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Crashworthiness Optimization of Crash Box in Gas Turbines using Modified Firefly Algorithm

Qusay Abdullah Shayyal Al-boslemi
Department of Mechanical Engineering
E-Mail: qusayalabady20@Gmail.com

ABSTRACT

One of the biggest challenges in gas turbine design is the design of parts that have the best performance in damages and protect the main parts of the turbines. Based on the studies, it has been found that hollow thin wall crash boxes can be a suitable option for energy absorbers, according to the way of destruction and appropriate weight. The destruction of these crash boxes depends on various factors like geometry and material used in their construction. Due to the importance of the geometry of these structures in absorbing impact energy and their destruction, in this paper, the axial destruction of the composite thin-wall crash box reinforced with long fibers was numerically simulated. Then crashworthiness of these structures with a smooth longitudinal profile and various common geometric cross-sections were analyzed and effective parameters on crashworthiness were investigated. After examining the common geometric cross-sections, finally to optimize the cross-section of the composite crash box, using the modified firefly algorithm and experiment design, the optimal cross-section geometric profile was obtained. Also, in order to obtain a suitable longitudinal profile, by defining curves in the form and deriving their mathematical equations, the longitudinal profile that performed best was presented.

Keywords: Energy Absorption; Composite; Optimization; Crash Box

1. Introduction

The gas turbine designers aim to reduce the weight of their structures without compromising the safety of the main components. To achieve this main goal, new materials and technologies have been used to design lightweight structures with high strength in various forms. Crash box (also called a blow-out or containment box), bottom plates of aerial structures for emergency landing, fuel tanks, etc. are examples of this type of lightweight structures with high resistance. These structures should be tested in different loading conditions so that their crashworthiness behavior and destruction are evaluated before the final design and use in the structure. Therefore, it is inevitable to study the destruction behavior, failure modes and energy absorption capabilities of this class of structures. So many researchers are studying experimental and numerical studies on thin-walled structures to investigate their actual degradation behavior and energy absorption performance.

Examining the behavior of energy absorption of composite materials provides a combination of reducing the weight of the structure and improving gas turbine safety or at least equal safety compared to metal structures in damages; In other words, using composites in the crash box increases specific energy absorption due to its lower density than metals. Investigating the degradation behavior of composites can be investigated on two scales, micromechanical and macro mechanical. Micromechanical modeling requires more data and higher computer memory and performance, and thus it is much more difficult for engineers to analyze collision phenomena [1]. In the following, the studies carried out on the macro-mechanical scale will be examined to check whether there is a research gap in this field or not.

Kathirsan et al. [2] analyzed the energy absorption capacity of conical aluminum shell and conical aluminum and glass fiber/epoxy hybrid thin shell with both experimental and numerical methods. Failure modes and load-deformation diagrams are extracted from experimental and numerical simulations with ABAQUS software. The performance or energy absorption rate of the sample was calculated by the load-deformation curve. Both the hybrid and uncoated aluminum specimens show a similar trend in the load-deformation curve, but the hybrid cone has a higher initial yield and higher average load than the uncoated aluminum shell. As the compressive load progressed, the transformation of diamond symmetric fracture mode to asymmetric fracture mode was observed in the crushed samples. Kathiresan et al. [3] investigated incomplete conical shells under axial load in 3-layer and six-layer GFRP. In their work, the experimental results of quasi-static axial loading on cones were compared with the results of the mode shapes predicted by ABAQUS software. Kathiresan and Manisekar [4] studied the crushing behavior and energy absorption of conical shells in aluminum (AC) and glass epoxy (CWAC). The samples were analyzed under axial impact load at low speed by two numerical methods with ABAQUS and laboratory software, and a good agreement between the results was observed. Chahardoli and Alavinia [5] investigated the collapse characteristics of conical tubes made of 430 steel alloy with closed ends and circular holes under quasi-static axial load experimentally and numerically with LS-Dyna software. In addition to reporting the appropriate match between numerical and laboratory models, they concluded that creating a hole at a distance from the bottom of the cone can improve the collapse characteristics. Rouzegar et al. [6] investigated the axial buckling of conical aluminum tubes under axial load experimentally and numerically with ABAQUS software. Then, using Minitab software, they tried to choose the optimal sample among the bumpers. Kathiresan [7] investigated the effects of cone cutting and different shock loading conditions on aluminum cone. As in his previous research, he used two laboratory methods and ABAQUS numerical model to simulate crushing and applied the load directly and inclined to the cone.

