy Absorption (SEA)

Specific energy absorption (SEA) is a measure of energy absorbed relative to the tube's mass. Figure 7 shows that adding fillers generally decreases SEA, with empty tubes showing the highest SEA at all conditions. This suggests that the empty tube provides an optimal balance between weight and energy absorption capacity. This finding is similar to Kavi et al. [20], where the foam filling in thin-walled aluminum tubes increases energy absorption but is less effective in increasing specific energy absorption. Besides that, kenaf filled tube exhibits higher SEA compared to that of rice husk filled tube in both lengths. In summary, for SEA results, the implementation of rice husk and kenaf are not suitable for the application of crashworthiness. However, it is suitable if the application does not involve humans and life.

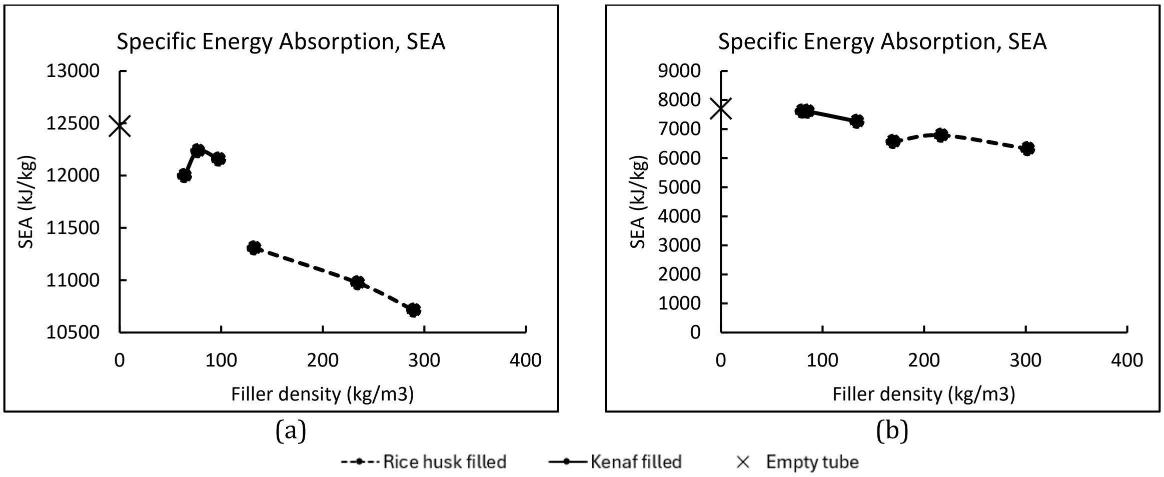


Figure 7: Effect of filler density on the specific energy absorption, SEA of filled tubes with different tube lengths: (a) L=100mm and (b) L=160mm.

4. CONCLUSION

In conclusion, this study successfully investigates the energy absorption characteristics of thin-walled tubes filled with rice husk and kenaf fiber compressed under axial compression. The results indicate that filling thin-walled tubes with rice husk and kenaf improves energy absorption capacity compared to empty tubes. Thus, there is the potential to utilize these materials for lightweight and sustainable energy-absorbing applications. Although both rice husk and kenaf fillers greatly improved the overall energy absorption (EA) compared to empty tubes, the specific energy absorption (SEA) was lower than expected, indicating potential for further enhancement. This research supports the integration of green materials into industrial applications, offering a sustainable approach aligned with modern engineering requirements.

