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Bio-Inspired Thin-Walled Straight and Tapered Tubes with Variable Designs Subjected to Multiple Impact Angles for Building Constructions

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Academic Editor: Tadeh Zirakian

Received: 19 January 2025

Revised: 6 February 2025

Accepted: 12 February 2025

Published: 17 February 2025

Citation: Ma, Q.; Yusof, N.H.M.; Sahu, S.K.; Song, Y.; Radzuan, N.A.M.; Sun, B.; Nasution, A.Y.; Kumar, A.P.; Rejab, M.R.M. Bio-Inspired Thin-Walled Straight and Tapered Tubes with Variable Designs Subjected to Multiple Impact Angles for Building Constructions. *Buildings* **2025**, *15*, 620. <https://doi.org/10.3390/buildings15040620>

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Abstract: Thin-walled structures are extensively utilized in construction because of their lightweight nature and excellent energy absorption efficiency, especially under dynamic loads. Improving the energy-absorbing performance of thin-walled structures by inspiring natural multi-cell designs is a sufficient approach. This paper investigates the energy-absorbing characteristics of variable novel cross-section designs of thin-walled structures subjected to oblique impact loading. Straight and tapered types with seven cross-sectional designs of novel thin-walled structures were studied. The nonlinear ABAQUS/Explicit software 6.13 version was implemented to analyze the crashworthiness behaviors for the proposed variable cross-section designs under different loading angles. The crushing behaviors of the proposed thin-walled structures were examined for various wall thicknesses of 0.5 mm, 1.5 mm, and 2.5 mm and impact loading angles of 0°, 15°, 30°, and 45°. It was determined that the energy-absorbing characteristics of novel thin-walled structures can be efficiently controlled by varying two geometries and seven cross-section designs. A multi-criteria decision-making method (MCDM) using a complex proportional assessment method (COPRAS) was performed to select the optimum thin-walled structures with cross-section designs. It was shown that a tapered square thin-walled structure with 2.5 mm thickness had the best crashworthiness performances with energy absorption (EA) of 11.01 kJ and specific energy absorption (SEA) of 20.32 kJ/kg under a 30° impact angle. Moreover, the results indicated that the EA of the thin-walled structure decreased with the increase in the impact loading angle. In addition, with the increase in the impact loading angle, the peak crushing force (PCF) decreased and reflected the reduction in energy absorbed at a larger angle. The MCDM method in conjunction with the COPRAS method is proposed, it provides valuable insights for safer and more resilient building construction.

Keywords: thin-walled structure; energy-absorbing characteristic; multi-criteria decision-making method; oblique impact loading; geometric structures; finite element modeling

1. Introduction

Thin-walled structures are progressively utilized in automotive [1], aerospace [2], civil engineering, and several other industries due to their lightweight nature, superior energy absorption capacity, high strength-to-weight ratio, and elevated stiffness [3]. In civil engineering, the thin-walled tubular truss structure is mainly used in large-span structures, where it is vital for the architectural structures to absorb and distribute impact loadings effectively, as shown in Figure 1. It is essential to investigate the crashworthiness and the lightweight design of the thin-walled structures, which could be used as favorable parts for automotive bumpers [4]. As the optimized results show, numerous energy absorbers exhibit a variety of innovative structural designs, including hollow structures [5], multi-infill pattern structures [6], foam-filled structures [7], origami structures [8], and bio-inspired structures [9]. A conical structure is preferable in terms of energy absorption compared to a straight structure with a relatively stable load versus a displacement curve under oblique loading [10]. Furthermore, the design domain of conical-based thin-walled structures is larger than that of traditional straight structures, and they are less likely to fail due to global buckling [11].

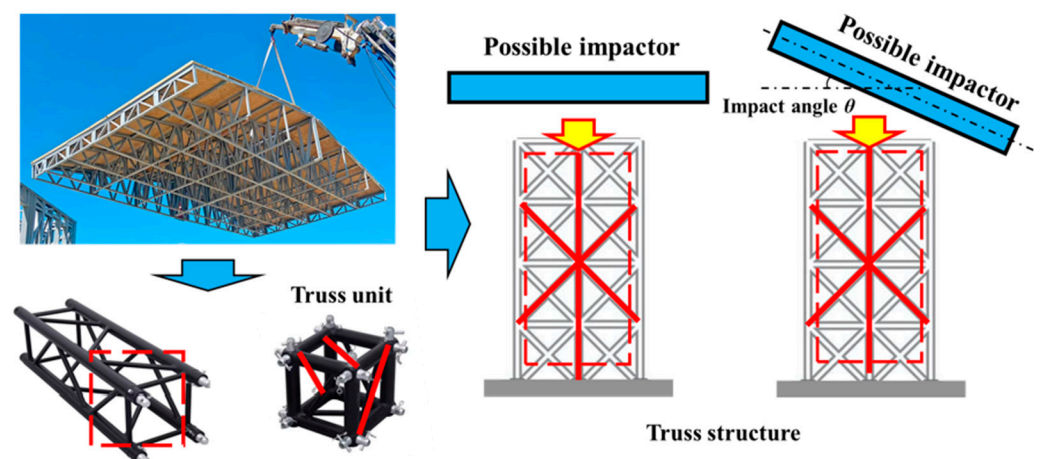


Figure 1. Thin-walled structure as tubular roof truss element in civil engineering under multi-angle impacts.

Nature creates various inspirational design examples of thin-walled structures with high strength and energy absorption capabilities, such as bone [12], bamboo [13], and beetles [14], which inspire the construction of bio-inspired structures with superior energy-absorbing properties. As the main branch of inspired structures, bio-inspired structures are mainly proposed, and it has been proven that they effectively enhance the energy absorption when used as energy absorbers, as illustrated in Figure 2. To deeply understand the potential function of bio-inspired structures, researchers have conducted experimental, numerical, and theoretical investigations of lightweight bio-inspired thin-walled structures; these investigations mainly focus on energy absorption evaluation and structural design optimization. For example, San Ha et al. [9] examined the energy absorption capacity of a novel bio-inspired cylindrical sandwich structure (BCSS), demonstrating that the wall thickness of both the core and the skins greatly influenced the energy absorption properties of the BCSS.

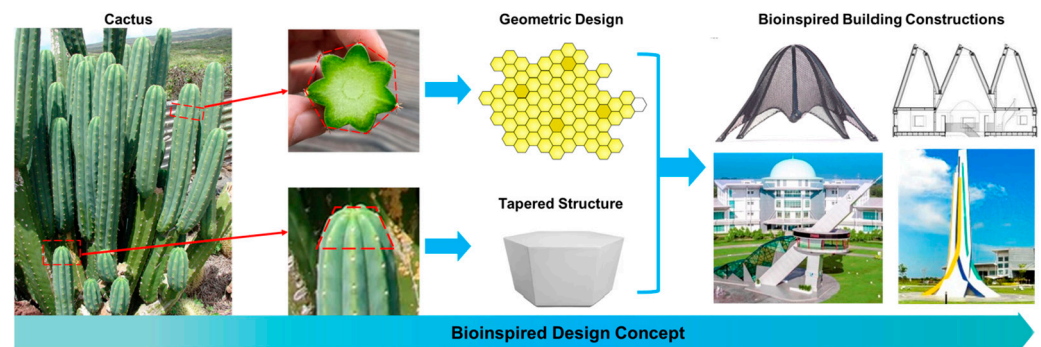


Figure 2. Bio-inspired design concepts from the cactus for building constructions in civil engineering.

Moreover, Najibi et al. [15] conducted a numerical analysis to assess the crashworthiness characteristics of a novel bio-inspired DNA tube under axial quasi-static loading conditions. Their findings emphasized that tubes with lower cross-sectional aspect ratios exhibited significantly higher initial peak forces and specific energy absorption capacities. Furthermore, Wu et al. [16] investigated the energy absorption performance of composite bio-inspired multi-cell tubes featuring lotus root, lotus root–horsetail, and lotus root–honeycomb designs under axial, radial, and three-point bending loadings. The study underscored the potential of these bio-inspired multi-cell structures to serve as lightweight, high-strength, impact-resistant, and efficient energy-absorbing components. For the bio-inspired thin-walled design, the first challenge is inspired and replicated in natural structures to achieve high energy absorption capabilities. This is required and ensures that bio-inspired structures can consistently perform under multiple impact angles. Moreover, the second challenge is to use the optimization algorithm method to achieve the maximum energy absorption. The integration of bio-inspired structures and optimization methods can solve the challenges, but it is still necessary to deeply understand the potential designs for enhancing the structural safety and resilience of building constructions.

To efficiently propose the bio-inspired design as an excellent energy-absorbing element, an increasing number of researchers have been concerned with the bio-inspired thin-walled structures under axial, oblique, and lateral loadings in order to better understand the failure mechanism for bio-inspired structures [17–19]. For instance, He et al. [20] presented a folding-based design approach for thin-walled origami tubes with geometric gradients, including uniform, tapered, hourglass-shaped, and ellipsoidal configurations. Their study demonstrated that gradient-shaped, thin-walled origami tubes exhibited significantly enhanced energy absorption capacity and improved deformation behavior. Furthermore, the thin-walled structure inspired by the multi-cell core and conical pattern has drawn much attention [18,21–23]. For example, Chen et al. [22] developed novel cactus-inspired bionic tubes (CBTs) modeled after the ribbed structures of the cactus. Their research analyzed key factors, such as structural mass, wall thickness, loading velocity, and cross-sectional design. It was shown that CBTs exhibited excellent crashworthiness compared with typical multi-cell structures, attaining an impressive SEA of 11.44 J/g. Bio-inspired structures can comprehensively evaluate energy absorption capabilities and structural integrity under multiple impact angles, which is particularly important in critical infrastructure, such as large-span roofs, bridges, and buildings.

Bio-inspired thin-walled straight and tapered tubes have emerged as innovative solutions for enhancing structural safety in building construction. These bio-inspired designs, which emulate the structural efficiency of natural materials, are particularly effective in energy absorption and crashworthiness. Bio-inspired building applications can significantly improve anti-earthquake and resistance performance under impacts, which is crucial for structures in seismically active regions or those exposed to high-impact risks.

The use of thin-walled tubes in reinforced concrete columns can reduce structural damage by efficiently absorbing and distributing forces during an impact event, thus contributing to the overall durability and safety of the construction. Moreover, these bio-inspired designs align with sustainable construction practices by utilizing materials and methods that are both energy-efficient and environmentally friendly, potentially leading to more resilient and sustainable building solutions. Although some studies have been carried out to work on the crashworthiness performance of bio-inspired thin-walled straight and tapered tubes with variable designs, there is limited investigation on the energy-absorption characteristics of the thin-walled structure using a multi-criteria decision-making method to select the optimum thin-walled bio-inspired structures under various multiple impact angles. Compared to the traditional impact studies, this study is focused on bio-inspired thin-walled straight and tapered tubes with seven geometric designs; it investigates the effect of geometric designs under multiple impact angles. Moreover, bio-inspired structures can enhance energy absorption and structural impact resilience; this is optimized and evaluated using a multi-criteria decision-making method (MCDM) and using a complex proportional assessment method (COPRAS).

This paper investigates the energy-absorbing performance of thin-walled structures in building construction, focusing on enhancing energy efficiency through novel multi-cell designs inspired by the natural cactus. The study examines both straight and tapered geometries alongside seven cross-sectional designs, utilizing numerical investigation and nonlinear explicit finite element models to assess the crashworthiness under impact angles of 0° , 15° , 30° , and 45° . The paper focuses on the effect of wall thickness and impact angles to compare and analyze the crushing deformation behavior. To optimize the design selection procedure, a multi-criteria decision-making method (MCDM) with the complex proportional assessment method (COPRAS) is obtained, which provides a systematic approach to identify the excellent energy-absorbing characteristics of bio-inspired thin-walled straight and tapered tubes with cross-sectional designs.

2. Finite Element Method

2.1. Finite Element Modeling

2.1.1. Material Properties

The thin-walled tubular structures considered in this study are made up of aluminum 2024 T3 with several mechanical properties: density $\rho = 2770 \text{ kg/m}^3$, Poisson's ratio $\mu = 0.3$, Young modulus $E = 73 \text{ GPa}$, yield stress $\sigma_y = 369 \text{ MPa}$, and ultimate stress $\sigma_U = 684 \text{ MPa}$. Material characterization is set as per the Johnson–Cook constitutive isotropic hardening model. This phenomenological model incorporates strain hardening, strain rate sensitivity, and thermal softening effects. A summary of the mechanical properties of aluminum 2024 T3 material is presented in Table 1. The tensile properties of aluminum 2024 T3 material are modeled and described in the elastic and plastic deformation stages. In the elastic deformation stage, it behaved according to Hooke's law and reached 73.02 GPa. The engineering stress was directly proportional to the engineering strain. In the plastic deformation stage, the stress exceeded the yield stress of 369.18 MPa, which deformed to plastic deformation. The stress concentration rapidly caused the deformation, showing the combination of ductile and brittle fractures. Moreover, the central part of the fracture showed a more brittle fracture due to the rapid separation of the martial characterization.

Table 1. Mechanical properties of aluminum 2024 T3 material in finite element modeling [24].

Mechanical Properties	Value
Density $\rho/\text{kg/m}^3$	2770
Poisson ratio μ	0.3
Yield stress A/MPa	369
B/MPa	684
C	0.0083
n	0.73
m	1.7
$\varepsilon_0/\text{s}^{-1}$	1000
$T_{\text{room}}/^{\circ}\text{C}$	20.2
$T_{\text{melt}}/^{\circ}\text{C}$	502.15

2.1.2. Geometric Design

The development of the finite element model under oblique impact loading is detailed by addressing its key components, including the geometry, finite element meshing, interaction and boundary conditions, and material properties. The oblique dynamic impact energy absorption behavior of straight and tapered tubes for circular, ellipse, square, rectangle, triangle, hexagon, and nonagon designs was compared. Figure 3 presents the straight and tapered thin-walled structure geometry used in this study.