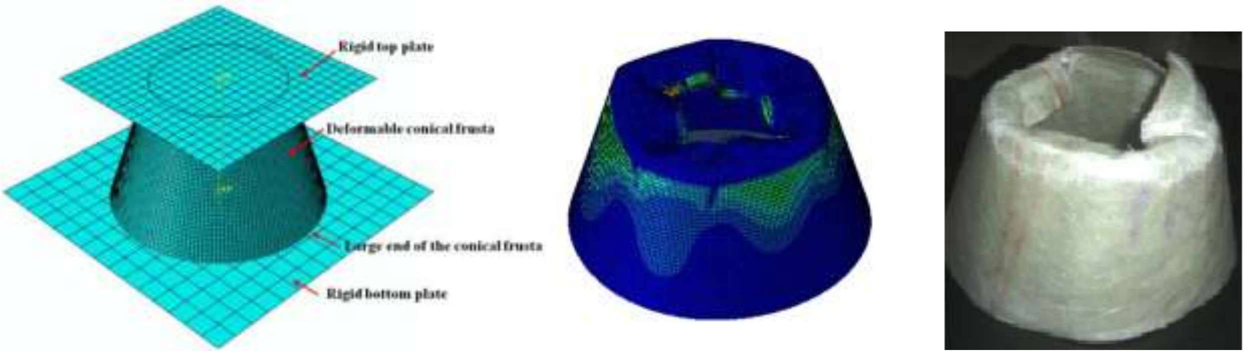
Also, new studies have been conducted on crashworthiness, some of which will be reviewed in the following. Zhang et al. [8] studied the specific energy absorption of the hierarchical honeycomb in comparison with the traditional hexagonal one. They tried to achieve maximum value of specific energy absorption and minimum value of peak crushing force with the help of genetic algorithm and results of their work showed better energy absorption with optimized hierarchical honeycomb. Yin et al. [9] studied the crashworthiness of grooved tube with proposing two-stage grooved tube. They used three approaches for improving the performance of material against axial crushing. Zhou et al. [10] studied the crashworthiness behavior of Nomex® honeycombs with five different specifications. They presented numerical model based on finite element method (FEM) for energy absorbers and verified the model by compression tests. Zhang et al. [11] studied the crashworthiness of subway vehicle collision accident. They presented FEM model and verified it by field investigation to reduce the structural weakness. Liu et al. [12] studied the crashworthiness of thin-walled tapered tubes. They used compressive test to verify their presented FEM model. Goel and Bhutada [13] studied axial crushing behaviour of tubes in an overview research. They investigated from previous researches the role of change in geometry and filling the tubes with foam for optimization of their performance. Taghipoor et al. [14] in an experimental work studied the effect of hole on the behavior of thin tubes under high speed impact. Results of their work showed that collapse force is significantly under the effect of holes up to 46%. Asgari et al. [15] studied the crashworthiness of tubes with lateral corrugations. They tried to find optimum geometry for tubes under different states of loading. Some of recent studies about crashworthiness and its importance have been done by Swati et al. [16] about UCAV's main landing gear, Fuerbeth [17] about crashworthiness among side pole testing, Lee et al. [18] around optimization of automobile components by crashworthiness diagram and Djamaluddin [19] about crashworthiness of double tubes. The tendency of recent researches has been towards optimization with artificial intelligence or using meta-heuristic algorithms due to their special features, including the simultaneous minimization and maximization of objective functions. Among those researches, the following researches can be mentioned. Algorithms like Non-Sorting Genetic Algorithm 2 (NSGA2) by Ghanbari and Panirani [20], Genetic algorithm by Zhengbao and Jijian [21], artificial intelligence techniques by Mishra et al. [22], improved whale optimization algorithm by Gu et al. [23] have been used in the last researches.

Based on mentioned literature, there are limitations mentioned below, which have been tried to be solved in this study: 1- In previous studies, different cross-sections have been investigated in different analyses, but it has not been done in such a way that structures with the same weight and the same loading conditions are compared. For this reason, the process of destruction and impact of structures with different cross-sections under the same loading conditions have been compared with each other. Also, apart from the geometrical parameters, other relevant and important parameters such as loading speed and mass, material and porcelain layer have been investigated, unlike previous articles. 2- In most of the previous studies, the tested or modeled parts were without edge actuators or had a special actuator, and different actuators were not considered and compared with each other. In addition, three types of edge actuators have been examined in this study and a comparison between the performances of each has been presented. 3- In the previous works, it has been tried with another approach to define a general cross-sectional profile and use the response surface method and the optimal cross-section replacement model. 4- In previous studies, linear profiles (Tapered) with angles different half vertices have been investigated.

In this paper, in addition to the conical thin wall structures with different half vertex angles, non-linear profiles have also been investigated and their results have been compared with each other. The purpose of this research is to simulate the behavior of the composite crash box and validate the numerical results with the experimental results used in the references. Then, various parameters such as diameter, thickness, composite material, arrangement of layers, orientation of unidirectional and bidirectional fibers, different drivers, loading speed and impactor mass are investigated on the characteristics of energy absorption. After validating and checking the effective parameters, in this regard, finite element simulation of thin wall structures, or in other words, crash boxes with different common geometric sections including square, elliptical, and pentagonal has been done so that their destruction behavior can be compared with each other. In these geometries, the longitudinal profile is considered straight and inclined so that the destruction of each of these situations can be investigated.

2. Method of Research

In this paper, ABAQUS software is used for axial impact analysis. This software is able to simulate the destruction behavior of composites with the existing fracture theories in the software, both in dynamic mode and in quasi-static mode, using an explicit solver. First, experimental test of Kathiresan & Manisekar [24] were simulated in ABAQUS and results of simulation were verified by experimental tests. Rigid top and bottom plates were simulated by discrete rigid parts of planar shell type and conical frusta was modeled as deformable part. Fig. 1 shows the mentioned parts that assembled by finite element method (FEM) and deformation contours in finite element analysis (FEA) in comparison with experimental sample. It should be noted that presented model showed higher accuracy relative to FEM model of [24]. In the presented model, two rigid plates with dimensions of 160mm x 160mm and composite parts of the conventional shell type were modeled. In the composite layup of the parts, three integration points were used for each layer. The material of the structure was made of 6 layers of glass-epoxy composite with a thickness of 2.34 mm and impact loading with a speed of 4-6 m/s was considered. Explicit solver was used for the analysis and two time steps were defined for it, the first time step includes the time to travel the distance of 0.001 mm of the upper plate and the second time step is the total impact time. To define the contact between the plates and the part, the interaction between the upper plate and the part of the surface-to-surface type with a friction coefficient of 0.17 and the interaction between the lower plate and the part of the node-to-surface type with a friction coefficient of 0.4 was established by penalty method. The self-contact feature was also defined for the composite piece. Rigid plates with discrete rigid elements with a mesh size of 4.8 mm and a composite part with a 4-node shell element with a mesh size of 1.8 mm were modeled by the reduced integration method (S4R).



a) Presented model b) Finite Element Analysis c) Experimental test [24]

Fig. 1. First Presented Model

Five different mesh sizes (4, 2.5, 2, 1.5 and 1.25 mm) were investigated to study the sensitivity analysis of the mesh size on the responses, which is shown in Fig. 2. The results showed that the mesh size between 1.5 and 2 mm is the optimal mesh size. The average load variable was investigated as a variable sensitive to the mesh size, whose change graph is shown in Fig. 3.

