Improving the crashworthiness of bi-tubular architectures with ABS cores under axial loading: Experimental and Numerical Investigation

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Abstract

In this study, quasi-static axial compression tests were conducted on mild steel bi-tubular architectures with Rectangular Nested Tube (RNT) and Square Nested Tube (SNT) geometries to evaluate their crushing and crashworthiness performance. A multi-criteria decision-making approach was employed to identify the optimal energy-absorbing architecture. The SNT structure, with the smallest gap size between the inner and outer tubes, exhibited the most desirable energy absorption characteristics among the considered cases. ABS cores, with either rhombic or square cell configurations, were used to enhance the energy absorption performance of the SNT structure. A Finite Element (FE) model was created to evaluate the responses of the SNT structure filled with ABS cores. The validity of finite element simulations of the ABS cores and optimal architecture under axial compression were confirmed by comparing them with experimental results. The integration of the cores into the nested architecture enhanced crashworthiness performance and contributed to the control of the structure deformation. The SNT structure filled with rhombic ABS core exhibited superior crashworthiness

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performance compared to the counterpart filled with square core. The energy absorption of nested SNT structures filled with rhombic ABS core can be 116.93% greater than the corresponding non-filled structure. The crashworthiness indices of ABS-filled structures were highly sensitive to the number of cells and wall thickness of the core. A nested architecture with an ABS core could serve as a novel architecture for energy-absorbing devices.

Keywords: Nested structure; Crashworthiness, Energy absorption; Axial loading; ABS; multi-criteria decision making.

1. Introduction

Thin-walled structures receive widespread use as impact energy absorbers in different fields due to their cost-effectiveness, ease of manufacturing, excellent crushing performance, and high energy absorption-to-mass ratio. Such structures are vital for the automobile industry as they can enhance safety and reduce potential injuries to passengers during car crashes [1]. Crashworthiness is defined as the competence of a structure to dissipate the impact energy, minimize the forces transferred to the passenger compartment, and reduce the acceleration felt by the passengers [2]. The high capability in energy absorption of such structures is crucial to enhance the crashworthiness performance without raising its weight.

Over the past decades, extensive studies have been conducted on the structural performance of thin-walled structures under lateral loading [3-5], oblique loading [6], axial loading [7, 8], as well as impact loading [9, 10]. The early research focused on hollow thin-walled tubes with simple cross-sections such as square and circular. One of the pioneering investigations on the axial crushing of the circular tube was carried out by Alexander [11], who examined the effect of diameter-to-thickness ratio on the crushing behaviour and introduced a theoretical formula to calculate the average crushing load in the case of axis-symmetrical collapse. For the square tube, Abramowicz [12] studied its axial crushing behaviour and proposed a formula estimating the crushing distance, which agreed well with the experimental data. Two main deformation mechanisms, including in-extensional and extensional crinkling modes, were observed for square tubes under axial loading [13]. Wierzbick and Abramowicz [14] analysed the plastic deformation of square tubes and proposed a theoretical model to predict mean crushing load. In addition to the square and circular tubes, the crashworthiness performance of other sections such as triangular, square, hexagonal, and octagonal have been investigated and compared. Waleed et al. [15] investigated thin-walled energy absorption structures which consist of two end-capped frusta and a cylindrical shell. These structures absorb the energy through the processes of inversion, folding and expansion. It was found that increasing lower frustum thickness enhanced energy absorption during inversion while heightening the middle shell reduced energy absorption. The contribution of energy absorption in the expansion process was found to be low. Nia and Hamedani [16] compared the energy absorption characteristics of the thin-walled tubes with various geometries under axial compression and noted that the energy absorption depends on the cross-sectional shape where the circular tube offers the highest energy absorption capacity. Nia and Parsapour[17] compared the energy absorption features of simple and multi-cell tubes with five different sections. It was found that the energy absorption increases by increasing the number of corners in the section. Also, it was noticed that multi-cell tubes with wall-to-wall connections provide better energy absorption performance than those with wall-to-corner connections. Baykasoğlu et al. [18] compared the crashworthiness performance of tubes with graded and uniform thicknesses and pointed out the superior performance of the tube with graded thickness configuration. Looi et al. [19] conducted rigorous numerical simulations on sandwich structures featuring thin-wall hexagonal cores, identifying key parameters that influence the maximum mid-span deflection and subsequently developing an empirical formula for predicting this deflection. Mustaffa et al. [20] investigated the application of thin-walled honeycomb structures as reinforcement in the lithium-ion battery (LIB) pack of electric vehicles and demonstrated significant reductions in both damage and deflection when compared to non-reinforced scenarios.

Nested tube structures were proposed as solutions to meet the demand for larger energy absorption capacity. Nested tube structures have two or more deformable tubes stacked together in a limited deformation zone; therefore, they absorb greater energy per unit length compared to a single hollow tube [21]. Such structures have been studied vastly in the literature. Alavi Nia and Chahardoli [22] investigated the influence of the number of tubes on the crashworthiness characteristics of the nested system and pointed out that the specific energy absorption of the five-tubular system was increased by 88% compared to a single tube. The work of Vinayagar and Kumar [23] also concluded that the specific energy absorption of the bi-tubular system was more than twice compared to that of a single tube. Chahardoli et al. [24] examined the quasi-static crushing of nested tube structures composed of an inner tube placed vertically inside a horizontal outer tube. It was found that increasing the diameter and decreasing the thickness of the inner tube resulted in a reduction of the specific energy absorption.