The tubes were modeled with a height of 200 mm and variable thicknesses of 0.5 mm, 1.5 mm, and 2 mm, while a 5° angle was applied to the tubes for the tapered tubes. A detailed description of the tube cross-sections' geometries and dimensions are provided in Table 2. The entire model in this study included a thin-walled tube, a base plate, and an impactor. The figure illustrates the mesh and finite element setup to simulate thin-walled tubular structures under oblique impact. The bottom end of the tube is clamped in a constraint, while a rigid wall with a weight impacts the other end at a constant velocity. The normal to the rigid wall lies in the X-Z plane and forms an oblique angle α with the axis of the tube. Each thin-walled tube structure was modeled using four-node shell continuum (S4R) elements, incorporating five integration points through the thickness of each component. Moreover, the shell elements were assigned an element size of 5 mm, while the impactor and base plate were modeled as rigid bodies with a 10 mm mesh shell size.

Table 2. Geometries and dimensions of thin-walled tube structure used in this study.

Geometrical Design	Design Type	Thickness (mm)	Height (mm)	Mass (kg)	Outer Diameter (mm)
Circular	Straight	0.5/1.5/2.5	200	0.069/0.209/0.348	D = 80
	Tapered	0.5/1.5/2.5	200	0.108/0.325/0.542	Dupper = 80, Dbottom = 115
Ellipse	Straight	0.5/1.5/2.5	200	0.053/0.161/0.268	Dmax = 80, Dmin = 40
	Tapered	0.5/1.5/2.5	200	0.069/0.207/0.345	Dupper = 80, Dbottom = 115
Square	Straight	0.5/1.5/2.5	200	0.088/0.266/0.443	D = 80
	Tapered	0.5/1.5/2.5	200	0.108/0.325/0.542	upper = 80×80 , bottom = 115×115
Rectangular	Straight	0.5/1.5/2.5	200	0.066/0.199/0.332	80×40
	Tapered	0.5/1.5/2.5	200	0.086/0.259/0.431	upper = 80×40 , bottom = 115×75
Triangle	Straight	0.5/1.5/2.5	200	0.066/0.199/0.332	Each side = 80
	Tapered	0.5/1.5/2.5	200	0.092/0.276/0.460	Each upper side = 80, each bottom side = 141

Table 2. *Cont.*

Geometrical Design	Design Type	Thickness (mm)	Height (mm)	Mass (kg)	Outer Diameter (mm)
Hexagonal	Straight	0.5/1.5/2.5	200	0.066/0.199/0.332	Each side = 40
	Tapered	0.5/1.5/2.5	200	0.083/0.251/0.418	Each upper side = 40, each bottom side = 60.2
Nonagon	Straight	0.5/1.5/2.5	200	0.068/0.205/0.341	Each side = 27.4
	Tapered	0.5/1.5/2.5	200	0.084/0.253/0.422	Each upper side = 27.4, each bottom side = 40

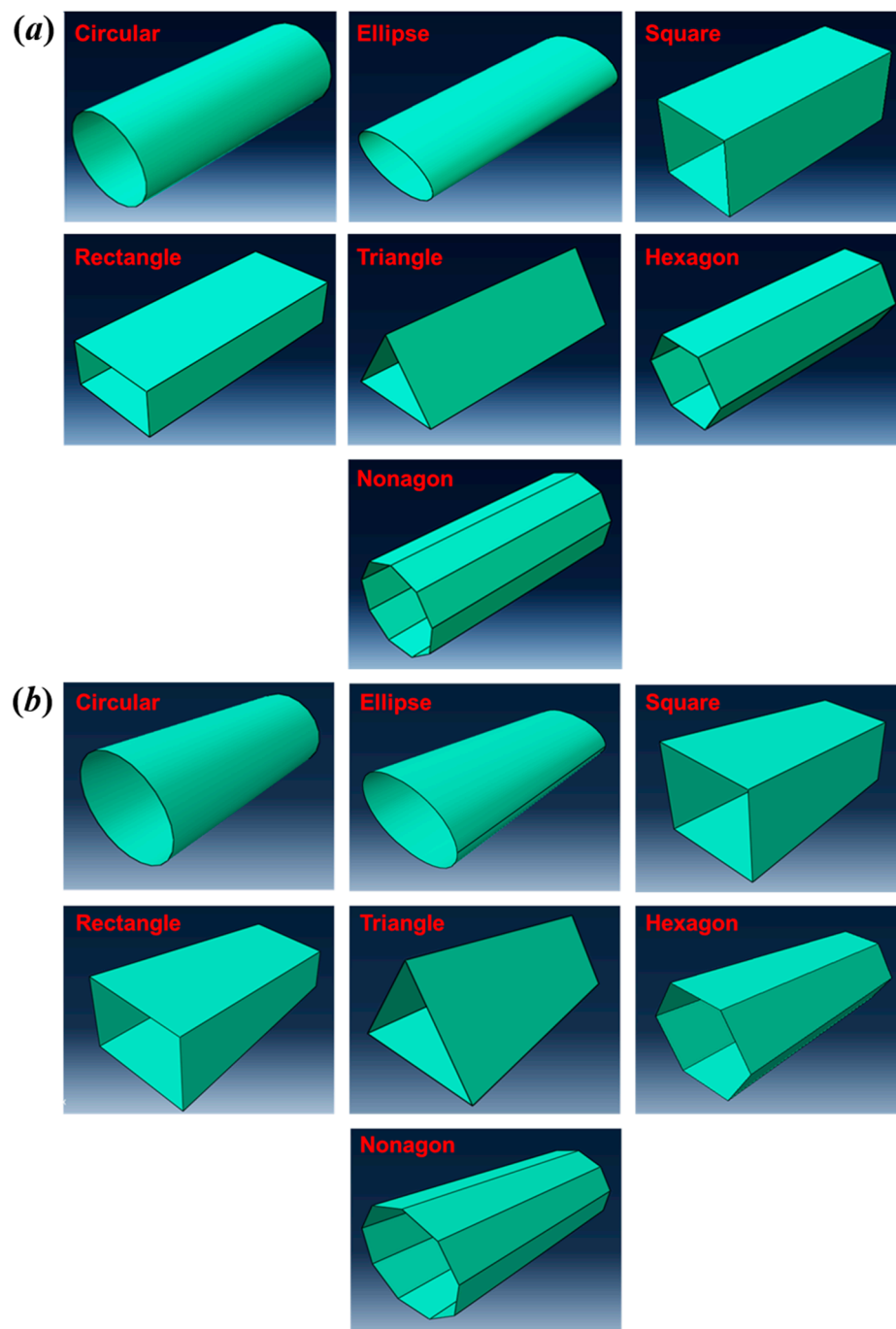


Figure 3. Seven designs of the thin-walled structures were used in this study: (a) straight tube; (b) tapered tube.

2.1.3. Mesh Generation, Boundary, and Loading Conditions

The impactor was modeled as a rigid body with only one permitted translational degree of freedom, while all the other translational and rotational degrees of freedom were constrained. The base plate was modeled as an analytical rigid surface, constrained to translate vertically, ensuring that the free end of the tubes was compressed against a fully fixed rigid body. A reference node was assigned to each rigid body, allowing the motion of the entire rigid body to be controlled by applying boundary conditions to the reference node. Figure 4a illustrates the impact angle and boundary conditions of thin-walled tapered nonagon tubes. All the tubes, the impactor, and the base plate were positioned relative to one another within the assembly module using the global coordinate system, forming a complete assembly. The impactor was located approximately 20 mm above the tubes to avoid failure/error in the analysis due to penetrations between the impactor and tubes. The step analysis was used to determine the step time for the dynamic nonlinear crushing analysis. The step sequence offers an effective method to capture any changes in the model during the analysis. Moreover, it enables modifications to the analysis procedure, data output settings, and various control parameters. In this study, the explicit analysis step time for the dynamic impact simulation was 0.015 s. Output requests can be defined to specify which variables will be recorded during the analysis steps, and these requests can be propagated to subsequent steps to ensure consistent data collection throughout the simulation. Figure 4b presents the mesh convergence sensitivity analysis of the thin-walled structure in terms of CPU time consumption and percentage of correlation. It was shown that the correlation percentage was improved by decreasing the mesh size, thereby significantly increasing CPU time consumption. Based on the initial experimental data on thin-walled tubular straight tubes [25], the mesh size was 2.0 mm to balance the CPU time consumption of 0.5 h and an 8.21 percentage of correlation between the numerical and experimental data. The time and step size are adjusted to produce the effect of convergence by varying the mesh sensitivity in thin-walled structures. For example, in regions with high stress concentrations, the element size and step size are reduced by a proportional amount with stable analysis.

An output request defines some variables and which region of the model is used, and the frequency at which data are output during an analysis step can be specified within the output request settings. In the current crush impact study, energy, force, and displacement are the criteria chosen for the output request. The step time frequency taken for force and displacement output was 0.0001 s. As the number of step time frequencies decreases, more data are observed in the resulting output. The resulting output shows the graphs of force versus time, displacement versus time, and energy versus time. The impact angle is chosen from the common thin-walled truss element in civil engineering. Two cases of the different truss elements are provided, subjected to various angles, as shown in Figure 4c. The multiple impact angles are determined for the structural safety, material efficiency, cost-effectiveness, and structural optimization by varying the structural angle. Therefore, the proposed thin-walled structures simulate the impact loading with four impact angles: 0°, 15°, 30°, and 45°.

Under dynamic impact loading, the base of each tube was fully fixed to a supporting base plate modeled as a rigid body, utilizing a tied constraint. A tied constraint is a multi-point constraint (MPC) that ensures the translational motion, and all the other active degrees of freedom of the nodes along the tube's base edge are identical to those of the supporting rigid body. Contact interactions within each tube and the applied impact load were modeled using the 3D self-contact interaction option in ABAQUS/Explicit. Self-contact between the tube walls during the collapse and surface-to-surface contact between each rigid surface and the tube were defined using the finite sliding "penalty"-based contact

algorithm. This approach employed contact pairs with a hard contact formulation. All surface-to-surface contact was of the “master-slave” type. All surface contact in the finite element models for straight and tapered tubes was treated with a 0.2 coefficient of friction. For the applied load, the impact displacement of 200 mm was controlled to investigate the energy-absorbing characteristics of the load versus displacement and stress versus strain curves.

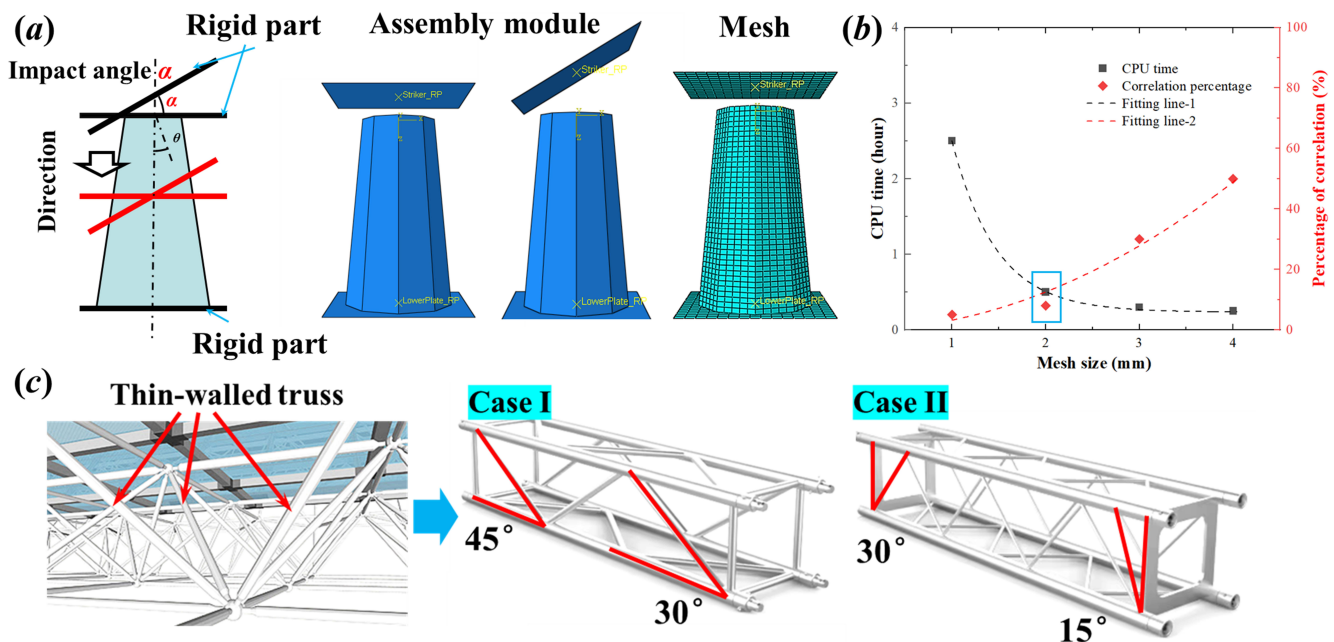


Figure 4. Procedure of finite element modeling: (a) Example of impact angle and boundary conditions of tapered nonagon tubes; (b) mesh convergence sensitivity analysis of thin-walled tube in terms of CPU time and percentage of correlation; (c) oblique impact angles from thin-walled truss in civil engineering.

Dynamic loading was simulated by assigning a point mass element and an initial velocity to the supported rigid body. This setup transferred the crushing impact to the fully fixed base plate rigid body. The impact velocity of the impactor on the tube was set at 15.6 m/s, with a lumped mass of 275 kg. This mass was assumed to represent 25% of the total weight of a compact safety car, which is 1100 kg. It was assumed that each tubular energy-absorbing structure could absorb the equivalent kinetic energy of a 275 kg mass. Here, the maximum energy absorbed by two tubes in operation is significantly less than 50% of the car’s total energy. In the nonlinear dynamic analysis, thin-walled structures are highly sensitive to geometric parameters and imperfections. The convergence tolerance of the iterative solver is set, and low tolerance may lead to inaccurate results, while high tolerance can increase the number of iterations and computational time. Furthermore, the stiffness matrix of the thin-walled structure changes based on material and geometric nonlinearities, and it is regularly updated to accurately predict the structural response and prevent incorrect predictions of stability loss.