4mm mesh 2.5mm mesh 2mm mesh 1.5mm mesh 1.25mm mesh

Experimental sample [24]

Fig. 2. Sensitivity analysis of mesh size

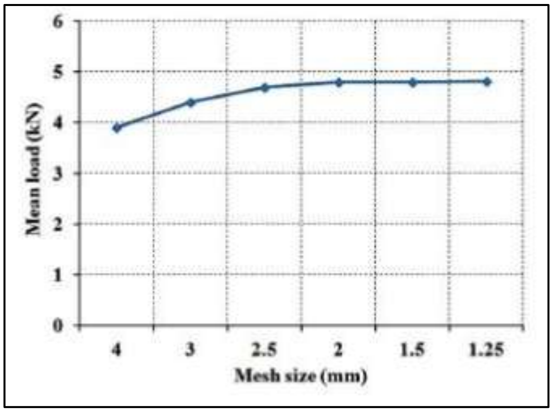


Fig. 3. Variation of mean load by mesh size

To investigate the effect of the type of cross-section and the type of trigger and its modeling method, as well as to study the effect of the type of elements used (shell or solid), the researches Huang and Wang [25], Luo et al. [26] and Chiu et al. [27] in the software ABAQUS were modeled. In [25], Huang & Wang in an experimental work researched the effect of Bevel trigger in comparison with crown trigger. They concluded that 18.4% lower specific triggering stress and 21.2% higher crushing load efficiency take place in crown trigger than Bevel one. In current paper, we modeled their research in ABAQUS software and two conventional shells were used to model the bevel trigger, each of which had 7 composite layers. To model the damage, the new damage criterion of Hashin (1980) was used that presents better results than older version of Hashin criterion (1973), and the alpha coefficient, which controls this criterion, was considered to be 0.8. Other specifications of the model are given in the Table 1. Also Fig. 4 shows our modelling of experimental work of [25] and comparison of the results.

Table 1. Specification of presented FEM model for simulation the experimental works of [25]

Effective parameter	Value
Failure energy	$G_{ft}^{c} = 67\ (kJ/m^2)$; $G_{ft}^{t} = 98\ (kJ/m^2)$
Step time	0.31 s
Mass scaling increment	10e-04
Velocity of impact	100 m/s
Interaction type	Surface to Surface
Friction coefficient	0.27
Mesh size of discrete rigid elements	4mm
Mesh size of 4 node shell elements (S4R)	1.5mm

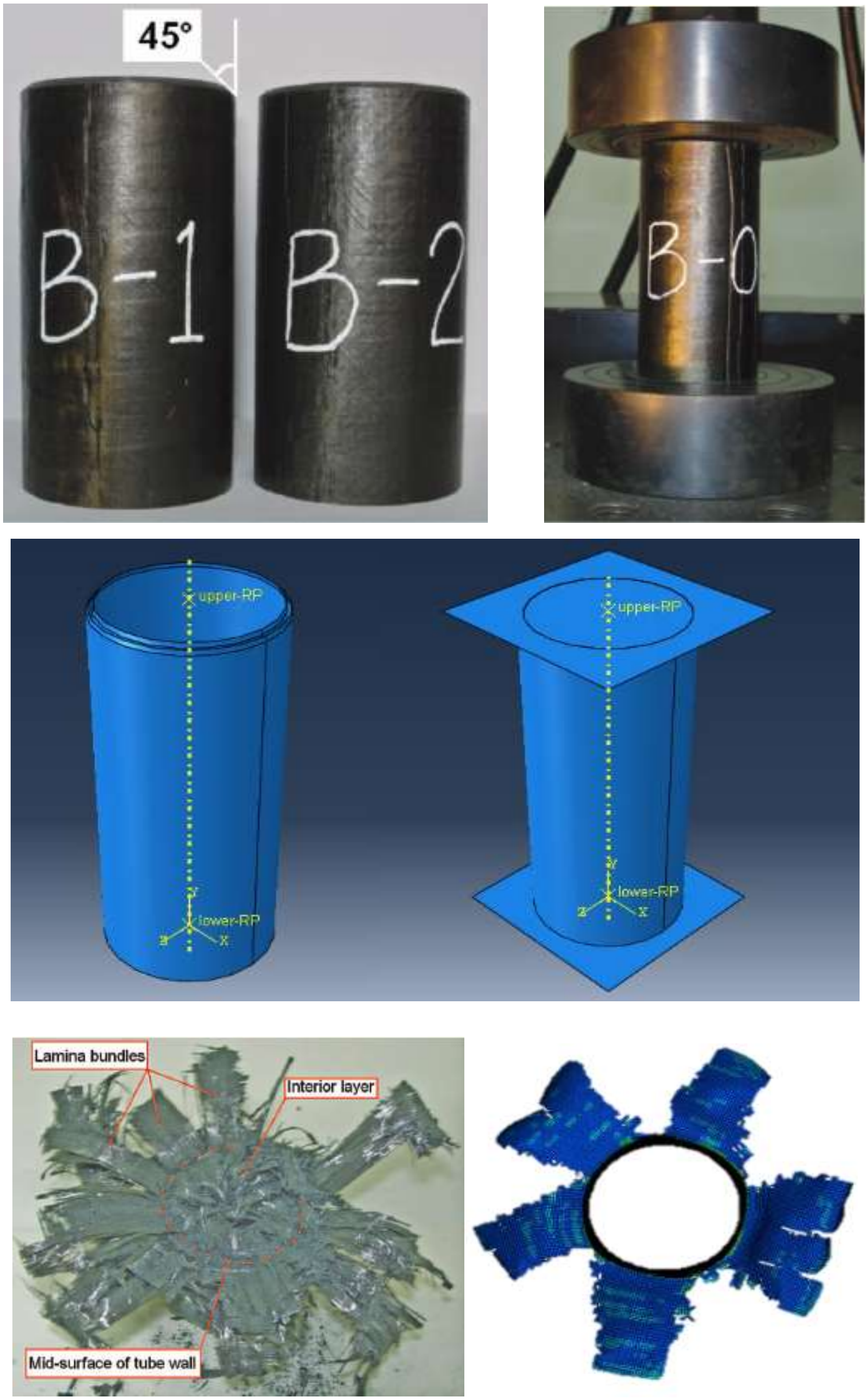


Fig. 4. Second presented model

Lou et al. in [26] studied the progressive failure analysis of carbon/epoxy composite tubes. It should be noted that two elements, conventional shell and continuum shell, were used in their article. To check the effect of modeling with each of these two types of elements and also to check the crashworthiness parameter, their experimental research was also modeled in ABAQUS software. Figure 5 shows the comparison of the results of the progressive method in the laboratory and our presented model in which CD denotes crushing displacement.