With the advancement of technology, 3D printers are widely used in producing energy-absorbing structures and many researchers have explored the behaviour of such structures. Dar et al. [25] investigated the compression behaviour of 3D-printed polymeric micro-lattice structures. It was observed that the size and number of cells play a vital role in the compressive and energy absorption characteristics. Sharma and Hiremath [26] studied the energy absorption features of bio-inspired lattice structures. They explored the impact of strut thickness, relative density, and unit cell size on energy absorption. These structures demonstrated improved energy absorption capacity and high mean value stress, making them promising for energy absorber development. Kumar and Sezhian [27] considered the crushing resistance of the structures with different sections made of different polymer filaments. It was concluded that structures made of polymer composite have a higher energy absorption compared to structures made of traditional polymer. Usta et al. [28] investigated the behaviour of the sandwich panels with different auxetic cores. The insertion of a re-entrant core composed of ABS filament has been found to exert no significant impact on the peak load. Kucewicz et al. [29] investigated the crashworthiness properties of different cellular structures. These cellular structures showed a stable plateau stress and the honeycomb one has better crashworthy characteristics. Le et al. [30] investigated 3D-printed multicellular structures made from two materials using various geometries. Six experimental and 30 numerical samples were examined and the results showed that as the number of cells increased, the energy absorption also increased. Ramakrishnan et al. [31] examined the deformation behaviour and energy absorption of a novel 3D-printed bioinspired Xylotus lattice structure under quasi-static compressive loading. Inspired by xylem and lotus elements, the Xylotus lattice exhibited a sequential failure pattern, with axial cracks followed by buckling.

While nested tube structures have received attention in the literature, a systematic comparison of energy absorption responses among nested structures with various geometrical shapes remains limited. Furthermore, the application of polymer cores, such as 3D-printed ABS structures, into energy absorbers is increasing. However, studies on the behaviour of the nested structure with a polymer core are still limited. This study aims to address this gap by conducting a comparative analysis of nested bi-tubular architectures with both rectangular and square sections as well as investigating the effect of the ABS core on the crashworthiness performance of the structure. To achieve this, the axial crushing and energy absorption responses of the nested structures with different configurations were extracted experimentally first. Then, the CRITIC-MOORA approach was used to compare their crashworthiness performance and identify the best-performing nested structure. Following that, experimentally validated finite element simulations were constructed and utilized to compare the crashworthiness responses of the best-performing nested structure with and without ABS cores. Finally, an efficient crashworthiness design is proposed.

2. Methodology

2.1 Structural geometry and materials

In this study, two bi-tubular structures, specifically the rectangular nested tube (RNT) and square nested tube (SNT), are examined as components for absorbing impact energy. The square and rectangular tubes have been extensively utilized in previous research as parts for energy absorption, thus justifying their selection for this work. One RNT configuration and three SNT configurations, each with varying dimensions and gap sizes between the inner and outer tubes, are analysed and compared. All constituent tubes, namely the inner and outer tubes, possess a length (l) of 200 mm and a thickness (t) of 1.3 mm. Fig. 1(a) provides a visual representation of the geometric configurations of the distinct nested tubes. Moreover, to further enhance the crashworthiness performance, two types of cores, A1 and A2, made from Acrylonitrile Butadiene Styrene

(ABS) filament [30], are incorporated into the optimal nested architecture (Fig. 1(b)). The cell shapes of A1 and A2 cores are rhombic and square, respectively. It is assumed that there is no adhesive between the walls of the nested structure and the core. To fully explore the influence of core geometry on crashworthiness performance, a parametric study was conducted by considering two main variables, including the number of cells (n) and the wall thickness (t), of both cores. Three levels are adopted for n and t resulting in nine configurations for each core. A naming convention is adopted for composite structures, i.e., nested structures with ABS core. For instance, the term S_A2-5 refers to the SNT1 structure filled with an A2 core, featuring 4 cells in the horizontal direction and a wall thickness of 1.4 mm. Table 1 lists the key geometrical parameters for the different structures investigated in this work. The crushing behaviours of nested tubes without and with cores are then studied using experimental testing and numerical simulation, respectively.

The tubes utilized for the construction of both RNT and SNT are composed of mild steel CT3. To determine the mechanical properties of the mild steel, a standard tensile test was carried out. The tensile stress-strain relationship and the corresponding mechanical characteristics of both the steel and ABS materials are depicted in Fig. 2.

Fig.1. a) Nested bi-tubular architectures and b) composite architecture.

Table 1. Details of the samples

Fig.2. Stress-strain curve of: a) mild steel CT3 and b) ABS[30].

Fig.3. Crushing test machine

2.2 Crushing tests

The quasi-static axial compression experiments were conducted using a universal testing machine, shown in Fig. 3, with a maximum loading capacity of 500 kN. The samples were placed between the upper and lower platens of the machine. To maintain as perfect as possible alignment for the samples during the crushing test, a specially designed fixture is employed to position the sample on the lower platen, as shown in Fig. 3. All tests were conducted at room temperature where the nested tube samples were compressed axially to 136 mm, due to the densification of all samples. During the tests, the load-displacement responses were recorded via the data-gaining system and the deformation history was captured using a video recorder.

2.3 FE Model

FE models of the SNT1 structure and ABS cores were built using the finite element-based solver LS DYNA. The numerical responses of FE models were compared with experimental compression data to validate their accuracy. These numerical simulations provide insight into the deformation process of bi-tubular structures with core and help to optimize the configuration for better compression and energy absorption characteristics. The Belytschko–Tsay 4-node shell elements were used to model the walls of the components. Unrefined meshing was applied to upper and lower plates as they were defined as rigid. The piecewise linear plasticity material model MAT024 was used to model the materials, with the properties and stress-strain curves shown in Fig. 2. The lower plate is fully fixed in all degrees of freedom while the upper compression plate is allowed to move along the axial direction (i.e., z direction) of the tube at a rate of 1 mm/s. Two contact types were applied to capture the interaction between different surfaces of the FE model. Automatic single-surface and surface-to-surface contact types were employed to model the self-contact of the tube and the interaction between the tube and plates, respectively. All contacts used a friction coefficient of 0.3 to inhibit any possible lateral movement, i.e., slippage, between the surfaces [32].