2.2. Multi-Criteria Decision-Making Method (MCDM)

For the multi-criteria decision-making (MCDM) process, the complex proportional assessment (COPRAS) method was selected [26], primarily due to its simplicity and ease of application. This method operates on the assumption of direct and proportional relationships between the significance and utility levels of the available alternatives in the presence of mutually conflicting criteria. It evaluates the performance of the alternatives with respect to various criteria and incorporates the associated criteria weights into the

analysis. The COPRAS method identifies the optimal decision by considering the ideal and the least preferred solutions. The COPRAS method has been widely applied to solve design selection problems across diverse fields, including construction, project management, and economics [27]. The process involves several systematic steps, which are detailed as follows:

Step 1: Construct the initial matrix (X) and calculate the relative coefficient (R). The first step is to create a straightforward matrix that links the alternatives (design concepts) to the selection criteria. This matrix is denoted as X and is represented by the following formula:

Here, x_{ij} represents the performance value of the i -th design alternative with respect to the j -th design criterion, while m and n denote the total number of design criteria (or performance indicators) and design alternatives, respectively.

Step 2: Normalize the decision matrix.

The normalized decision matrix R is obtained by converting the criteria into dimensionless values, ensuring all criteria become directly comparable.

Step 3: Determine the weighted normalized decision matrix D.

To calculate the individual weightages of various criteria, the following steps are undertaken:

The total number of comparisons is given by $N = (n \times (n - 1)/2)$, where n is the total number of criteria. For each pair of compared criteria, a score of three is assigned to the criterion deemed more important and a score of one to the less important. If the two criteria are equally significant, a score of two is assigned to both. This is repeated for all possible pairs of criteria. In this study, n is four criteria, including mean crushing force, peak crushing force, crushing load efficiency, and specific energy absorption. Then, N is 6, as provided in Table 3, on the weighting setting for each performance indicator.

Table 3. Weighting setting for each performance indicator used in this study.

Criteria	Number of Comparison Sets: 6						W_{ij}	w_{ij}
	1	2	3	4	5	6		
MCF	3	3	2				8	0.33
PCF	1			2	1		4	0.16
CLE		1		2		1	4	0.16
SEA			2		3	3	8	0.33
Total W_{ij}							24	1.00

Then, calculate the total score for each criterion using the following formula:

$$\sum_{i=1}^m w_{ij} = W_j \quad (1)$$

W_j , the weightage of the j -th criterion, is determined by dividing the total score of that criterion by the global total score for all the criteria $G = \sum_j^n W_j$.

Step 4: Compute the decision of matrix D.

$$D = [y_{ij}]_{mn} = r_{ij} \times w_j \quad (2)$$

where r_{ij} indicates the normalized performance value of the i_{th} alternative for the j_{th} criterion.

Step 5: Summing of beneficial and non-beneficial attributes.

The weighted normalized values in the D matrix include beneficial and non-beneficial attributes. For non-beneficial attributes (e.g., F_{max}), a lower value is preferred for selection,

whereas a higher value is desired for beneficial attributes (e.g., EA). These sums are calculated using the following two formulas, respectively:

$$S_{+i} = \sum_{j=1}^n y_{+ij} \quad (3)$$

$$S_{-i} = \sum_{j=1}^n y_{-ij} \quad (4)$$

where y_{ij} and y_{-ij} are the weighted normalized values for the beneficial and non-beneficial attributes, respectively. The greater the value of S_{+i} the better the design concept and the lower the value of S_{-i} . It is observed that $\sum S_{+i}$ and $\sum S_{-i}$, representing the sums of the beneficial and non-beneficial attributes, respectively, always equal the total weights assigned to these attributes. This relationship is expressed by the following equations:

$$Sum_{positive} = \sum_{i=1}^m S_{+i} = \sum_{i=1}^m \sum_{j=1}^n y_{+ij} \quad (5)$$

$$Sum_{negative} = \sum_{i=1}^m S_{-i} = \sum_{i=1}^m \sum_{j=1}^n y_{-ij} \quad (6)$$

Step 6: Determine the minimum value of S_{-i} :

$$S_{-min} = \min S_{-i} \quad (7)$$

Step 7: Relative significant priority (Q).

For each candidate's alternative, their priorities were determined using the concept of relative significance Q_i . The relative significance value Q_i for the i_{th} alternative can be calculated mathematically as follows:

$$Q_i = S_{+i} + \frac{S_{-min} \sum_{i=1}^m S_{-i}}{S_{-i} \sum_{i=1}^m \left(\frac{S_{-min}}{S_{-i}} \right)} \quad (8)$$

where S_{-min} is the minimum value of S_{-i} .

Step 8: Determine the quantitative utility (U).

The values of the quantitative utility U_i result in a complete ranking between the alternatives and can be calculated as follows:

$$U_i = \frac{Q_i}{Q_{max}} \times 100\% \quad (9)$$

The maximum value of the relative significance is represented as Q_{max} . The quantitative utility is directly proportional to the relative significance, with a utility value of 100 assigned to the best design concept according to this method.

2.3. Crashworthiness Criteria

Based on foundational studies on the crushing performance of tubular structures in the literature, several standard compressive parameters were selected and calculated to evaluate the energy-absorbing characteristics [4,6,28–30]. Crashworthiness indicators are mainly used in the early design stage of energy-absorbing systems; energy absorption (EA), specific energy absorption (SEA), mean crushing force (MCF), peak crushing force (PCF), and crushing load efficiency (CLE) are commonly used [28–30].

The crushing force is defined as the required force to cause a permanent deflection, which increases as the crushing progresses. The force–displacement response of an energy-absorbing device can mainly measure the energy absorption performance. Energy

absorption capacity can then be calculated as the area under the force–displacement curve. The EA is typically defined as the total strain energy absorbed during the deformation of the structure and can be theoretically calculated from the crushing force–displacement curve [3]:

$$EA(d) = \int_0^{\delta} F(x)dx \quad (10)$$

where $F(x)$ represents the instantaneous crushing load, and δ denotes the current attainable crush distance of the structural deformation at a specific time when the mean crushing force (MCF) is calculated. Based on Equation (10), the MCF for a given structural deformation is defined as follows:

$$MCF(d) = \frac{1}{\delta} \int_0^{\delta} F(x)dx \quad (11)$$

where δ is the effective stroke length, which is taken as 0.7 L in this study, and L is the initial length of the energy-absorbing structure [6]. The MCF indicates a structure's energy-absorbing capacity in relation to the displacement needed to absorb that energy.

The force generally oscillates throughout the crush impact process, and the highest initial force point is defined as peak crushing force (PCF) [13]. The PCF represents the force required to initiate structural collapse, triggering energy absorption. The PCF, which is closely associated with the deceleration of the structure, is often a crucial parameter in crashworthiness design. The PCF, defined as the peak crush force during the entire impact event, can be expressed as follows:

$$PCF = \max[F(x)] \quad (12)$$

where $F(x)$ is the force when stroke length equals l.

The most critical criterion for energy absorbers is their specific energy absorption (SEA) capacity. When structural weight is a significant consideration, the SEA is a combined criterion [16]. It is defined as the ratio of the absorbed energy to the total mass of the structure M_t , and is expressed as follows:

$$SEA = \frac{EA}{m} \quad (13)$$

When the SEA value is higher, the structure has a higher energy absorption capability in terms of weight. Weight saving must not compromise safety or structural performance. Ideally, the energy absorbers should be designed to achieve maximum crashworthiness under axial and oblique loading conditions across all possible impact angles. The crush force efficiency (CFE) is a valuable metric for evaluating the uniformity of crush impact loads [20]. For an ideal energy absorber, the CFE should approach 100%. The crush force efficiency is defined as the ratio of the mean crushing force (MCF) to the peak crushing force (PCF).

$$CFE = \frac{MCF}{PCF} \quad (14)$$

The geometric efficiency, also referred to as the stroke efficiency (STE), is defined as follows:

$$STE = \frac{\delta_{max}}{L_c} \quad (15)$$

where δ_{max} is the maximum crush displacement of the energy absorber at which crush impact occurs, and L_c is the projected length in the comprehensive direction. Obviously, the goal is to design an energy absorber that deforms along the maximum possible length of its structure, thereby optimizing energy absorption.

3. Results and Discussion

3.1. Deformation Behavior of Thin-Walled Straight and Tapered Tubes with Seven Geometric Designs

Through the validated FE modeling method, the FE model of seven kinds of profiles of thin-walled tubular structures of aluminum 2024 T3 was developed, and their dynamic response was simulated and compared. The crushing responses of the seven different profiles were compared under axial (0°) and oblique impact (15° , 30° , 45°) angles. Figures 5–10 show the deformation modes of the straight and tapered thin-walled structures under different oblique impact loading. The Mises stress distribution of straight and tapered tubes was shown in finite element analysis, where the blue color represents the lower Mises stress of 1.38 MPa, and red color denotes the higher Mises stress of 5.45×10^2 MPa. The tubes mostly absorb energy in progressive collapse modes, and their magnitude decreases further when the tubes begin to experience global bending collapse [31–33]. All seven types of tubes, under load angles of 0° and 15° , exhibited progressive buckling initiated at the impacted end, forming lobe folds through a progressive collapse mode. The initial observation from the visual deformation showed that the tapered tubes were more stable and only started to bend at a larger angle than that of the straight tubes [34,35]. For instance, the tapered tubes still experienced a progressive collapse mode at a 30° angle, while the straight tubes tended to bend at the same angle. A single bending mode developed in all tubes occurred at 45° , in which one side of the tubes was bent inwards, and the other side was bent outwards with respect to the load angle compression. The crushing behavior of thin-walled straight and tapered tubes under 0° , 15° , 30° , and 45° impact angles were numerically simulated. It was shown that the impact angle significantly affected the crushing response of those thin-walled straight and tapered tubes. Under the axial loading ($\alpha = 0^\circ$) or a small impact angle, e.g., $\alpha = 15^\circ$, seven designs of thin-walled tubes deformed progressively from the impacted end to the fixed end. It was observed that the so-called “accordion-type” failure mode was associated with high energy-absorbing capabilities. Under oblique impact loading at 45° , a few foldings were shown at the loading end of the thin-walled tubes. Then, a plastic hinge occurred near the fixed end of the thin-walled tubes around the plastic hinge during the subsequent crushing process. The seven thin-walled tubes exhibited global buckling deformation. Then, the crushing force increased instantly under impact loading and fluctuated around a mean value during the progressive crushing process. As the impact angle increased, the crushing force level decreased in seven designs of thin-walled tubes, which reduced energy absorption at large impact angles.

This study examines the influence of key geometric parameters, such as wall thickness and impact load angle, on the behavior of tubular thin-walled structures under impact loading conditions. Such information will guide the design of structures in applications subjected to oblique loading conditions. In developing the finite element model, the load tubes are impacted by discrete rigid striker walls with an increased load angle α from 0° to 45° , with the typical interval of 15° . Specific consideration is given to the influence of the displacement, load angle, and wall thickness on the EA, SEA, and PCF of the thin-walled tubular structure under investigation. In addition, at a relatively large impact angle, seven designs of thin-walled straight and tapered tubes experienced progressive collapse and showed a large crushing force and energy-absorbing characteristics. It maintained the energy-efficient deformation mode to an impact angle of 45° , at which the thin-walled straight and tapered tubes had failed. Furthermore, global buckling deformation was observed by increasing the impact angles to 45° . The range of efficient absorbance of impact energy went down to 50 mm. Then, the force rapidly decreased and was a large force throughout the crushing process.

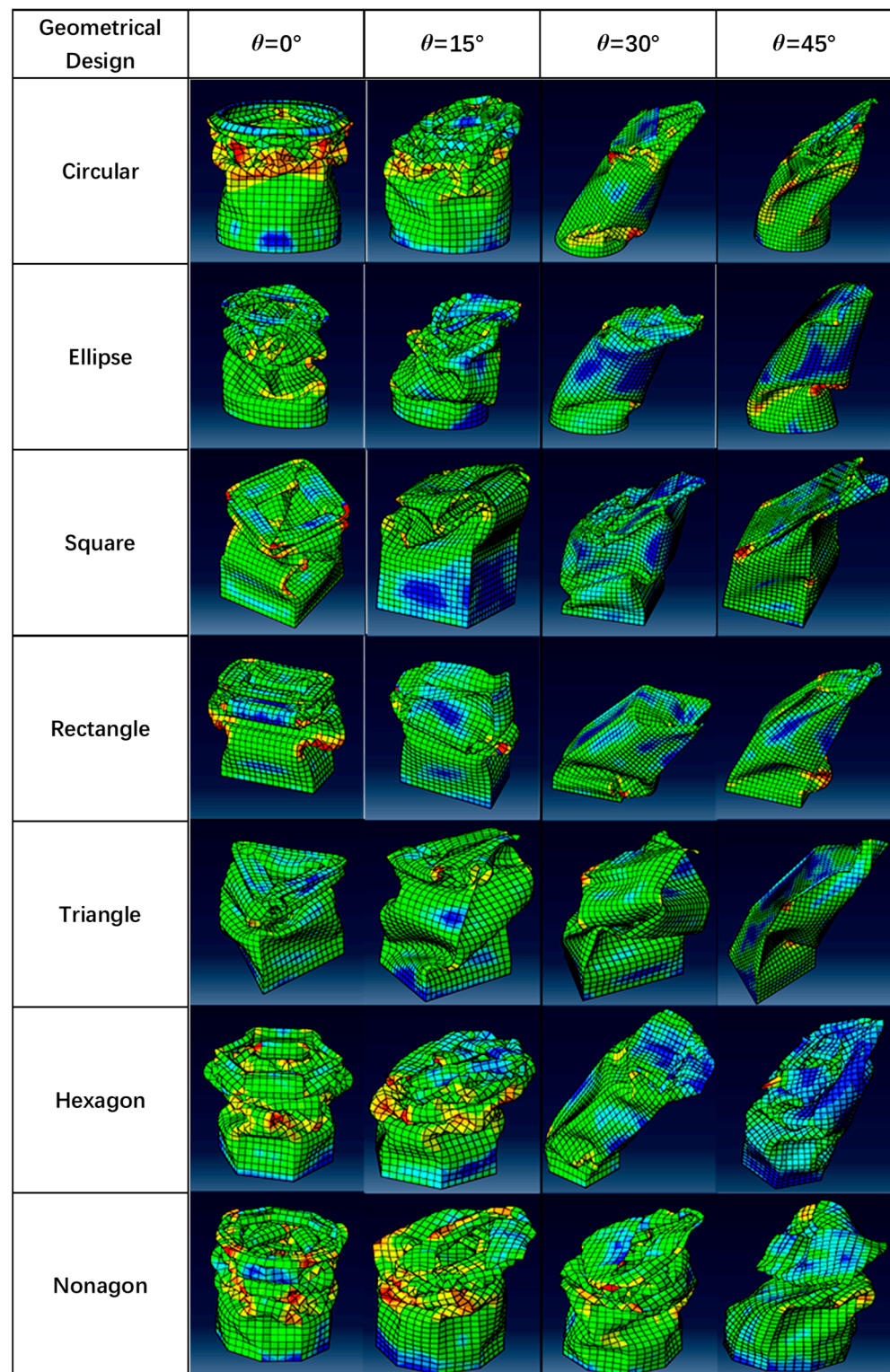


Figure 5. Deformation modes of thin-walled straight tubes with 0.5 mm wall thickness under 0° , 15° , 30° , and 45° impact angles.