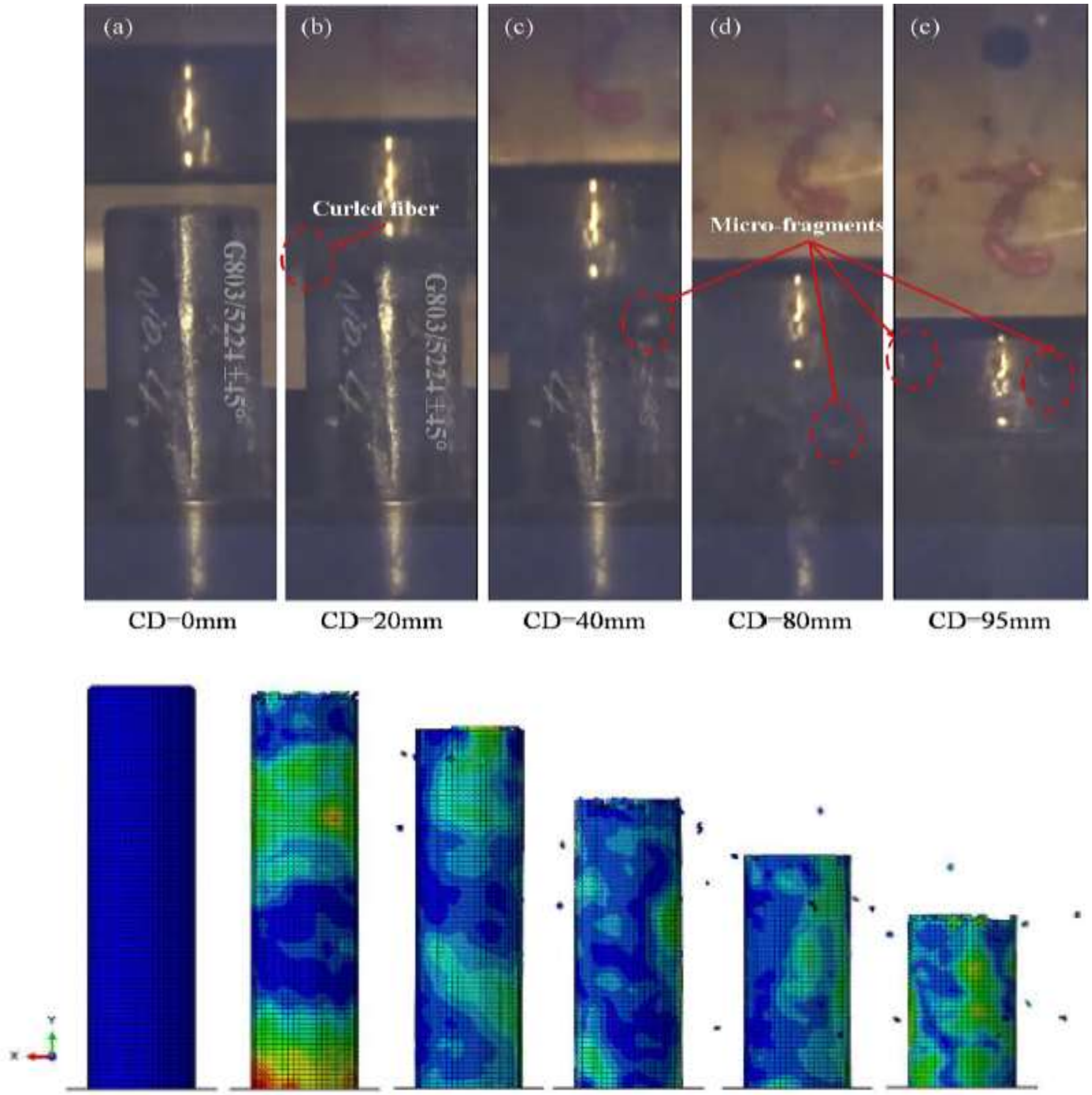


Fig. 5. Third presented model

As shown in Fig. 5, considering that the impact speed is 10 m/s, at first the structure resisted the loading and then the elements started to be damaged and removed. To simulate the deletion of elements, the element deletion tool of the software was used and the degradation coefficient was considered to be 0.9. In the simulation process, the software obtains the stress value at which complete damage occurs by multiplying the degradation coefficient in the stress matrix, and during the analysis, the elements in which the stress reaches this value are removed. Removing elements at lower speeds, as expected, has less corrosion intensity and transmits less maximum force to the structure.

To check the shape of the trigger on crashworthiness, the study of Chiu et al. [27] was simulated in ABAQUS. In this model, a Tulip trigger was used, which is made of 8 layers of carbon-epoxy composite with a thickness of 3mm, and the loading was carried out in the form of crushing and at a constant speed as shown in Fig. 6. Other features of our presented model are listed in Table 2.