A comparison between experimental and numerical responses was conducted to verify the capability of FE models to simulate the required crush behaviour. Fig. 4(a) compares load and deformation responses for cores. The numerical deformation modes and load responses agree with those of experimental tests. Peak Crush Loads (PCLs) derived from the simulation exhibited minor discrepancies when compared to those obtained from experiments, with errors of only 2.05% and 3.47% for A1 and A2 cores, respectively. For the SNT1 architecture, the deformation mode, PCL, Mean Crush Load (MCL), and load-displacement curves obtained from numerical simulations and tests are revealed in Fig. 4(b). As can be seen from this figure, both numerical and experimental deformation modes are comparable showing that the nested architecture exhibits an in-extensional deformation pattern with three folds. The differences between the test and the simulation for MCL and PCL responses were 2.59% and 3.47%, respectively. Overall, the above comparison results affirm the validity and reliability of FE models.

Fig. 4. Validation of: a) the ABS filament core[30] and b) SNT1 architecture.

Table 2. Equations of energy absorption indicators

2.4 Crashworthiness indicators

To evaluate and compare the crashworthiness performance of the different nested tubes, the main crashworthiness indicators, including the Energy Absorption (EA), the initial PCL, MCL, Crush Load Ratio (CLR), and Specific Energy Absorption (SEA), are determined. Such indicators are commonly used to assess the energy absorption capacity of thin-walled structures [33]. The equations to calculate these indicators are summarized in Table 2. EA is the work done by the crushing force, during the deformation process, and it can be obtained as the area under the force-displacement curve. PCL is the initial maximum load experienced by the structure in the axial direction. PCL is closely related to the formation of the first lobe during axial compression and it affects the survival rate of the passengers in the vehicle's cabin [23]. MCL is defined as the total energy absorption capacity divided by the total crushing displacement. SEA refers to the energy absorption capacity per unit mass of the structure. CLR is the ratio of MCL to PCF; it is a measure of the load fluctuations during the crushing process. Generally, for a good energy absorption design, the structure should provide high CLR, high SEA, and low PCL.

2.5 Multi-Criteria Decision Making

According to many literature studies, selecting a suitable energy absorption architecture from a group of candidates is not an easy task. This is because the desirable energy absorption responses, i.e., high SEA and low PCL, conflict with each other significantly as the structure that absorbs the highest energy is not necessarily the same one that has the lowest peak force. This conflict complicates the process of selecting the best energy absorption architecture among the multiple candidates. Therefore, Multi-Criteria Decision Making (MCDM) methods are normally employed in crashworthiness design problems to reach a final decision regarding the best architecture. Being one of the highly efficient and reliable MCDM approaches, the multi-objective optimization based on ratio analysis (MOORA) approach [34] is applied to determine the best structural configuration in the current study.

In MCDM, each criterion possesses its own weighting coefficient, underscoring the significance of determining these weights. Weights assigned to criteria in multi-criteria evaluation incorporate both qualitative and quantitative data to facilitate a more accurate and well-informed decision-making process. However, the use of qualitative data for weight assignment can be influenced by decision-maker bias. Objective weighting methods derive criteria weights from information obtained through mathematical models for each criterion, effectively mitigating decision-maker influence. Several methods for deriving weighting coefficients include entropy, mean weight, statistical variance procedure, and Criteria Importance Through Inter-criteria Correlation (CRITIC). To enhance the outcome of the MOORA approach, its weighting coefficients are estimated using the CRITIC method. Consequently, the comprehensive implementation of the CRITIC-MOORA approach involves the following steps.

Step 1: Constructing an initial decision matrix X which maps the design alternatives, i.e., the RNT and SNT architectures, to their attributes, i.e., energy absorption indicators.

$$\mathrm{X} = \left[\mathrm{x_{ij}}\right]_{\mathrm{mn}} = \begin{bmatrix} \mathrm{x_{12}} & \mathrm{x_{12}} & \cdot\cdot & \mathrm{x_{1n}} \\ \mathrm{x_{21}} & \mathrm{x_{22}} & \cdot\cdot & \mathrm{x_{2n}} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ \mathrm{x_{m1}} & \mathrm{x_{m2}} & \cdot\cdot & \mathrm{x_{mn}} \end{bmatrix} \tag{1}$$

where m is the number of the alternatives and n is the number of attributes. Thus, $\mathrm{x_{ij}}$ is the response $\mathrm{j_{th}}$ of the $\mathrm{i_{th}}$ architecture.

Step 2: Constructing the normalized the decision matrix X^* using equation 2

$$X^* = \left[x_{ij}^*\right]_{\mathrm{mn}} = \frac{x_{ij}}{\left[\sum_{i=1}^{m} x_{ij}^2\right]^{1/2}} \, (j = 1,2,\cdots,n) \tag{2}$$

Step 3: Estimating the assessment values using Eq. (3)

$$y_i = \sum_{i=1}^{g} w_j x_{ij}^* - \sum_{j=g+1}^{n} w_j x_{ij}^* \, (j = 1,2,\cdots,n) \tag{3}$$

where g is the number of beneficial attributes and $(n-g)$ is the number of the non-beneficial attributes. w_j is the weight of the $\mathrm{j_{th}}$ attribute (so-called significance coefficient).