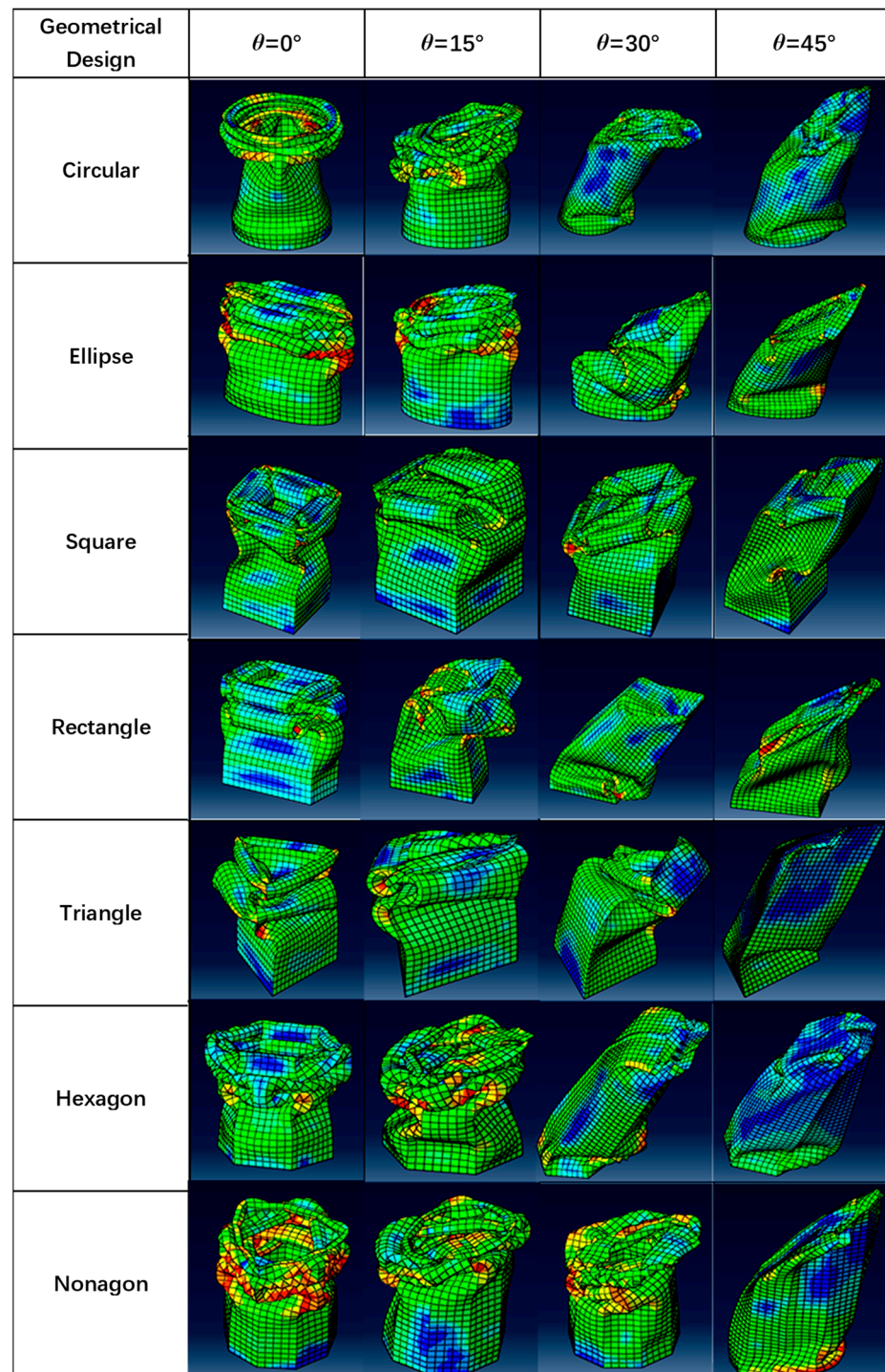


Figure 6. Deformation modes of thin-walled straight tubes with 1.5 mm wall thickness under 0° , 15° , 30° , and 45° impact angles.

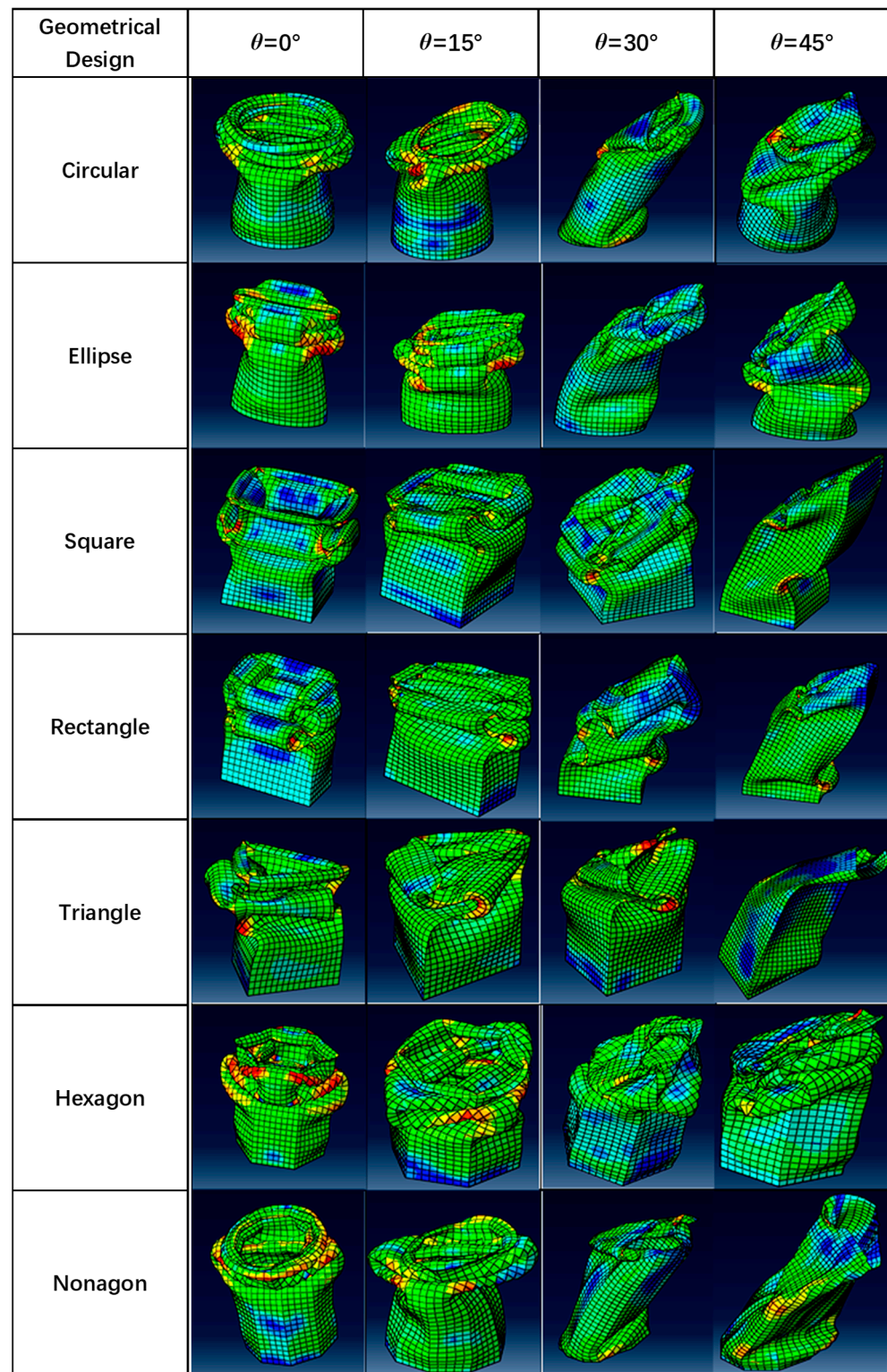


Figure 7. Deformation modes of thin-walled straight tubes with 2.5 mm wall thickness under 0° , 15° , 30° , and 45° impact angles.

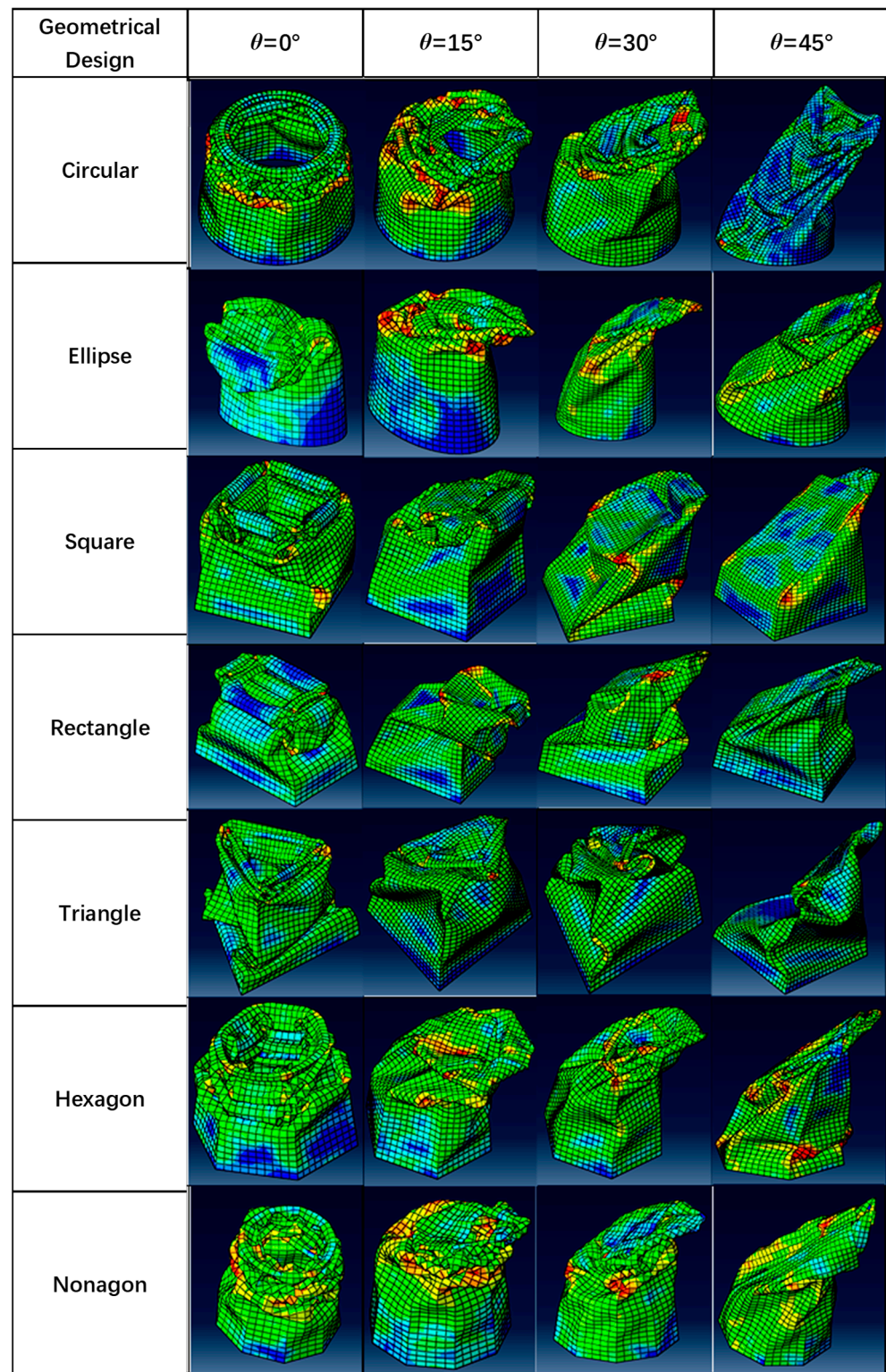


Figure 8. Deformation modes of thin-walled tapered tubes with 0.5 mm wall thickness under 0° , 15° , 30° , and 45° impact angles.