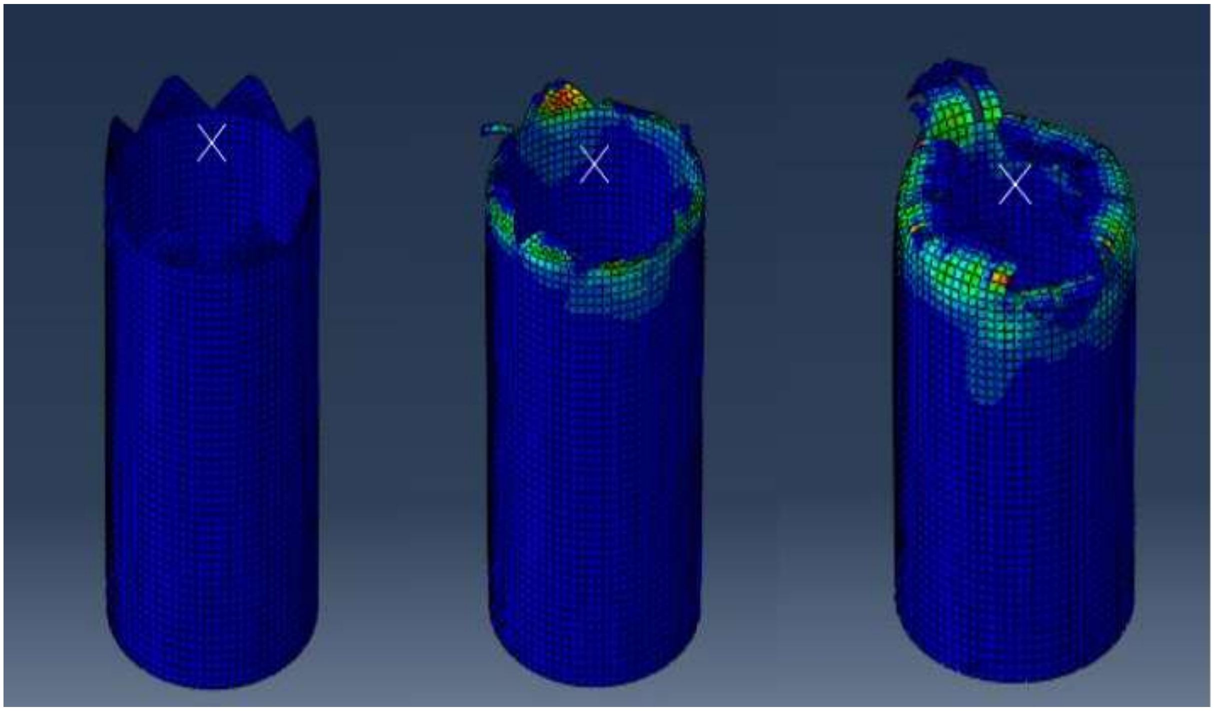


Fig. 6. Fourth presented model

Table 2. Specification of presented FEM model for simulation the experimental works of [27]

Effective parameter	Value
Step time	0.61 s
Interaction type	Surface to Surface
Friction coefficient	0.3
Mesh size of discrete rigid elements	4mm
Mesh size of 4 node shell elements (S4R)	1.2mm

3. Optimization and Results

3.1. Optimization problem

With the multi objective optimization method and using finite element software responses, the optimal cross-sectional area was obtained according to the design variables and the objective function. Then, due to having the optimal angle of the semi-vertice in the conical frusta by considering Spline profiles for the longitudinal profile, the optimal curve has also was obtained.

To optimize the cross section of the crash box with a straight profile, a closed curve [28] was defined as follows:

$$\begin{Bmatrix} X = r(\theta)\cos(\theta)\,, Y = r(\theta)\sin(\theta) \\ r(\theta) = r_0(1 + C_1\cos(4\theta) + C_2\cos(8\theta)) \end{Bmatrix} \tag{1}$$

This equation produces different geometric shapes for different values of c1 and c2. The range of parameters of this equation is as follows:

$$0 \le C_1 \le 0.4 \tag{2}$$

$$-0.1 \le C_2 \le 0 \tag{3}$$

$$2mm \le t \le 2.6mm \tag{4}$$

$$20 \le r_0 \le 40 \tag{5}$$

Now, if we define the objective function in the form of specific energy absorption (SEA), we have the optimization problem with the constraints of equations 2 to 5 and maximize the objective function. In this paper, we solve this problem with the modified firefly algorithm as presented by Niknam et al. in [29]. SEA shows the structure's ability to absorb energy against loading, but the larger value of this parameter does not always make a structure efficient against this type of loading, hence the specific energy absorption parameter is more important in composite structures; because the mass of the structure and consequently its price is important in the industry. Therefore, the priority of designing such structures is to maximize this design parameter.

3.2 Results

3.2.1 Effect of diameter on crashworthiness

To investigate the effect of diameter on tube crashworthiness parameters, diameters were considered in the range of 30 to 100 mm and parameters of mass and loading speed, height, layer arrangement, material and thickness were kept constant. The result is shown in Fig. 7.

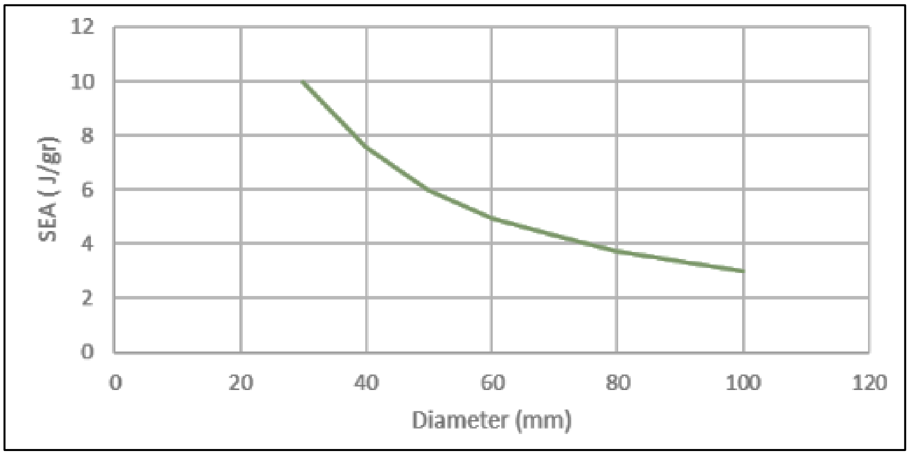


Fig. 7. Effect of diameter on crashworthiness

From Fig. 7 and the analysis, it can be concluded that the specific absorbed energy is the highest in the diameter of 30 mm, while the total absorbed energy is the highest in the diameter of 100 mm. The reason is that with the increase in diameter, the mass of the structure increases and causes a decrease in specific energy. Also, the maximum amount of impact force occurs in the diameter of 30 mm.

3.2.2 Effect of thickness on crashworthiness

To investigate the effect of thickness on crashworthiness parameters, thicknesses are considered in the range of 1.8 to 2.8 mm. In this part, the mass and speed of loading, the height and arrangement of the layers, the material and the diameter (which was considered 30 mm in the previous part) were kept constant. The results are shown in Fig. 8.