As mentioned earlier, w_j is obtained using the CRITIC method which involves the following steps

a) Normalizing the decision matrix according to Eq. (4)

$$\overline{X_{ij}} = \frac{X_{ij} - X_j^{worst}}{X_j^{best} - X_j^{worst}} \quad (4)$$

b) Calculating the standard deviation σ_j for each response

c) Determining the symmetric matrix of nxn with element r_{jk}

d) Calculating the measure of the conflict created by criterion j with respect to the decision situation defined by the rest of criteria

$$\sum_{k=1}^{m} (1 - r_{jk}) \quad (5)$$

e) Determining the quantity of the information in relation to each criterion using Eq. (6)

$$C_j = \sigma_j \cdot \sum_{k=1}^{m} (1 - r_{jk}) \quad (6)$$

f) Determining the objective weights based on Eq. (7)

$$w_j = \frac{C_j}{\sum_{k=1}^{m} C_k}, \quad (7)$$

Step 4: Finding the rank of each architecture based on the value of y_i where the architecture with highest y_i is ranked first and the architecture with lowest y_i value is ranked last.

3. Compressive behaviour

When a thin-walled structure made of a metallic ductile material, such as aluminium or steel, is subjected to axial loading, it undergoes a progressive collapse mode and exhibits a typical force-displacement response as depicted in Fig. 4(b). During the crushing process, the force increases initially to a peak value and then drops and starts to fluctuate around a mean level. Three distinct regions can be recognized in the force-displacement curve including elastic or pre-buckling, plastic or post-bucking, and finally self-contact or stacking. In the elastic region, the crushing force increases rapidly to a peak value at which the plastic deformation process starts with the local buckling of the structure wall and forming the first wrinkle. The value of the peak force depends on the axial stiffness of the structure. In the plastic region, progressive plastic deformation takes place where many wrinkles form in the structure giving rise to fluctuations in the crushing force. Finally, at the end of the deformation process, self-contact of the structure's material takes place where the formed wrinkles stack one over another leading to a significant increase in the crushing force. In the remainder of this section, the experimental crushing responses of the nested bi-tubular architectures will be examined. To ensure the reliability of the experimental results, three compressive tests were performed for each configuration of the nested architectures, except two tests for SNT1 structure.

3.1. RNT Architecture

The compressive responses, deformation modes, and crashworthiness metrics of all RNT specimens are shown in Fig. 5. The RNT specimens exhibit similar pre-buckling (elastic) responses where the first buckling lines, i.e., the first wrinkles, were formed at the upper end of the samples. Unlike the elastic responses, the post-buckling stages of the RNT samples are somewhat different. In fact, such differences are expected as the experimental responses are normally sensitive to the geometrical and material imperfections within the specimens which vary from specimen to specimen even if they are prepared carefully. The deformation mechanism of the RNT (SP1) sample was slightly different compared to the other samples, i.e., RNT (SP2) and RNT (SP3). RNT (SP1) formed two complete lobes during the crushing process (Fig. 5(a)) while no complete lobes were developed during the crushing of RNT (SP2) and RNT (SP3) samples. This is an indication that the two constituent tubes of the RNT (SP1) sample may have developed lobes at the same axial location leading to the alignment between the formed lobes. For RNT (SP2) and RNT (SP3) samples, the outer tubes swelled and didn’t form completed lobes during their deformation. Such behavior may be due to the lack of alignment between the wrinkles of the inner and outer tubes. In these samples, the formed lobes of the inner tube acted as stiffeners to the outer tube preventing it from forming completed lobes and causing greater contact and interaction between the inner and outer tubes. The higher interaction between the two constituent tubes of RNT (SP2) and RNT (SP3) samples resulted in an increase in the overall crushing resistance of these samples compared to RNT (SP1). This has been reflected in the force-displacement curves (Figs. 5(b and c)) which show that RNT (SP1) deform at lower force levels compared to those of RNT (SP2) and RNT (SP3). Similarly, the higher interaction effects observed in RNT (SP2) and RNT (SP3) caused higher plastic deformation of the tubes’ materials and led to greater energy dissipation. Fig. 5(d) clearly shows that the SEA of RNT (SP1) is lower than its SP2 and SP3 counterparts. The MCL and SEA responses of the RNT (SP3) are the highest among all the tested RNT samples meaning that the interaction effect in this sample is the greatest.

3.2. SNT Architectures

3.2.1 SNT1 architecture

According to the geometrical dimensions, the SNT1 architecture has a gap of 5 mm between the inner and outer tubes. The deformation modes of the SNT1 samples are shown in Fig. 6(a). The initial plastic deformation, i.e., the formation of the first wrinkle, took place at different locations in the different SNT1 samples. The deformation started at the upper end in SNT1 (SP1) while it started at both the upper and lower ends simultaneously in SNT1 (SP2). Similar observations have also been reported in [35]. The SNT1 samples have overall shown good progressive deformation modes but the number of lobes developed in each SNT1 sample was slightly different. The SNT1 (SP1) developed three completed lobes while SNT1 (SP2) developed two completed lobes and one non-completed lobe. These small variations in the deformation modes between the different samples are linked to how the inner and outer tubes of each sample have interacted with each other.

Fig.5. Crushing responses of RNT specimens: a) deformation mode, b) load-displacement curves, c) MCL-displacement curves and d) SEA-displacement curves.

Fig.6. Crushing responses of the SNT1 specimens: a) deformation mode, b) load-displacement curves, c) MCL-displacement curves and d) SEA-displacement curves.

Fig.7. Crushing responses of SNT2 specimens: a) deformation mode, b) load-displacement curves, c) MCL-displacement curves and d) SEA-displacement curves.