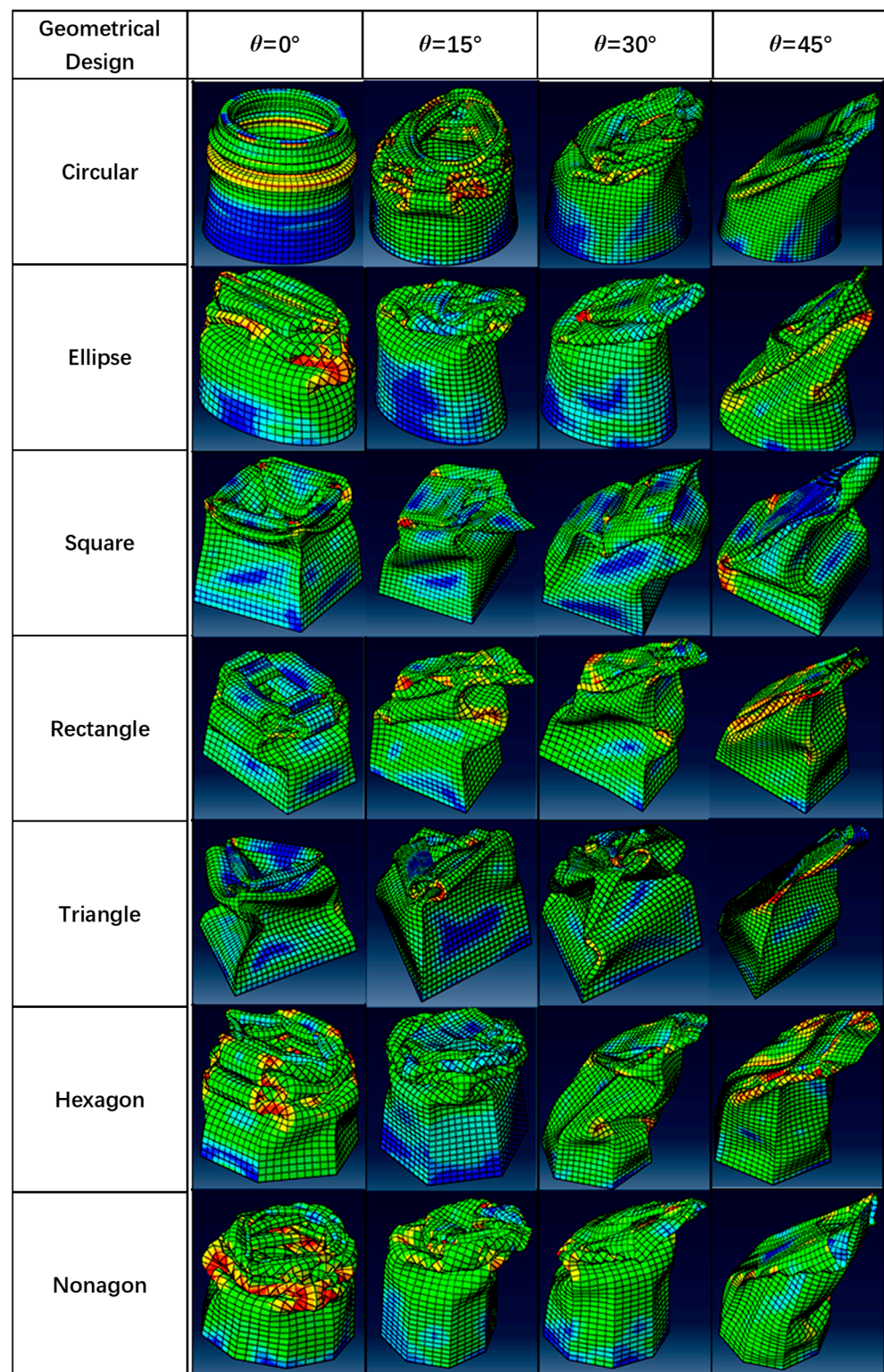


Figure 9. Deformation modes of thin-walled tapered tubes with 1.5 mm wall thickness under 0° , 15° , 30° , and 45° impact angles.

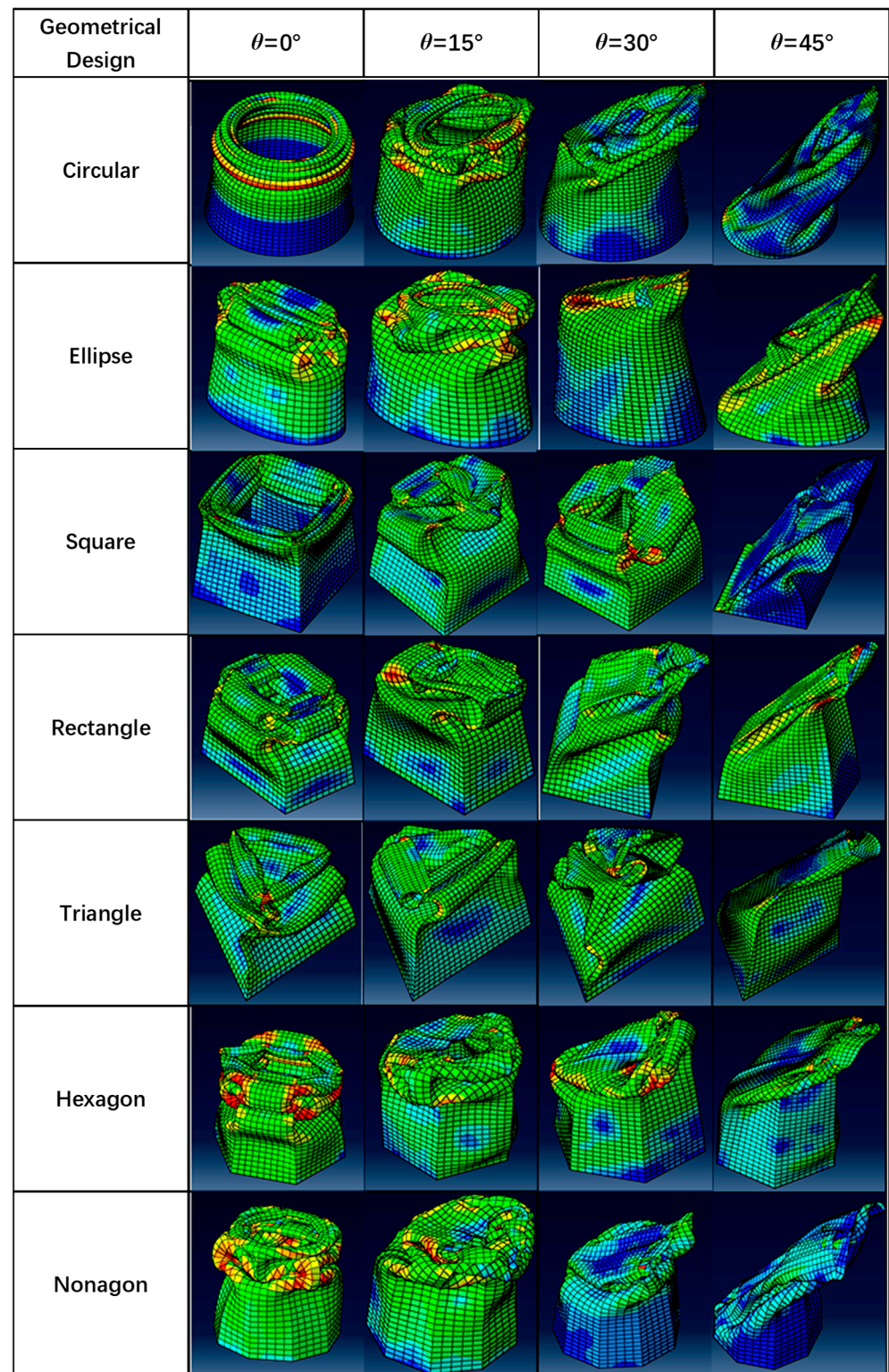


Figure 10. Deformation modes of thin-walled tapered tubes with 2.5 mm wall thickness under 0° , 15° , 30° , and 45° impact angles.

3.2. Load Versus Displacement Curves with Seven Geometric Designs

The dynamic crushing load versus displacement curves from finite element analysis represent the energy absorption for each kind of profile. The variables of oblique impact loading and wall thickness analyzed in this study are presented in Figures 11–13. The plotted load–displacement curves were obtained from the processing data values of force versus time and displacement versus time in the finite element analysis using the nonlinear

explicit method. The displacement in this study refers to the displacement when the rigid striker is in full contact with the tubes during crash impact. It is evident that the impact angle significantly influences the response of the thin-walled tubular structure. The PCF of the tubes occurs instantly at the beginning, corresponding to the initiation of tube buckling by the striker plate load impact. As the impact angle increased, the PCF values decreased, which reflected the reducing energy absorbed at a larger angle [36]. Then, the crush responses fluctuated around a mean value throughout the remainder of the crushing process and increased again once it had achieved its densification phase. The densification phase refers to the inability of the tubes to absorb energy.

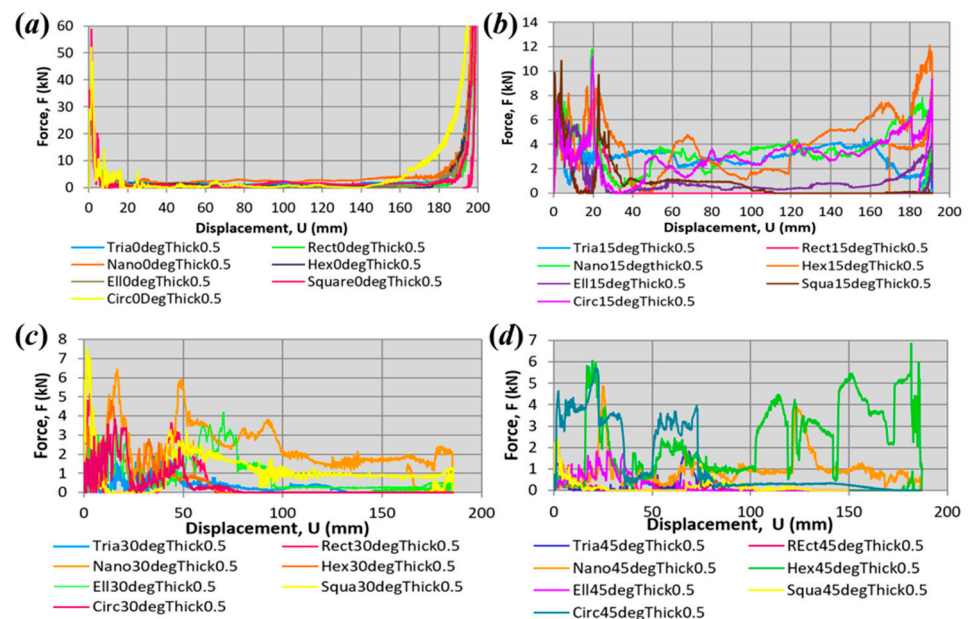


Figure 11. Load–displacement curves of thin-walled straight tubes with 0.5 mm wall thickness subjected to multiple loading angles: (a) 0°; (b) 15°; (c) 30°; (d) 45°.

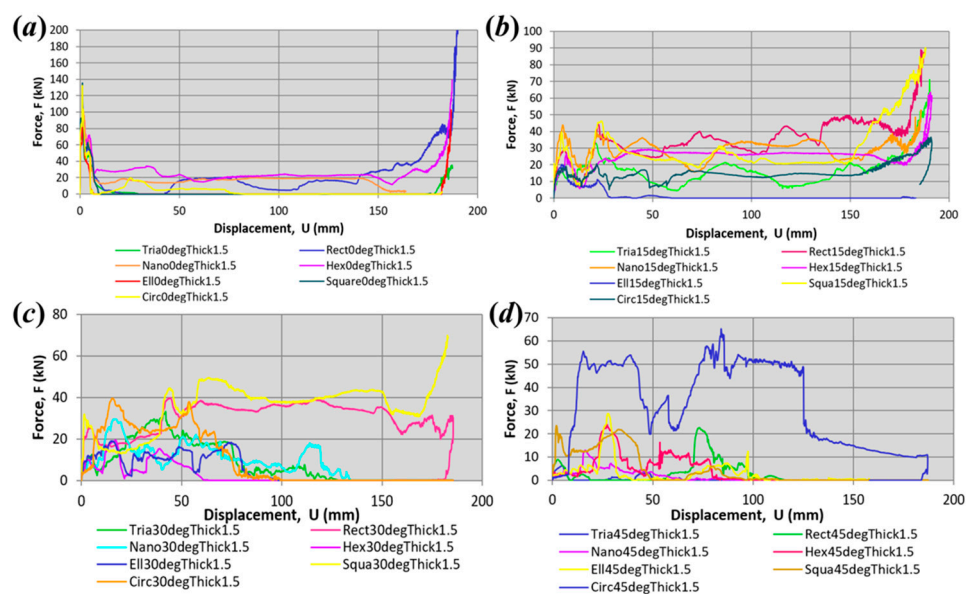


Figure 12. Load–displacement curves of thin-walled straight tubes with 1.5 mm wall thickness subjected to multiple loading angles: (a) 0°; (b) 15°; (c) 30°; (d) 45°.

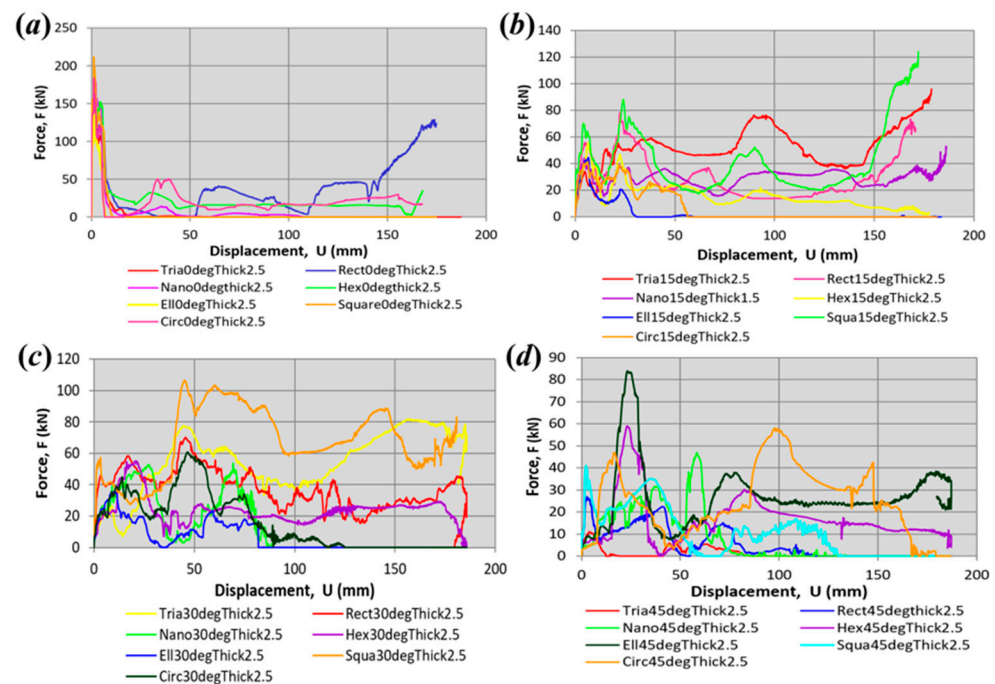


Figure 13. Load–displacement curves of thin-walled straight tubes with 2.5 mm wall thickness subjected to multiple loading angles: (a) 0° ; (b) 15° ; (c) 30° ; (d) 45° .