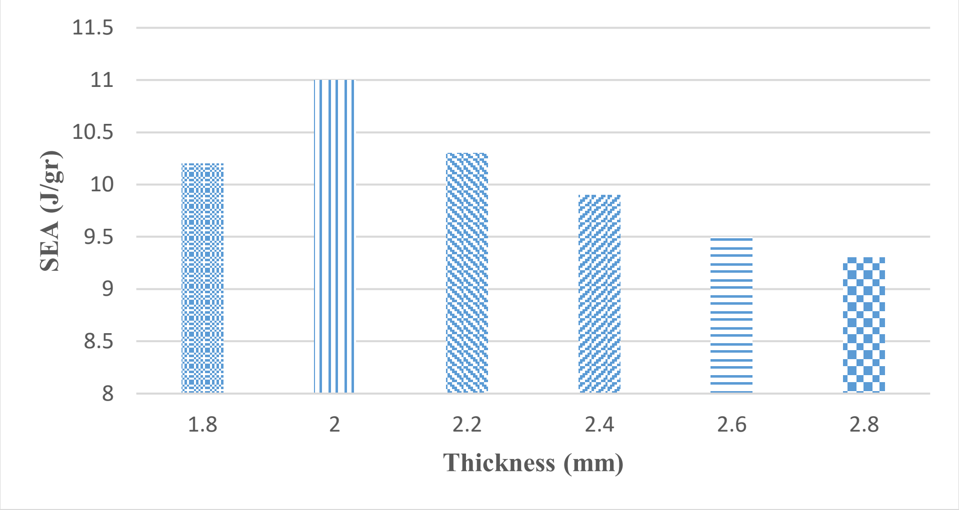


Fig. 8. Effect of thickness on SEA

From Figure 8 and the analysis, it can be concluded that the absorption of specific energy is the highest in the thickness of 2 mm. In the thickness of 2.2 mm, the highest amount of absorbed energy has been observed, and in the thickness of 1.8 mm, the highest amount of impact force efficiency has occurred.

3.2.3 Effect of velocity of loading and the mass of impactor on crashworthiness

To investigate the impact of impactor speed and mass on crashworthiness, speed in the range of 4.2 to 10 m/s and mass in the range of 50 to 80 kg were studied.

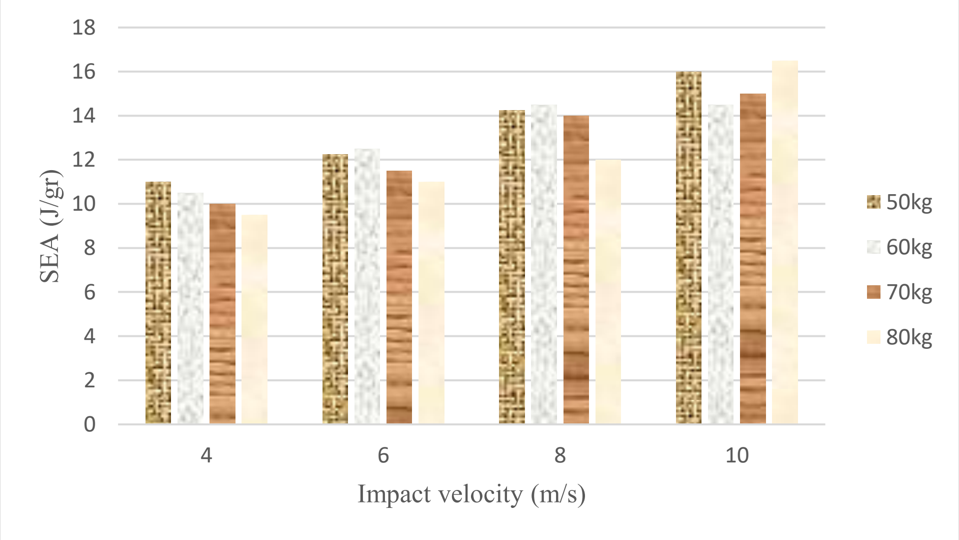


Fig. 9. Variation of SEA by impact velocity

As shown in Fig. 9, it is expected that with the increase in loading speed, the value of the maximum force has increased and due to more kinetic energy during impact, the length of destruction has increased and the structure has absorbed more energy. An important issue in increasing the impact speed is that the efficiency of the impact force is acceptable in the range and severe damage does not occur.

3.2.4 Effect of trigger on crashworthiness

In this part, the effect of three types of trigger on the collapse and impact behavior of the structure was investigated, which are: chamfer, tulip and perforated trigger as shown in Fig. 10. At the angle of 60 degrees, a reduction of more than 30% of the maximum force has occurred, which is the largest reduction among the angles, but at the angle of 45 degrees, the best performance has been seen in terms of specific energy absorption and impact force output. In this angle, the specific energy has increased by more than 35%. It is worth noting that by using these triggers, the length of destruction has increased significantly. This is the main reason for the increase in specific energy and power efficiency, for example, at an angle of 45 degrees, the length of destruction has increased by more than 1.2.

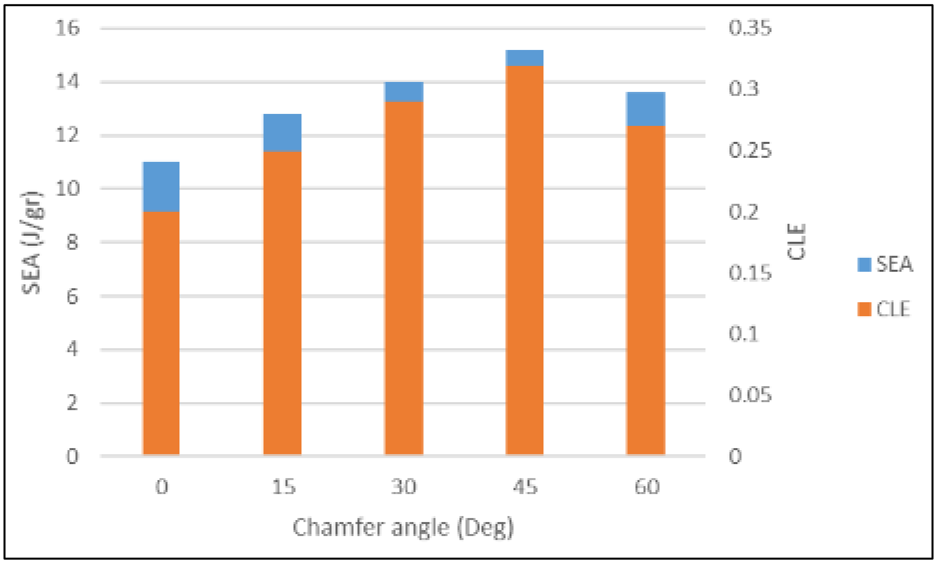


Fig. 10. Variation of chamfer angle with SEA

3.2.5 Effect of number of layers on crashworthiness

For investigation the effect of chamfer trigger in shell elements, effect of number of stack shell layers on crashworthiness were studied as shown in Fig. 11.