Fig.8. Crushing responses of the SNT3 specimens: a) deformation mode, b) load-displacement curves, c) MCL-displacement curves and d) SEA-displacement curves.

The variations of load, MCL, and SEA responses with the crushing displacement during the deformation process are displayed in Figs. 6(b, c, and d). Overall, all the SNT1 samples exhibit similar force-displacement responses due to the similar deformation modes noted earlier. Fig. 6(c) shows that the SNT1 (SP1) has slightly higher levels of MCL in the post-collapse region indicating a greater interaction effect for this sample. Similarly, the SEA of SNT1 (SP1) was higher than its counterpart, i.e., SNT1 (SP2), throughout the deformation process as can be seen from Fig. 6(d).

3.2.2 SNT2 architecture

The deformation history along with the crushing responses of SNT2 samples are presented in Fig. 7. It is clear from Fig.7a that the positions of the first buckling lines vary from sample to sample. The buckling lines appeared near the lower end of SNT2 (SP1 and SP3) while developed near the middle region of the SNT2 (SP2). All the samples developed three lobes during the crushing process.

Figs. 7(b, c, and d) show that all SNT2 samples have comparable load, MCL, and SEA responses. This is expected due to similar deformation modes of these samples as revealed in Fig.7a. The SNT2 (SP3) sample develops the peak force at lower crushing displacement compared to the other two samples; therefore, the MCL of this sample is greater than the other two samples during the pre-buckling stage of the deformation process. In the post-collapse stage, the SNT2 (SP2) yields slightly higher MCL and SEA responses than the other samples.

3.2.3 SNT3 architecture

The deformation patterns and force-displacement curves of the SNT3 specimens are displayed in Fig. 8. It can be seen from Fig.9a that the initial plastic hinges were developed at the upper ends of samples one and three (i.e., SP1 and SP3), whereas they simultaneously appeared at the upper end and middle region of the SP2 sample. All the samples developed three lobes during their deformation with different wavelengths. The lobes of the SP2 sample were compact while the lobes of the SP1 and SP3 samples were non-compact, i.e., bulging mode.

The load-displacement curves (Fig. 8(b)) show that PCLs of the SP1 and SP2 samples develop earlier than that of the SP3 sample, resulting in larger MCL values during the early stages of the compression process (Fig. 8(c)). Fig.8b also shows that the load fluctuations of the SP1 and SP3 samples are greater than that of the SP2 which shows almost a flat load-displacement response during most of the compression process. Figs. 8(c and d) show that the SEA and MCL of the SP2 sample are greater than their counterparts, i.e., SP1 and SP3 samples, at any crushing displacement.

3.3. Comparison of crashworthiness performance

Generally, high SEA and low PCL and mass are the main design requirements for an effective energy absorber [36]. Therefore, crashworthiness engineers should aim to develop energy-absorbing devices with a high energy dissipation to mass ratio while maintaining PCL under the allowed threshold to reduce the risk of injury to the passengers during an accident event.

Table 3 lists all the energy absorption metrics, including EA, SEA, MCL, and CLR, for all tested samples and the mean metrics for each architecture type. The RNT architecture absorbs greater energy offering the highest EA among all investigated architectures. The EA of the RNT architecture is 5.22%, 10.74%, and 11.82% higher than SNT1, SNT2, and SNT3, respectively. Similarly, the RNT architecture yielded MCL of 77.09 kN which is higher than those of the square nested architectures. This trend could be due to the higher interaction effects between the constituent tubes and the greater material deformation in the RNT architecture. Despite the good EA and MCL performance of the RNT architecture, its SEA is less than that of the SNT1 architecture which absorbed the highest SEA among all tested architectures. Thus, SEA depends primarily on the mass of the structure.

For PCL response, the SNT2 and SNT1 architectures offer the highest and lowest PCL values, respectively. The PCL of the SNT1 architecture is 2.75%, 6.54%, and 4.48% lower than those of RNT, SNT2, and SNT3 architectures, respectively. As it is known, PCL is the force required to develop the first buckling lines in the structure. The lower PCL values observed in the SNT1 architectures are due to the fact that they have slightly lower masses compared to other architectures; therefore, they have lower stiffness and require smaller forces to initiate plastic deformation.

From inspecting the CLR values, one can see that all architectures yield CLR values ranging from 0.5 to 0.6. The RNT architecture outperforms other architectures yielding

CLR which is 2.48%, 15.18%, and 12.47% greater than SNT1, SNT2, and SNT3 architectures, respectively.

As described in section 2.1, the SNT architectures were prepared with different gap sizes between the inner and outer tubes. Therefore, it is important to compare the energy absorption characteristics of the SNT architectures to understand the role of the gap size. It can be seen from Table 1 that the SNT1 architecture, which has the lowest gap size of 5 mm, offers the highest SEA, highest CLR, and lowest PCL among all SNT architectures. The small gap size in the SNT1 architecture causes higher interaction effects, i.e., greater contacts between the inner and outer tubes, during the crushing process which in turn was translated into greater plastic deformation of these tubes and led eventually to increasing the energy absorption capability. SNT2 and SNT3 architectures with gap sizes of 10 mm and 15 mm, respectively, exhibit comparable energy absorption capability and similar SEA values indicating that the interaction effects in these architectures are comparable.

Table 3. Energy absorption indicators for all tested RNT and SNT samples

Table 4. Weighting coefficients and mean value of each attribute for all groups

Table 5. Rank of the architectures

3.4. Best architecture for crashworthiness design

In the field of crashworthiness, a critical consideration for structures is their ability to absorb energy effectively. This is crucial for maintaining a desirable level of safety for occupants. The efficiency of such structures is often measured through the SEA index, which evaluates the amount of energy absorbed relative to the mass of the structure. When designing vehicles with passenger safety in mind, it is important to also consider the potential for high PCL or deceleration, as this factor significantly increases the risk of injury. Consequently, minimizing the PCL index and keeping it within a safe range becomes fundamental.