It was observed that the maximum force values increased with the increase in wall thickness from 0.5 mm to 2.5 mm. This was because a thicker wall provided more material to resist deformation and failure, thereby enhancing the overall strength of the tube. The increased wall thickness allowed the tube to withstand higher loads before yielding or breaking, where high structural integrity is required. The loading angles also play a crucial role in determining the mechanical behavior of the tubes. At a 0° angle, where the load was applied perpendicular to the tube axis, the tubes exhibited a sharp increase in force followed by a decrease, indicating a more brittle failure mode. This was because the load was directly transferred to the tube wall without any angular distribution, leading to a higher stress concentration. In contrast, at angles of 15° , 30° , and 45° , the load was distributed over a larger area of the tube wall, leading to more plastic deformation before failure. This resulted in a more ductile behavior, as evidenced by the multiple peaks and troughs in the load–displacement curves. The ductility of the material is another critical factor that affects the load–displacement behavior of the tubes. As the wall thickness increased, the tubes exhibited more ductile behavior, as seen in the more complex load–displacement curves for the 1.5 mm and 2.5 mm wall thicknesses. A thicker wall allowed more deformation before the thin-walled structure reached its ultimate strength. The increased ductility means the tubes can absorb more energy before failure, making them more suitable for applications where energy absorption is essential. Additionally, the more ductile behavior at higher angles was due to the load being distributed over a larger area of the tube wall, reducing the stress concentration and allowing progressive deformation before failure.

3.3. Effect of Impact Angle and Wall Thickness on Crashworthiness Characteristics

When the weight of the structure is considered, the evaluation of energy absorption is re-evaluated in terms of SEA and overall SEA_α . SEA is the absorbed energy with respect to the mass of tubular structures, while the overall SEA_α is the summation of SEA at each angle multiplied by the corresponding weighting factor W^{α_i} . Overall, SEA_α and the weighting factor represent the relative significance of each individual SEA^{α_i} . The structural SEA calculation accounts for the effect of impact load angle uncertainty. In the current study,

the similar and dissimilar weighting factors for each load impact angle are CASE I and II, respectively. The composite indices of α_i are selected as 0° , 15° , 30° and 45° , respectively, with $W^{\alpha_{0^\circ}} = W^{\alpha_{15^\circ}} = W^{\alpha_{30^\circ}} = W^{\alpha_{45^\circ}} = 1/3$. Changing the weights allows a different SEA_{α} value to be obtained by highlighting different impact load angles. More weights are given to a large impact angle with the weighting factors $W^{\alpha_{0^\circ}} = 0.1$, $W^{\alpha_{15^\circ}} = 0.3$, $W^{\alpha_{30^\circ}} = 0.6$, $W^{\alpha_{45^\circ}} = 0.9$.

Figures 14 and 15 illustrate the effect of the load angle on the SEA, calculated up to an effective crash displacement of 140 mm (equivalent to 70% of the tube's total length) for each tube under oblique impact loading. Essentially, the collapse response of the tubes can be divided into three distinct regions based on the relationship between the SEA and the load angle: Region 1: Progressive collapse dominates the response (progressive region); Region 2: A transition occurs from progressive collapse to a global bending-dominated collapse (bending region), which is consistent with the findings from previous research studies [9,22,32].

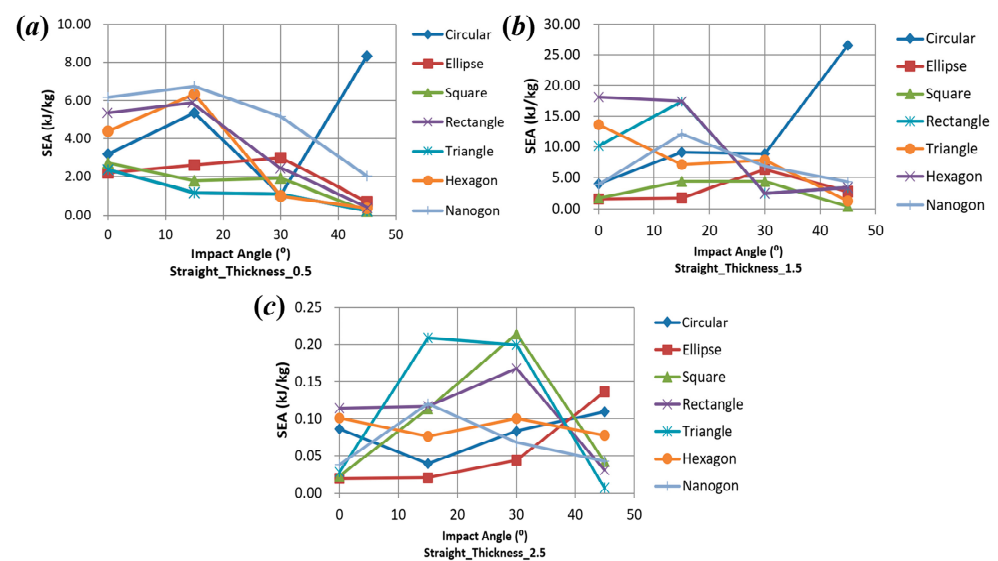


Figure 14. Effect of impact angle and wall thickness of specific energy absorption (SEA) on thin-walled straight tubes under three wall thicknesses: (a) 0.5 mm; (b) 1.5 mm; (c) 2.5 mm.

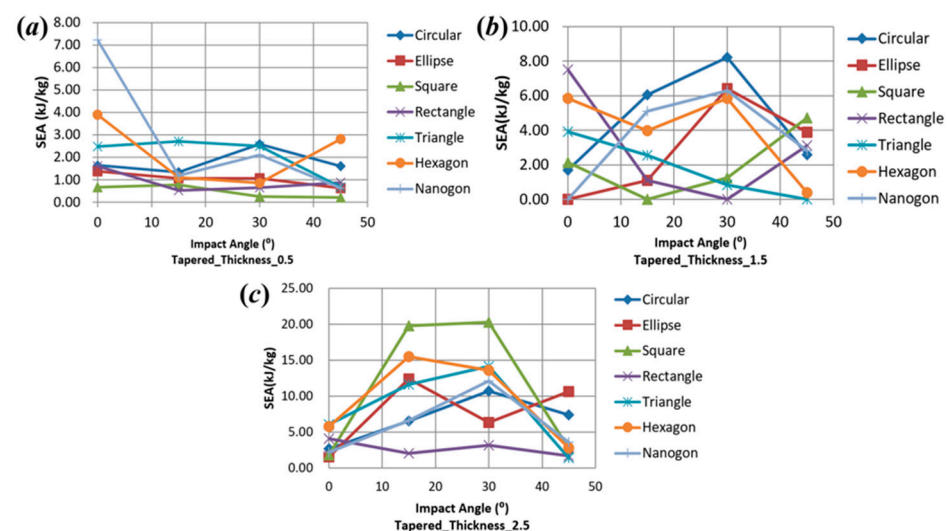


Figure 15. Effect of impact angle and wall thickness of specific energy absorption (SEA) on thin-walled tapered tubes under three wall thicknesses: (a) 0.5 mm; (b) 1.5 mm; (c) 2.5 mm.

Figure 16 shows the summary relation between SEA and impact load angles for each profile design. It is demonstrated that the energy absorption is higher with a wall thickness of 2.5 mm compared to 0.5 mm for both geometries, straight and tapered. In addition, it is observed in the graph that the energy absorption is higher with an impact load angle in the range of $10^\circ \leq \alpha \leq 40^\circ$.

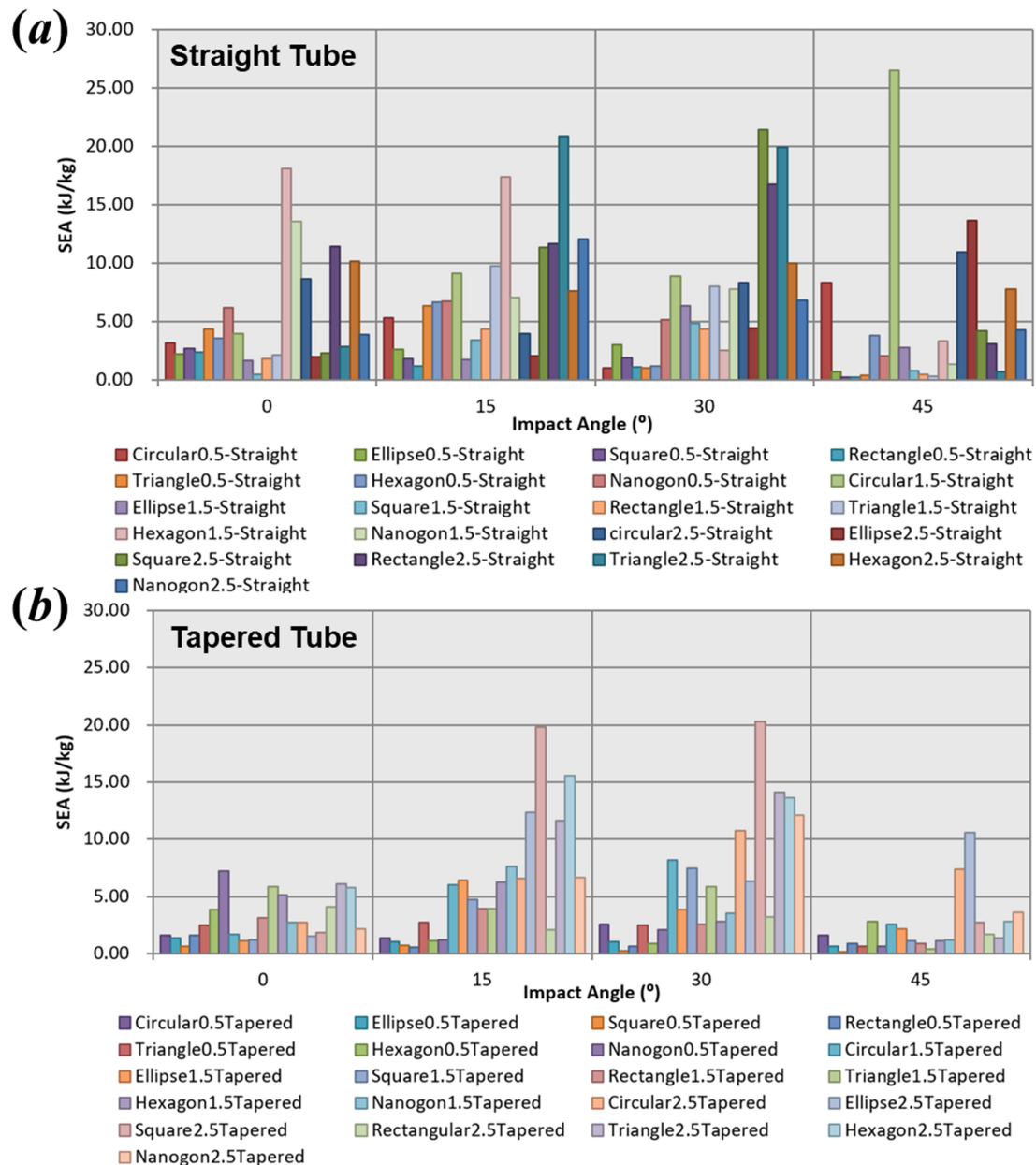


Figure 16. Results of SEA of thin-walled tubes as a function of impact angle and wall thickness: (a) straight type; (b) tapered type.

Figure 17 summarizes the overall SEA_α , with straight and tapered tube geometry for CASE I and II. It showed evidence of the wall thickness effect, whereas when the wall thickness increased, the overall SEA_α also increased for both straight and tapered tubes. The weighting factor of different impact angles, incorporated into the calculation of SEA_α , should be determined based on the occurrence probabilities of each crash angle in real-world applications. The energy absorption capability trend improved when different weighting factors were assigned to different impact angles.

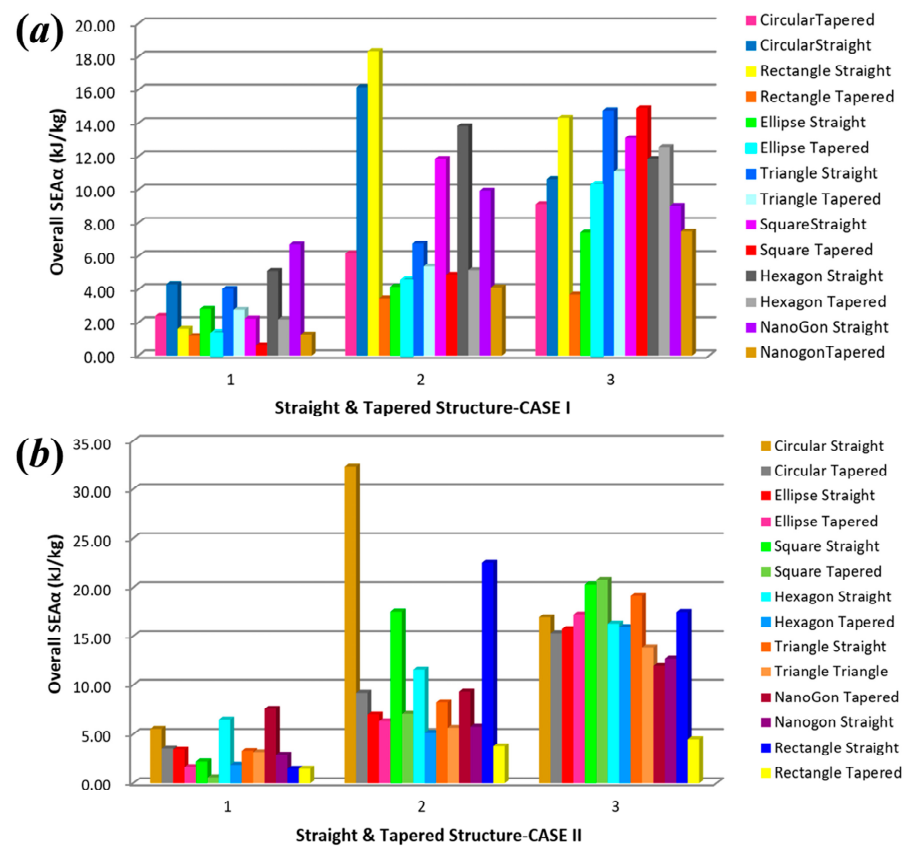


Figure 17. Result of overall SEAα with thin-walled straight and tapered tubes with seven geometry profiles: (a) CASE I; (b) CASE II.