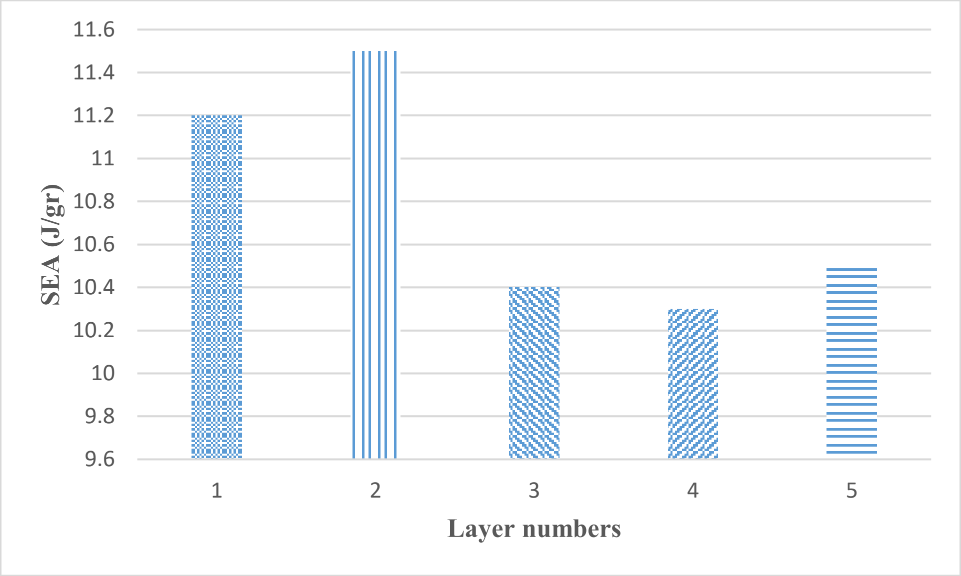


Fig. 11. Variation of number of layers with SEA

3.2.6 Effect of different cross sections on crashworthiness

Effect of different cross sections on crashworthiness were studied and variation of different cross sections with absorbed energy and SEA were investigated as shown in Fig. 12 and Fig. 13.

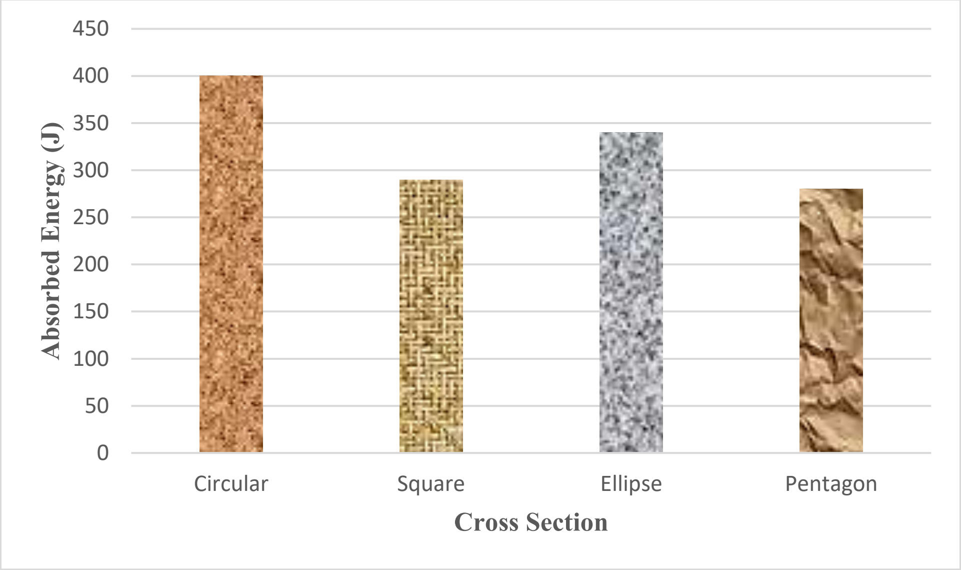


Fig. 12. Variation of different cross sections with absorbed energy

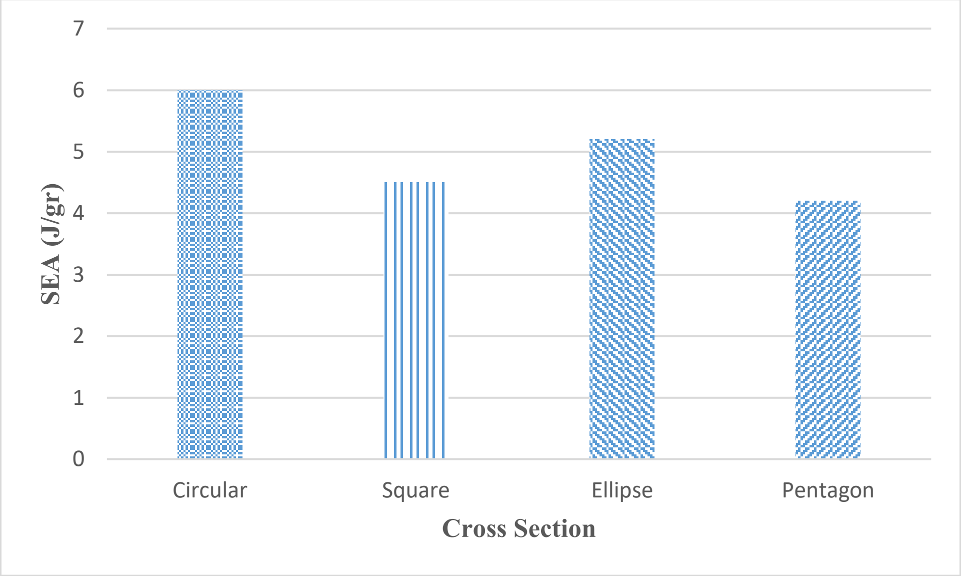


Fig. 13. Variation of different cross sections with SEA

As shown in Fig. 12 and Fig. 13, on average, the absorbed energy of the entire circular cross-section is 30%, 15%, and 32%, respectively, compared to the square, elliptical, and pentagonal cross-sections, and the absorbed specific energy is 24%, 12%, and 27%, respectively.