To apply the modified CRITIC-MOORA approach, SEA and CLR are set as the beneficial responses, whereas m and PCL are selected as the non-beneficial responses. The mean values of the energy absorption response for each architecture are used. The decision-making matrix for the current work consists of four architectures, including RNT, SNT1, SNT2, and SNT3, and four attributes encompassing m (mass), SEA, PCL, and CLR. Table 4 shows the used responses and their weighting coefficients as obtained by Eq. (7). Table 5 displays the ranking of the four architectures based on the modified CRITIC-MOORA approach. As can be seen, the SNT1 architecture is ranked first while the SNT3 architecture is ranked last. Thus, SNT1 and SNT3 are the best and worst energy-absorbing architectures in this paper.

4. Effect of core on crashworthiness performance

4.1. Effect of core on force-displacement responses and deformation mode

Based on the validated FE models of SNT1 and ABS cores, FE models of ABS-filled nested structures (named S_Ai-j) were created to investigate the effect of cores on their crushing. The cores comprise 3, 4, or 5 cells in the horizontal direction with a thickness of 1, 1.4, or 1.8 mm. When compared to the S_A2-j architecture (with square core), the corresponding S_A1-j architecture (with rhombic core) possesses a larger mass, which negatively impacts the SEA. This is due to the fact that an increase in mass invariably results in a decrease in SEA, as observed in Table 2.

The behaviours of S_A1-j and S_A2-j architectures under quasi-static loading are illustrated in Figs. 9 and 10. Although the crushing resistance of the steel tube surpasses that of the ABS core, the integration of the ABS core and the SNT1 architecture enhances the stability of the deformed architecture and governs the deformation process, resulting in a superior crashworthiness performance compared to the non-filled SNT1 architecture. A comparison of the SNT1 and S_Ai-j, as depicted in Figs. 6, 9 and 10, reveals that the S_Ai-j demonstrates a higher crushing resistance, thus requiring more energy for deformation. In comparison to the SNT1 architecture, the mass of the S_A1-6 is 30.1% larger, yet its EA is 116.93% larger.

Despite the similarity in deformation observed in Figs. 9 and 10, a difference in load response is noted for both S_A1-j and A2-j architectures, as evidenced by the fluctuation in load. The fluctuations in the load response of the S_A1-j architectures exceed that of the S_A2-j ones, thereby confirming the role of the core type in governing the mode of deformation. A larger fluctuation in load reveals a more substantial failure in the core, which leads to increased energy dissipation. Furthermore, the load levels of the S_A1-j architectures surpass those of the S_A2-j ones.

All four crashworthiness parameters, including PCL, EA, CLR, and SEA, of the S-A1-j architectures are larger than those of the S_A2-j ones (Fig 11), with the exception of the S_A2-9. In comparison to the S_A1-9 architecture, the S_A2-9 architecture exhibits a 13.08% larger EA, a 24.9% larger SEA, a 0.58% smaller PCL, and a 4.74% smaller CLR, resulting in larger EA, CLR, and SEA values than most of the other architectures.

Fig.9. Behaviours of the S_A1-j architecture.

Fig.10. Behaviours of the S_A2-j architecture.

Fig.11. Comparison of: a) PCL, b) EA, c) CLR and d) SEA for S_A1-j and S_A2-j architectures.

4.2. Role of cells and thickness

The comparison in Fig. 11 aims to examine the impact of cell number and wall thickness on crashworthiness indexes. When the wall thickness remains constant, an increase in the number of cells leads to an increase in PCL, EA, CLR, and SEA. However, a decrease in EA, SEA, and CLR is observed when the number of cells reaches 5. On the other hand, when the number of cells is kept constant, an increase in wall thickness results in an increase in PCL, EA, CLR, and SEA.

For both S_A1-j and S_A2-j architectures, a simultaneous increase in cells and thickness results in an increase in all parameters. The only exceptions are the smaller cells (3 and 4) of the S_A2-j architectures. The CLRs of S_A2-3 and S_A2-6 are 4% and 2%, respectively, smaller than those of S_A2-2 and S_A2-5. This discrepancy is attributed to a sharp increase in their PCLs. It can be seen that the number of cells and wall thickness of the core strongly influence four parameters.

These results demonstrate that the ABS core enhances the crushing and crashworthiness performance of the SNT1 architecture. Hence, the S_A1 architecture (the SNT1 tube filled with a rhombic ABS core) is considered the most efficient crashworthiness design.

5. Conclusion

In this research, the crashworthiness performance of different empty and ABS-filled nested tube structures was investigated experimentally and numerically.

Key findings from this study can be summarized as follows:

- Each empty nested tube structure, i.e., without a core, exhibited a distinct deformation pattern depending on the geometrical configurations of its inner and outer tubes. The interaction effects between the inner and outer tubes have a significant impact on the crashworthiness responses of these structures.
- SNT1 architecture, featuring a small gap size between inner and outer square tubes, was found to be the best empty nested tube structure. SNT1 design exhibited the highest specific energy absorption (SEA) among all empty nested tube architectures, meaning that it is the most weight-effective structure.
- Although they have higher masses, the nested tube structures filled with ABS core presented notable improvements in energy absorption performance compared to empty tubes.
- The crashworthiness indices of S_Ai-j architectures were highly sensitive to cell shape, number of cells, and wall thickness of the ABS core. This emphasizes the importance of core geometrical design optimization.