Figures 18 and 19 illustrate the effect of the load angle on the PCF for various thin-walled tubular structures. The results demonstrate that the PCF decreases as the impact angle increases, indicating that the maximum PCF is achieved when the tube is subjected to axial loading at 0° [11,28,32]. In addition, there is not much difference in the PCF values in the comparison between the tapered and straight tube analyses in this study.

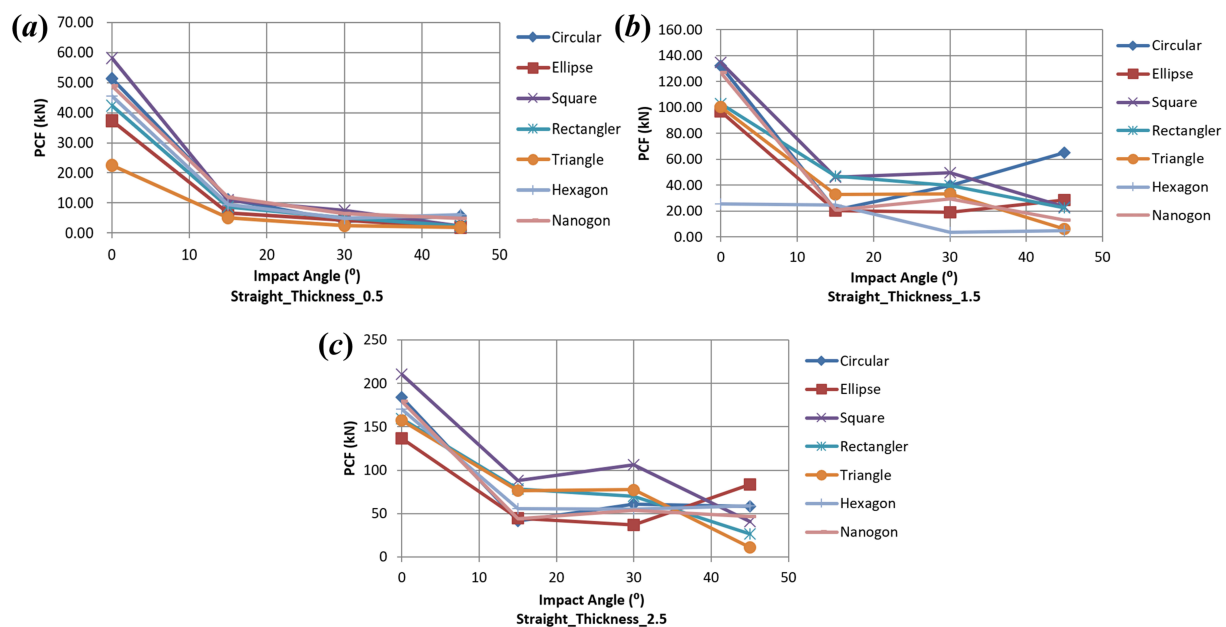


Figure 18. Effect of impact angle and wall thickness of PCF on thin-walled straight tubes with three wall thicknesses: (a) 0.5 mm; (b) 1.5 mm; (c) 2.5 mm.

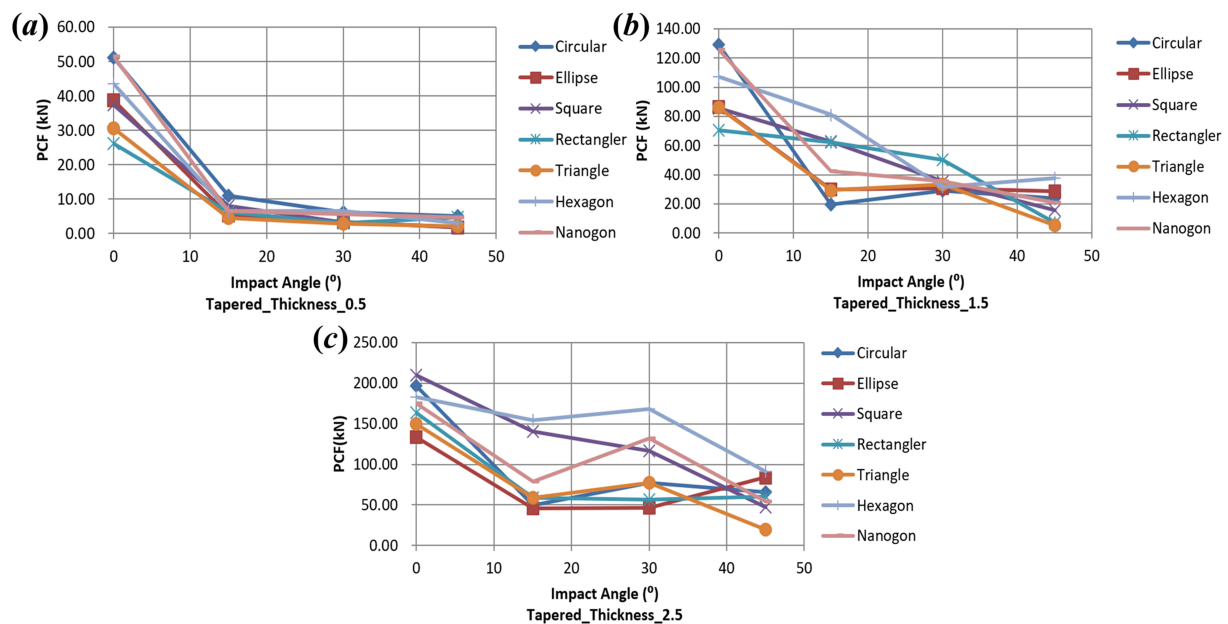


Figure 19. Effect of impact angle and wall thickness of PCF on thin-walled tapered tubes with three wall thicknesses: (a) 0.5 mm; (b) 1.5 mm; (c) 2.5 mm.

The higher the PCF value, the higher the kinetic energy received by the passengers/goods; thus, it needs to be reduced and constrained under a certain level to prevent severe injuries. Nevertheless, this reveals that the PCF does increase in magnitude as the wall thickness increases. Conversely, wall thickness is directly proportional to energy absorption, with energy absorption increasing as the wall thickness increases. Therefore, multi-criteria decision making was established to define the optimum design of thin-walled tubular structures under variable wall thickness and oblique impact loading.

3.4. Result of COPRAS Method for MCDM Process

The complex proportional assessment (COPRAS) method was selected for the multi-criteria decision-making (MCDM) process, with the complex proportional assessment method. This method was chosen for its practicality and simplicity, as it assumes direct and proportional relationships between the significance/priority (Q) and utility (U) of the available options in the presence of mutually conflicting criteria. The performance of the alternatives with respect to different criteria, along with their corresponding weights, was taken into account to select the optimal option profiles. This technique makes the optimum choice, considering the perfect and the least favorite results.

Firstly, it defines the related weightage for each performance criterion. Once the weightings are assigned to the respective indicators, the decision matrix is normalized, establishing the corresponding normalized decision matrix.

The purpose of the normalized decision matrix is to obtain dimensionless values for the various performance indicators, enabling meaningful comparisons across all criteria. Following this, the sums of the weighted normalized values are calculated separately for both beneficial and non-beneficial attributes. In this analysis, the only non-beneficial attribute is the ratio indicator, where a lower value is preferred. Subsequently, the quantitative utility U_i is determined for each tube profile, allowing all the tube profiles to be ranked. Table 3 presents the weighted normalized decision matrix, including beneficial and non-beneficial attributes, along with Q_i and U_i values for thin-walled tubular structures under varying impact angles and wall thicknesses.

The priorities of the tube structure profiles are measured based on the idea that higher priority is given to the greater value of relative significance (Q_i). The tubular structure

profiles with the maximum relative significance Q_{max} represent the best option for concept selection in the design process, whereas the profiles with the minimum relative significance Q_{min} are the least favorable choice. Therefore, in this case study, straight hexagon, tapered square, and straight, circular tubes with wall thicknesses of 1.5 mm, 2.5 mm, and 1.5 mm, respectively, have the maximum relative significance (Q_i) with respect to dynamic axial (0°) and oblique impact (15° , 30° , 45°) loading. A tapered square tube with a wall of 2.5 mm thickness is the best choice for designing an effective energy absorber due to its higher absorption energy capability among the best selections. The detailed weighted, normalized decision matrix, including both the beneficial and non-beneficial attributes and Q_i and U_i values for straight and tapered tubes under various impact angles, is presented in Supplementary Materials on weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for straight and tapered tubes under 0° , 15° , 30° , and 45° impact angle.

It can be concluded that the worst selection of tubular profiles is the tubes, which have a 0.5 mm wall thickness with the lowest quantitative relative rank (U_i), minimum priority/relative significance, Q_i , and the least absorption energy capability. The triangular tapered tube with a 0.5 mm thickness has the worst energy absorption. The details for the optimum profiles are shown in Figure 20, where the tube choice selections are highlighted in green and red in the comparison between the tapered and straight tubes. The highest energy absorption occurs at a 30° impact angle for square tubes with a wall thickness of 2.5 mm for 11.01 kJ. It is 99.5% higher than the worst option profiles, which are triangular tubes with a 0.5 mm wall thickness at 45° impact angles.

(a)	Impact angle (°)	Tapered tubes	Priority, Q_i	Straight tubes	Priority, Q_i	EA (kJ)	optimum design
	0°	TRI_2.5	0.319	HEX_1.5	0.353	3.603	
	15°	SQU_2.5	0.565	TRI_2.5	0.450	10.737	
	30°	SQU_2.5	0.548	SQU_2.5	0.437	11.012	
	45°	ELL_0.5	0.639	CIR_1.5	0.648	5.545	

(b)	Impact angle (°)	Tapered tubes	Priority, Q_i	Straight tubes	Priority, Q_i	EA (kJ)	worse design
	0°	SQU_0.5	0.034	TRI_0.5	0.080	0.239	
	15°	TRI_0.5	0.050	TRI_0.5	0.045	0.420	
	30°	TRI_0.5	0.043	HEX_0.5	0.044	0.230	
	45°	TRI_0.5	0.053	ELL_0.5	0.062	0.060	

Figure 20. Results of COPRAS method for MCDM process on straight and tapered tubes with different designs: (a) optimum design; (b) worst design.

Thin-walled tubular structures are largely used in civil engineering because of their efficient performance in material usage and strength-to-weight ratio. Some examples of the applications are shown in Figure 21. For instance, the truss bridge utilizes thin-walled members to provide a rigid structure with long distances, which distributes the loading evenly across the bridge. The roof truss structural framework is widely used in the roof structure of large buildings, such as stadiums, stations, ship sides, and arenas. Transmission tower uses thin-walled steel tubes with various angles to support the high-voltage power lines, which can withstand wind loadings while minimizing material usage. The thin-walled structures with architectural characteristics can provide a large open space to form a visually striking and functional architectural element. In summary, thin-walled structures are versatile and efficient solutions in civil engineering, and they offer benefits in terms of cost, strength, and architectural flexibility across a large range of

applications. Moreover, the exploration of optimization methods in novel bio-inspired structures is a promising direction which provides innovative solutions. Optimization methods can enlarge the design possibilities and identify the optimal solutions to meet the specific criteria. The multi-criteria decision-making method (MCDM) using the complex proportional assessment method (COPRAS) is valuable for achieving the desired structures. The COPRAS method can systematically evaluate the various design options based on multiple criteria. By integrating MCDM with COPRAS in the design procedure, engineers can prioritize material usage and promote sustainability in structural design.

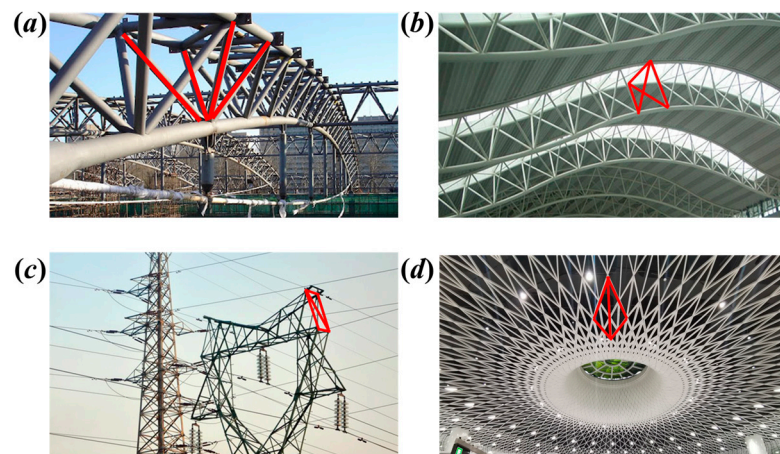


Figure 21. Thin-walled structures used in civil engineering applications: (a) truss bridge; (b) roof truss structural framework; (c) transmission tower; (d) “Eye of Shenzhen” of Gangxia North Hub Station.