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3.2.7 Effect of two different materials on crashworthiness

Effect of two types of materials i.e. GFRP and CFRP on crashworthiness were studied by different cross sections as shown in Fig. 14. It can be concluded from this figure that semi-apical angle of 18 degrees has been better in total energy absorption in all cases. The total absorbed energy in this angle compared to other angles was 6% and 11% higher for GFRP and CFRP models, respectively.

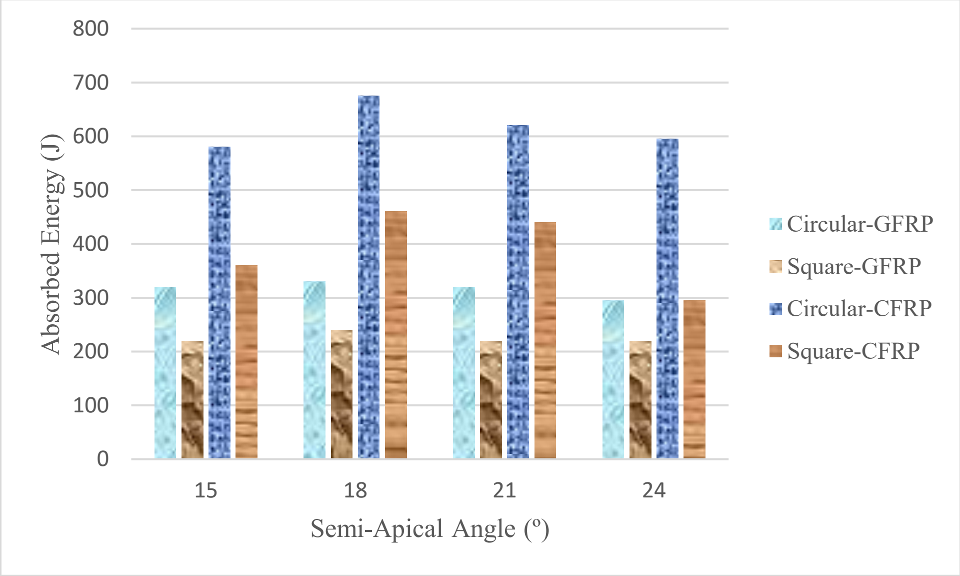

Fig. 14. Variation of different materials and cross sections with absorbed energy

In the last part of the work, optimized cross section profiled was obtained as shown in Fig. 15 based on optimization details mentioned in section 3.1.

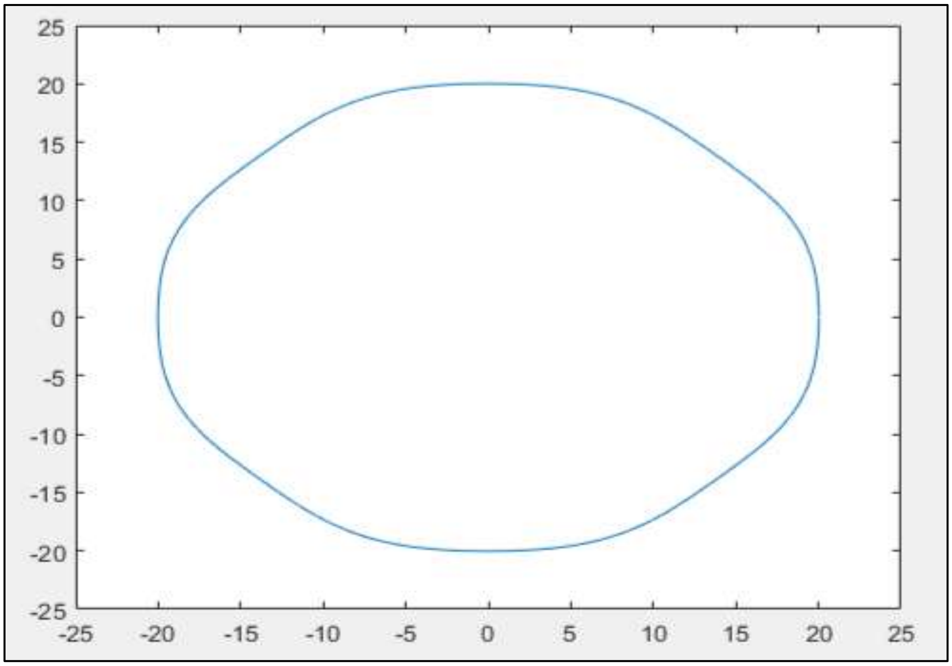

Fig. 15. Optimized cross section profile

4. Conclusion

In this paper, the impact and energy absorption of composite thin wall structures in crash box of the gas turbine were investigated and the effect of different parameters on their collapse behavior was evaluated. Then, by using the optimization method and defining the constraints and the objective function, the optimal cross-sectional area was obtained. The focus of the research was the geometric optimization and suitable design for composite thin wall structures in crash box of the gas turbine to strengthen their energy absorption performance. Due to the fact that the analysis for dynamic phenomena were done numerically, simulation errors are inevitable. Also, the analysis performed on geometries with closed cross-sections, if it is possible to analyze the energy absorption of composite structures with open cross-sections in future researches.

Conflicts of Interest

As behalf of all authors, the corresponding author states that there is no conflict of interest.

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No funding was received.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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