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REFERENCES

[1] Shanahan, D. F. Basic principles of crashworthiness. Pathological Aspects and Associate Biodynamics in Aircraft Accident Investigation. (2004) pp. 1-14.
[2] Chen, J., Li, E., Li, Q., Hou, S., & Han, X. Crashworthiness and optimization of novel concave thin-walled tubes. Composite Structures, vol 283, (2022) p. 115109.
[3] Zhang, Z., Feng, C., Zhao, L., Hu, N., Hou, S., & Han, X. Crashworthiness analysis and optimization design of special-shaped thin-walled tubes by experiments and numerical simulation. Thin-Walled Structures, vol 205, (2024) p. 112240.
[4] Xiao, Y., Wu, Q. W., Liu, Y., Wang, Y. J., Long, H., & Hu, H. L. Optimization design of crashworthiness of polyurethane foam filled Origami thin wall square tube based on an surrogate model. In Structures, vol 65, (2024, July) p. 106713.
[5] Wang, Z., Liu, Z., Tao, C., & Liang, X. Crashworthiness and optimization design of additive manufacturing double gradient lattice enhanced thin-walled tubes under dynamic impact loading. Engineering Failure Analysis, vol 166, (2024) p. 108865.
[6] Gao, S., Wang, Y., Guo, L., Xu, Y., & Iyama, J. Axial behavior of circular steel tube with localized penetrating corrosion simulated by artificial notch. Thin-Walled Structures, vol 172, (2022) p. 108944.
[7] 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, vol 101, (2016) pp. 222-230.
[8] Zhang, X., Leng, K., & Zhang, H. Axial crushing of embedded multi-cell tubes. International Journal of Mechanical Sciences, vol 131, (2017) pp. 459-470.
[9] Birman, V., & Kardomateas, G. A. Review of current trends in research and applications of sandwich structures. Composites Part B: Engineering, vol 142, (2018) pp. 221-240.
[10] Chung, J. G., Chang, S. H., & Sutcliffe, M. P. F. Deformation and energy absorption of composite egg-box panels. Composites science and technology, vol 67, issue 11-12 (2007) pp. 2342-2349.
[11] Xu, W., Zhou, C., Zhang, H., Liu, Z., & Zhu, P. A flexible design framework for lattice-based chiral mechanical metamaterials considering dynamic energy absorption. Thin-Walled Structures, (2024) p. 112108.
[12] Gupta, V., Kidane, A., & Sutton, M. Dynamic characteristics of density-graded cellular materials for impact mitigation. International Journal of Solids and Structures, vol 296, (2024) p. 112816.
[13] Liu, W., Lin, Z., Wang, N., & Deng, X. Dynamic performances of thin-walled tubes with star-shaped cross section under axial impact. Thin-Walled Structures, vol 100, (2016) pp. 25-37.
[14] Zhou, B., Zhang, H., Han, S., & Ji, X. Crashworthiness analysis and optimization of a novel thin-walled multi-cell structure inspired by bamboo. In Structures, vol 59, (2024) p. 105827.

[15] Mamalis, A. G., Manolakos, D. E., Ioannidis, M. B., Kostazos, P. K., & Dimitriou, C. Finite element simulation of the axial collapse of metallic thin-walled tubes with octagonal cross-section. Thin-walled structures, vol 41, issue 10 (2003) pp. 891-900.

[16] Rahim, M. R. U., Bharti, P. K., Azmi, A. A., & Umer, A. Axial crushing comparison of sinusoidal thin-walled corrugated tubes. Materials Today: Proceedings, vol 5, issue 9 (2018) pp. 19431-19440.

[17] Goel, M. D. Deformation, energy absorption and crushing behavior of single-, double-and multi-wall foam filled square and circular tubes. Thin-walled structures, vol 90, (2015) pp. 1-11.

[18] Hussein, R. D., Ruan, D., Lu, G., Guillow, S., & Yoon, J. W. Crushing response of square aluminium tubes filled with polyurethane foam and aluminium honeycomb. Thin-Walled Structures, vol 110, (2017) pp. 140-154.

[19] Alkhatib, S. E., Tarlochan, F., Hashem, A., & Sassi, S. Collapse behavior of thin-walled corrugated tapered tubes under oblique impact. Thin-Walled Structures, vol 122, (2018) pp. 510-528.

[20] Kavi, H., Toksoy, A. K., & Guden, M. Predicting energy absorption in a foam-filled thin-walled aluminum tube based on experimentally determined strengthening coefficient. Materials & design, vol 27, issue 4 (2006) pp. 263-269.

[21] Darvizeh, A., Darvizeh, M., Ansari, R., & Meshkinzar, A. Effect of low density, low strength polyurethane foam on the energy absorption characteristics of circumferentially grooved thick-walled circular tubes. Thin-Walled Structures, vol 71, (2013) pp. 81-90.

[22] Cheng, P., Wang, Q., & Ke, S. Energy Absorption Characteristics of Thin-walled Steel Tube Filled with Paper Scraps. BioResources, vol 16, issue 3 (2021) pp. 5985-6002.

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