In summary, this comprehensive investigation proved the promising potential of nested bi-tubular architectures with ABS cores as innovative solutions for energy-absorbing devices, paving the way for future advancements in crashworthiness design.

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Annexe: Weighting coefficients are determined using the CRITIC method

Architecture	PCL (kN)	m (kg)	CLR	SEA (kJ/kg)
RNT	132.48	1.281	0.58	8.20
SNT1	127.83	1.047	0.57	9.52
SNT2	137.70	1.175	0.51	8.06
SNT3	134.87	1.298	0.52	7.23
Worst	137.70	1.298	0.51	7.23
Best	127.83	1.047	0.58	9.52

Table A1. Decision matrix

Architecture	PCL	m	CLR	SEA
RNT	0.53	0.07	1.00	0.42
SNT1	1.00	1.00	0.87	1.00
SNT2	0.00	0.49	0.00	0.36
SNT3	0.29	0.00	0.16	0.00
Standard deviation (σ_j)	0.42	0.46	0.50	0.41

Table A2. Normalized decision matrix and standard deviation

	PCL	m	CLR	SEA
PCL	1.00	0.56	0.82	0.79
m	0.56	1.00	0.21	0.89
CLR	0.82	0.21	1.00	0.62
SEA	0.79	0.89	0.62	1.00

Table A3. Symmetric matrix

	PCL	m	CLR	SEA	$\sum_{k=1}^{m}(1-r_{jk})$	c_j
PCL	0.00	0.44	0.18	0.21	0.83	0.35
m	0.44	0.00	0.79	0.11	1.33	0.61
CLR	0.18	0.79	0.00	0.38	1.34	0.67
SEA	0.21	0.11	0.38	0.00	0.70	0.29
w_j	0.18	0.32	0.35	0.15		**1.92**

Table A4. C_j and weighting coefficients

Reference

1. Baroutaji A, Sajjia M and Olabi A-G. On the crashworthiness performance of thin-walled energy absorbers: Recent advances and future developments. *Thin-Walled Structures* 2017; 118: 137-163. DOI: https://doi.org/10.1016/j.tws.2017.05.018.
2. Soltani M, Topa A, Karim MR, et al. Crashworthiness of G4(2W) guardrail system: a finite element parametric study. *International Journal of Crashworthiness* 2017; 22: 169-189. DOI: 10.1080/13588265.2016.1243636.
3. Baroutaji A, Arjunan A, Stanford M, et al. Deformation and energy absorption of additively manufactured functionally graded thickness thin-walled circular tubes under lateral crushing. *Engineering Structures* 2021; 226: 111324. DOI: https://doi.org/10.1016/j.engstruct.2020.111324.
4. Al Rifaie M, Mian A and Srinivasan R. Compression behavior of three-dimensional printed polymer lattice structures. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2018; 233: 1574-1584. DOI: 10.1177/1464420718770475.
5. Dara A, Johnney Mertens A and Raju Bahubalendruni MVA. Characterization of penetrate and interpenetrate tessellated cellular lattice structures for energy absorption. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2022; 237: 906-913. DOI: 10.1177/14644207221129709.
6. Tran T and Baroutaji A. Crashworthiness optimal design of multi-cell triangular tubes under axial and oblique impact loading. *Engineering Failure Analysis* 2018; 93: 241-256. DOI: https://doi.org/10.1016/j.engfailanal.2018.07.003.
7. Baroutaji A, Arjunan A, Singh G, et al. Crushing and energy absorption properties of additively manufactured concave thin-walled tubes. *Results in Engineering* 2022; 14: 100424. DOI: https://doi.org/10.1016/j.rineng.2022.100424.
8. Abdulqadir SF, Bassam A, Ansari MNM, et al. Design of frontal longitudinal for enhancement in crashworthiness performance. *IOP Conference Series: Materials Science and Engineering* 2021; 1128: 012026. DOI: 10.1088/1757-899X/1128/1/012026.
9. Gungor E, Topa A and Kucukyıldırım B. *Numerical Investigation of Innovative Honeycomb-composite Sandwich Structure under Bird-strike Event*. 2021.
10. Khaire N, Tiwari G, Rathod S, et al. Perforation and energy dissipation behaviour of honeycomb core cylindrical sandwich shell subjected to conical shape projectile at high velocity impact. *Thin-Walled Structures* 2022; 171: 108724. DOI: https://doi.org/10.1016/j.tws.2021.108724.

11. Alexander JM. AN APPROXIMATE ANALYSIS OF THE COLLAPSE OF THIN CYLINDRICAL SHELLS UNDER AXIAL LOADING. *The Quarterly Journal of Mechanics and Applied Mathematics* 1960; 13: 10-15. DOI: 10.1093/qjmam/13.1.10.

12. Abramowicz W. The effective crushing distance in axially compressed thin-walled metal columns. *International Journal of Impact Engineering* 1983; 1: 309-317. DOI: https://doi.org/10.1016/0734-743X(83)90025-8.

13. Abramowicz W and Wierzbicki T. Axial Crushing of Multicorner Sheet Metal Columns. *Journal of Applied Mechanics* 1989; 56: 113-120. DOI: 10.1115/1.3176030.

14. Wierzbicki T and Abramowicz W. On the Crushing Mechanics of Thin-Walled Structures. *Journal of Applied Mechanics* 1983; 50: 727-734. DOI: 10.1115/1.3167137.

15. Waleed I, Ruhaima AAK, Farhan ZA, et al. Investigating energy absorption of thin-walled steel structures with combined mechanisms including inversion, folding and expansion. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2023: 14644207231173053. DOI: 10.1177/14644207231173053.