4. Conclusions

This study aimed to produce research and design insights into the crash impact and energy absorption behavior of aluminum thin-walled tubular structures using nonlinear explicit finite element analysis with ABAQUS software. This study compressively examined the crash and energy absorption behavior of seven types of empty thin-walled tube structure profiles, namely circular, ellipse, square, rectangular, triangular, hexagon, and nonagon designs under impact angles of 0° , 15° , 30° and 45° . The effects of variable parameters, including profile geometry, wall thickness, and impact angle, were extensively examined to observe and compute the tubular structure energy absorption performance in building construction. Based on the results obtained, the following conclusions can be drawn:

1. The results of the analysis study showed that energy absorption does increase with the increase in wall thickness from 0.5 mm to 2.5 mm. It is concluded that wall thickness influences the energy performance of the tubular structure. The thinner wall tube has less stiffness and thus quickly fails via the global bending mode, which reduces the energy performance capability.
2. In addition, the results show that energy absorption decreases as the load angle increases. In addition, the energy absorption is higher with an impact load angle of $10^\circ \leq \alpha \leq 40^\circ$. As the load angle increases, the PCF values will decrease, which reflects the reduced energy absorbed at a larger angle. The maximum PCF is achieved when the tube is subjected to axial loading at 0° .
3. The highest crush force efficiency (CFE) is observed in the tapered tube with a square profile and a wall thickness of 2.5 mm and in the straight tube with a hexagonal profile and a wall thickness of 1.5 mm. The efficiency was pointed out, and the square and hexagon tubes are potential design profiles of energy absorbers, which provide higher energy performance.

4. All seven types of tubes for impact angles with 0° and 15° were deformed by progressive buckling. Although the straight tubes already tended to bend at an angle of 30° , the tapered tubes experienced a progressive collapse mode under the same impact angle. A single bending mode was developed in all tubes, which occurred at 45° . When the tubes failed due to the global bending mode, the energy absorption was found to be decreasing.
5. From the multi-decision criteria using the COPRAS method, it can be concluded that the tapered square tube with a wall thickness of 2.5 mm was the optimum design profile, while the triangular tube with a wall thickness of 0.5 mm was the worst design profile.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/buildings15040620/s1>. Table S1: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for tapered tubes under 0° impact angle; Table S2: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for tapered tubes under 15° impact angle; Table S3: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for tapered tubes under 30° impact angle; Table S4: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for tapered tubes under 45° impact angle; Table S5: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for straight tubes under 0° impact angle; Table S6: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for straight tubes under 15° impact angle; Table S7: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for straight tubes under 30° impact angle; Table S8: Weighted normalized decision matrix, beneficial and non-beneficial, Q_i and U_i for straight tubes under 45° impact angle.

Author Contributions: Conceptualization, S.K.S., A.Y.N.; data curation, N.H.M.Y., Y.S., B.S., A.P.K.; formal analysis, N.H.M.Y., A.P.K.; funding acquisition, M.R.M.R.; investigation, Q.M., N.H.M.Y., N.A.M.R., B.S., A.Y.N.; methodology, Q.M., N.H.M.Y., S.K.S., Y.S., N.A.M.R.; project administration, M.R.M.R.; resources, A.P.K., M.R.M.R.; software, N.H.M.Y.; supervision, M.R.M.R.; validation, Q.M., Y.S., N.A.M.R., A.Y.N.; visualization, Q.M., S.K.S., B.S., A.P.K.; writing—original draft, Q.M., Y.S.; writing—review and editing, Q.M., S.K.S., N.A.M.R., M.R.M.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Education Malaysia: FRGS/1/2023/TK10/UMP/02/9.

Data Availability Statement: All data included in this study are available upon request by contact with the corresponding authors.

Acknowledgments: This research work was supported by the Structural Performance Materials Engineering (SUPREME) Focus Group, Universiti Malaysia Pahang Al-Sultan Abdullah, Malaysia.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

MCDM	Multi-criteria decision-making method
COPRAS	Complex proportional assessment method
EA	Energy absorption
SEA	Specific energy absorption
PCF	Peak crushing force
BCSS	Bio-inspired cylindrical sandwich structure
CBTs	Cactus-inspired bionic tubes
MPC	Multi-point constraint

CLE	Crushing load efficiency
STE	Stroke efficiency

References

- Wang, Y.; Yang, H.; Chen, J.; Ma, Q.; Song, Y. Load-bearing behaviors of sandwich plates with non-uniformly distributed grid cores: Dynamic impact and blast. *Mater. Today Commun.* **2024**, *40*, 110163. [\[CrossRef\]](#)
- Ma, Q.; Rejab, M.; Siregar, J.; Guan, Z. A review of the recent trends on core structures and impact response of sandwich panels. *J. Compos. Mater.* **2021**, *55*, 2513–2555. [\[CrossRef\]](#)
- Quanjin, M.; Salim, M.; Rejab, M.; Bernhardt, O.-E.; Nasution, A.Y. Quasi-static crushing response of square hybrid carbon/aramid tube for automotive crash box application. *Mater. Today Proc.* **2020**, *27*, 683–690. [\[CrossRef\]](#)
- Ma, Q.; Rejab, M.R.M.; Alang, N.A.; Hanon, M.M.; Yang, B.; Hu, H. Crashworthiness performance of sandwich panel with self-reinforced polypropylene (SRPP) and carbon fiber-reinforced plastic (CFRP) spherical-roof contoured cores. In *Thin-Walled Composite Protective Structures for Crashworthiness Applications: Recent Advances and Future Developments*; Springer: Berlin/Heidelberg, Germany, 2023; pp. 1–12.
- Govindarajan, P.R.; Shanmugavel, R.; Palanisamy, S.; Khan, T.; Ahmed, O.S. Crash-worthiness analysis of hollow hybrid structural tube by aluminum with basalt-bamboo hybrid fiber laminates by roll wrapping method. *BioResources* **2024**, *19*, 3106. [\[CrossRef\]](#)
- Quanjin, M.; Sahat, I.M.; Rejab, M.R.M.; Hassan, S.A.; Zhang, B.; Merzuki, M.N. The energy-absorbing characteristics of filament wound hybrid carbon fiber-reinforced plastic/polylactic acid tubes with different infill pattern structures. *J. Reinf. Plast. Compos.* **2019**, *38*, 1067–1088. [\[CrossRef\]](#)
- Liu, K.; Jing, L.; Wang, K.; Li, Q. Design optimization of the bamboo-inspired foam-filled tube for high-speed train collision energy absorption. *Int. J. Mech. Sci.* **2024**, *271*, 109128. [\[CrossRef\]](#)
- Hussain, K.F.; Cantwell, W.; Khan, K.A. Curved-crease origami hybrid structures with tailorable buckling and energy absorption. *Int. J. Mech. Sci.* **2024**, *284*, 109724. [\[CrossRef\]](#)
- Ha, N.S.; Lee, T.-U.; Ma, J.; Li, J.; Xie, Y.M. Energy absorption of a bio-inspired cylindrical sandwich structure. *Thin-Walled Struct.* **2024**, *195*, 111378. [\[CrossRef\]](#)
- Hou, S.; Han, X.; Sun, G.; Long, S.; Li, W.; Yang, X.; Li, Q. Multiobjective optimization for tapered circular tubes. *Thin-Walled Struct.* **2011**, *49*, 855–863. [\[CrossRef\]](#)
- Xiang, X.; Xiao, C.; Lu, G.; Xie, Y.M.; Zhu, M.; Ha, N.S. Crushing performance of bioinspired hierarchical tapered structures. *Mater. Des.* **2024**, *238*, 112611. [\[CrossRef\]](#)
- Huang, T.; Mao, Z.; Chang, L.; Huang, X.; Cai, Z. Study of impact resistance based on porcupine quills bionic thin-walled structure. *J. Bionic Eng.* **2023**, *20*, 1942–1955. [\[CrossRef\]](#)
- Liu, Y.; Qi, Y.; Sun, H.; Han, N.; Zhou, J.; Song, J.; Zou, M. Bionic design of thin-walled tubes inspired by the vascular structure of bamboo. *Thin-Walled Struct.* **2023**, *186*, 110689. [\[CrossRef\]](#)
- Song, Y.; Ruan, S.; Hao, N.; Okabe, Y. A novel cylindrical sandwich plate inspired by beetle elytra and its compressive properties. *Sci. China Technol. Sci.* **2024**, *67*, 3465–3476. [\[CrossRef\]](#)
- Najibi, A.; Zhang, L.; Zheng, D. On the crashworthiness analysis of bio-inspired DNA tubes. *Sci. Rep.* **2024**, *14*, 8531. [\[CrossRef\]](#)
- Wu, F.; Chen, Y.; Zhao, S.; Hong, Y.; Zhang, Z.; Zheng, S. Mechanical properties and energy absorption of composite bio-inspired multi-cell tubes. *Thin-Walled Struct.* **2023**, *184*, 110451. [\[CrossRef\]](#)
- Ha, N.S.; Lee, T.-U.; Tran, D.T.; Zhang, J.; Lu, G.; Ren, X.; Xie, Y.M. Efficient energy absorption of bio-inspired bi-directional gradient hierarchical multi-cell structure. *Int. J. Mech. Sci.* **2024**, *278*, 109492. [\[CrossRef\]](#)
- Chen, Y.; Deng, X.; Huang, H.; Ran, H.; Wang, C. Crashworthiness of bionic tree-shaped hexagonal hierarchical gradient structures under oblique crushing conditions. *Mech. Adv. Mater. Struct.* **2024**, *31*, 6923–6943. [\[CrossRef\]](#)
- Kocabas, G.B.; Yalcinkaya, S.; Cetin, E.; Sahin, Y. Energy Absorption of a Novel Lattice Structure-Filled Multi-cell Thin-Walled Tubes Under Axial and Oblique Loadings. *Adv. Eng. Mater.* **2024**, *26*, 2400483. [\[CrossRef\]](#)
- He, J.; Wen, G.; Zhao, S.; Liu, J.; Kitipornchai, S.; Yang, J. Energy absorption of graded thin-walled origami tubes. *Int. J. Mech. Sci.* **2024**, *282*, 109609. [\[CrossRef\]](#)
- Guo, W.; Yang, L.; Xu, P.; Li, S.; Yan, W.; Shen, Z.; Yao, S.; Yang, C. Crashworthiness analysis of okra biomimetic corrugated multi-cellular structure. *Int. J. Mech. Sci.* **2024**, *280*, 109459. [\[CrossRef\]](#)
- Chen, J.; Li, E.; Liu, W.; Mao, Y.; Hou, S. Crashworthiness analysis of novel cactus-inspired multi-cell structures under axial crushing. *Int. J. Mech. Sci.* **2024**, *268*, 109053. [\[CrossRef\]](#)
- Wei, Z.; Wang, H.; Bi, Y.; Li, Y.; Li, B.; Wang, B. Crashworthiness and gradient optimization of multi-cell thin-walled structures inspired by leaf venation in royal water lily. *Mech. Adv. Mater. Struct.* **2024**, *32*, 1–17. [\[CrossRef\]](#)
- Ma, Q.; Rejab, M.; Song, Y.; Yan, Y.; Sun, B.; Kumar, A.P.; Hu, H.; Nasution, A.Y. Numerical modeling of composite spherical-roof contoured core (SRCC) sandwich panels subjected to blast loading. *Mech. Adv. Mater. Struct.* **2024**, *32*, 1–23. [\[CrossRef\]](#)

25. Sudhanwa, M.K.; Priyal, V.; Kiran, D.M.; Dhananjay, M.K. Energy Absorption Characteristics of Aluminium Alloy Tubes Subjected to Quasi-static Axial Load. In *Recent Trends in Wave Mechanics and Vibrations: Proceedings of WMVC, Lisbon, Portugal, 4–6 July 2022*; Springer: Berlin/Heidelberg, Germany, 2022; Volume 125, p. 53.
26. Chakraborty, S.; Chatterjee, P.; Das, P.P. Complex Proportional Assessment (Copras) Method. In *Multi-Criteria Decision-Making Methods in Manufacturing Environments*; Apple Academic Press: Waretown, NJ, USA, 2024; pp. 147–155.
27. Haghighi, M.H.; Ashrafi, M. A novel framework for risk management of software projects by integrating a new COPRAS method under cloud model and machine learning algorithms. *Ann. Oper. Res.* **2024**, *338*, 675–708. [\[CrossRef\]](#)
28. Alagesan, P.K.; Dirgantara, T.; Jusuf, A.; Gladys, A.K.; Ma, Q. Comparison of the lateral crushing response of thin-walled aluminum-thermoplastic polymer composite cylindrical shells. *Mech. Adv. Mater. Struct.* **2024**, *32*, 1–16. [\[CrossRef\]](#)
29. Rejab, M.R.M.; Hassan, S.A.; Kumar, A.P. Potentiality of MWCNT on 3D-printed bio-inspired spherical-roof cubic core under quasi-static loading. *J. Mech. Behav. Biomed. Mater.* **2022**, *136*, 105514.
30. Quanjin, M.; Rejab, M.; Idris, M.; Hassan, S.A.; Kumar, N.M. Effect of winding angle on the quasi-static crushing behaviour of thin-walled carbon fibre-reinforced polymer tubes. *Polym. Polym. Compos.* **2020**, *28*, 462–472. [\[CrossRef\]](#)
31. Ma, X.; Guo, C.; Shen, J.; Hu, C.; Gao, H.; Wang, H. Crashworthiness analysis and optimisation of a multi-level bionic multi-cell tube under axial dynamic impact. *Int. J. Crashworthiness* **2024**, *30*, 1–18. [\[CrossRef\]](#)
32. Deng, X.; Liu, W. Crushing analysis and multi-objective crashworthiness optimization of multi-cell conical tube subjected to oblique loading. *Adv. Mech. Eng.* **2019**, *11*, 1687814018824467. [\[CrossRef\]](#)
33. Davoudi, M.; Kim, C. Evaluation of the axial crashworthiness of thin-walled structures with various and combined cross sections. *J. Mech. Sci. Technol.* **2018**, *32*, 4271–4281. [\[CrossRef\]](#)
34. Yıldızhan, S.; Kumlu, U.; Akar, M.A.; Keskin, A.; Hukumdar, O. Numerical crashworthiness analysis of improved elliptical cross-section straight and tapered thin-walled crashing boxes. *Mech. Based Des. Struct. Mach.* **2024**, *53*, 1–18. [\[CrossRef\]](#)
35. Koloushani, M.; Forouzan, M.R.; Niroomand, M.R. On the crashworthiness performance of thin-walled circular tubes: Effect of diameter and thickness. *Mech. Adv. Mater. Struct.* **2024**, *31*, 4805–4817. [\[CrossRef\]](#)
36. Qi, C.; Yang, S. Crashworthiness and lightweight optimisation of thin-walled conical tubes subjected to an oblique impact. *Int. J. Crashworthiness* **2014**, *19*, 334–351. [\[CrossRef\]](#)

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