16. Alavi Nia A and Haddad Hamedani J. Comparative analysis of energy absorption and deformations of thin walled tubes with various section geometries. *Thin-Walled Structures* 2010; 48: 946-954. DOI: https://doi.org/10.1016/j.tws.2010.07.003.

17. Alavi Nia A and Parsapour M. Comparative analysis of energy absorption capacity of simple and multi-cell thin-walled tubes with triangular, square, hexagonal and octagonal sections. *Thin-Walled Structures* 2014; 74: 155-165. DOI: http://dx.doi.org/10.1016/j.tws.2013.10.005.

18. Baykasoğlu C, Baykasoğlu A and Tunay Çetin M. A comparative study on crashworthiness of thin-walled tubes with functionally graded thickness under oblique impact loadings. *International Journal of Crashworthiness* 2019; 24: 453-471. DOI: 10.1080/13588265.2018.1478775.

19. Kim DK, Looi CK, Topa A, et al. Prediction of mechanical response of hexagonal honeycomb SPS blast wall under explosive loading: In-depth review and empirical formula. *Ocean Engineering* 2024; 293: 116578. DOI: https://doi.org/10.1016/j.oceaneng.2023.116578.

20. Mustaffa Z, Al-Qadami EHH, Topa A, et al. Numerical assessment of the side impacts on lithium-ion battery module integrated with honeycomb reinforcement. *Engineering Failure Analysis* 2024; 161: 108290. DOI: https://doi.org/10.1016/j.engfailanal.2024.108290.

21. Baroutaji A, Gilchrist MD and Olabi AG. Quasi-static, impact and energy absorption of internally nested tubes subjected to lateral loading. *Thin-Walled Structures* 2016; 98, Part B: 337-350. DOI: http://dx.doi.org/10.1016/j.tws.2015.10.001.

22. Nia AA and Chahardoli S. Mechanical behavior of nested multi-tubular structures under quasi-static axial load. *Thin-Walled Structures* 2016; 106: 376-389. DOI: https://doi.org/10.1016/j.tws.2016.05.012.

23. Vinayagar K and Senthil Kumar A. Crashworthiness analysis of double section bi-tubular thin-walled structures. *Thin-Walled Structures* 2017; 112: 184-193. DOI: https://doi.org/10.1016/j.tws.2016.12.008.

24. Chahardoli S, Alavi Nia A and Asadi M. A parametric study of the mechanical behavior of nested multi tube structures under quasi-static loading. *Archives of Civil and Mechanical Engineering* 2019; 19: 943-957. DOI: https://doi.org/10.1016/j.acme.2019.03.006.

25. Dar UA, Mian HH, Abid M, et al. Experimental and numerical investigation of compressive behavior of lattice structures manufactured through projection micro stereolithography. *Materials Today Communications* 2020; 25: 101563. DOI: https://doi.org/10.1016/j.mtcomm.2020.101563.

26. Sharma D and Hiremath SS. Bio-inspired repeatable lattice structures for energy absorption: Experimental and finite element study. *Composite Structures* 2022; 283: 115102. DOI: https://doi.org/10.1016/j.compstruct.2021.115102.

27. Praveen Kumar A and Vetrivel Sezhian M. Influence of curvy stiffeners on the axial crushing response of 3D-printed polymer composite cylindrical tubular structures. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2022; 237: 2473-2485. DOI: 10.1177/14644207221137545.
28. Usta F, Ertaş OF, Ataalp A, et al. Impact behavior of triggered and non-triggered crash tubes with auxetic lattices. *Multiscale and Multidisciplinary Modeling, Experiments and Design* 2019; 2: 119-127. DOI: 10.1007/s41939-018-00040-z.
29. Kucewicz M, Baranowski P, Małachowski J, et al. Modelling, and characterization of 3D printed cellular structures. *Materials & Design* 2018; 142: 177-189. DOI: https://doi.org/10.1016/j.matdes.2018.01.028.
30. Le D, Doan T, Do K, et al. Investigating and comparing the mechanical behavior of multicellular structures made with PLA and ABS under lateral loading. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2023: 14644207231162844. DOI: 10.1177/14644207231162844.
31. Ramakrishnan R, Hemanth Kumar J, Titus F, et al. Experimental investigation of 3D printed bio-inspired Xylotus lattice structure for energy absorption under quasi-static axial loading conditions. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications* 2024: 14644207241236856. DOI: 10.1177/14644207241236856.
32. Chen J, Li E, Li Q, et al. Crashworthiness and optimization of novel concave thin-walled tubes. *Composite Structures* 2022; 283: 115109. DOI: https://doi.org/10.1016/j.compstruct.2021.115109.
33. Aktaş C, Acar E, Güler MA, et al. An investigation of the crashworthiness performance and optimization of tetra-chiral and reentrant crash boxes. *Mechanics Based Design of Structures and Machines* 2022: 1-24. DOI: 10.1080/15397734.2022.2075382.
34. Brauers WKM, Kildienė S, Zavadskas EK, et al. The construction sector in twenty European countries during the recession 2008–2009 – country ranking by MULTIMOORA. *International Journal of Strategic Property Management* 2013; 17: 58-78. DOI: 10.3846/1648715X.2013.775194.
35. Langseth M and Hopperstad OS. Static and dynamic axial crushing of square thin-walled aluminium extrusions. *International Journal of Impact Engineering* 1996; 18: 949-968. DOI: http://dx.doi.org/10.1016/S0734-743X(96)00025-5.
36. Hou S, Han X, Sun G, et al. Multiobjective optimization for tapered circular tubes. *Thin-Walled Structures* 2011; 49: 855-863. DOI: http://dx.doi.org/10.1016/j.tws.2011.02.010.