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Abstract

Crash box is a vital component for a vehicle in absorbing kinetic energy in the event of a road collision. The thin-walled structure is emerging as a favorable geometry in designing the crash box. This article investigates the energy absorption performance of the corrugated nautilus shell bio-inspired thin-walled structure made of AA6061-T6 aluminum alloy. This structure's performance was evaluated using finite element analysis (FEA) under quasi-static and dynamic loading conditions in an axial direction, then validated by a quasi-static compression experimental test, which showed satisfactory agreement. The results show that the corrugated nautilus shell bio-inspired thin-walled structure integrated with corrugated grooves reduced peak crushing force (PCF) by 17.9% and increased specific energy absorption (SEA) by 1.3% and crush force efficiency (CFE) by 17.6% compared to non-corrugated design. It can be concluded that the proposed nautilus shell bio-inspired thin-walled structure integrated with corrugated grooves has the potential to replace conventional hollow square designs in vehicle crash box applications.

1. Introduction

Road traffic injuries are a serious public health concern worldwide [1]. Each year, an estimated 1 million people are killed in road crashes, while 20–50 million are injured or disabled [2]. According to the world health organization (WHO), the number of road traffic fatalities worldwide continues to increase annually [3]. Hendrie *et al* (2021) emphasized that investment in road safety management is needed to improve road safety [4]. Therefore, additional efforts need to be made to improve road safety by focusing on road safety, infrastructure, driver education and vehicle safety [5].

One of the most successful ways to increase vehicle safety is to develop thin-walled structures for vehicle crash box applications that are lightweight and capable of absorbing more kinetic energy during a collision. This structure is positioned at the front end of the vehicle and is able to deform in a controlled manner when during a crash. It absorbs the kinetic energy significantly, therefore protecting the occupants of the vehicle [6, 7].

The crashworthiness of this crash box can be assessed using five key indicators: energy absorption (EA), specific energy absorption (SEA), peak crushing force (PCF), mean crushing force (MCF), and crushing force efficiency (CFE).

These indicators' performance were significantly influenced by the materials used and the geometric design. New research reveals that bio-inspired geometric patterns may improve crashworthiness compared to conventional hollow designs [8, 9]. However, thin-walled structures inspired by biological shield structures, such as the nautilus shell, have yet to be investigated and fully understood.

The nautilus is a type of marine mollusk belonging to the cephalopod class. It is known for its distinctive coiled, spiral shell, which is divided into chambers. Nautiluses are considered 'living fossils' because their form

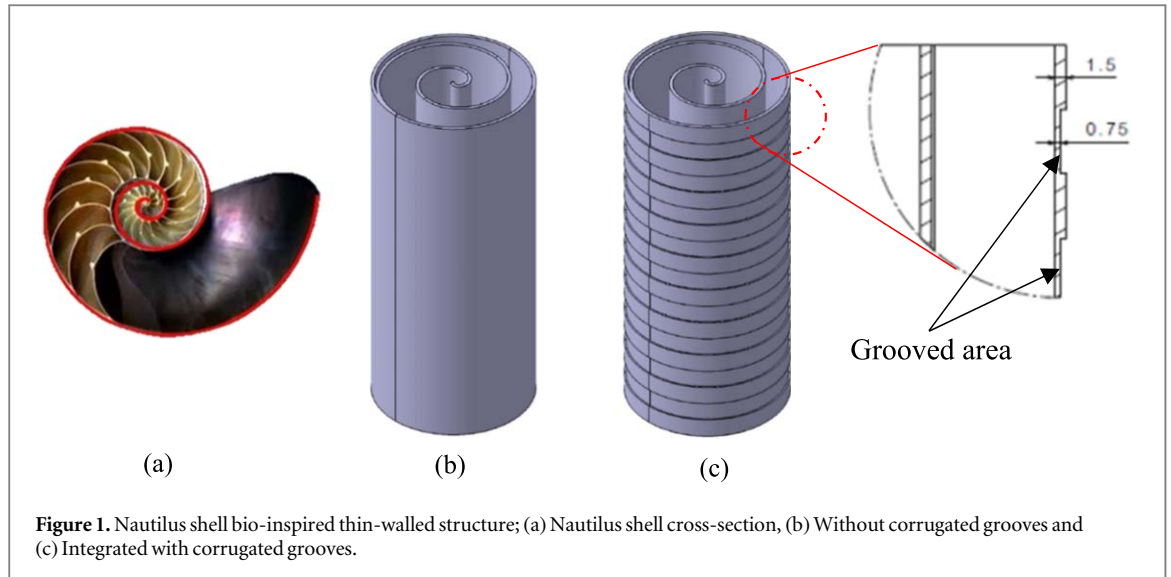


Table 1. Mechanical properties for AA6061-T6.

ρ (kg/m ³)	E (GPa)	σ_y (MPa)	σ_u (MPa)	ν
2,980	67.9	280	325	0.3

has remained relatively unchanged for hundreds of millions of years. This kind of bio-structure is lightweight, modest in size, and provides adequate mechanical protection to the organism's body from any risky circumstances.

Therefore, the goal of this study is to propose and evaluate the crashworthiness of a novel thin-walled structure design inspired by a nautilus shell cross-section and integrated with corrugated grooves. In this work, the quasi-static and dynamic loadings finite element model (FEM) were developed and validated by experimental quasi-static compression test. Then, the comparison of crashworthiness results for both nautilus shell bio-inspired thin-walled structures with/without corrugated grooves were compared against conventional hollow square crash box structure with similar material, size and thickness.

2. Methodology

Inspired by the nautilus shell cross-section as shown in figure 1(a), the bio-inspired thin-walled structure was designed and modeled using CAD software with a diameter of 73.5 mm, a height of 167 mm, and a thickness of 1.5 mm, as illustrated in figure 1(b) without corrugated grooves and figure 1(c) with nine corrugated grooves. The modeled spiral shape in this study is based on the Archimedean spiral type, which can be expressed by equation (1) in polar coordinates where r is the radial distance from the central point, θ is the angle measured from a reference direction, a is a constant that determines the starting radius of the spiral and b is a constant that determines the rate of increase or decrease in radius as θ increases.

$$r = a + b\theta \quad (1)$$

The material selection for this investigation is AA6061-T6 aluminum alloy. This material was selected due to its reliability and lightweight for structural purposes and is widely utilized in automotive components [10, 11].

In order to obtain the mechanical properties of the material, a tensile test was performed on the tensile test specimen using the universal testing machine (UTM) at a speed of 3 mm min⁻¹ in accordance with ASTM standard E8M [12]. Table 1 shows the mechanical properties obtained from the tensile test.

The material properties obtained from the tensile test are applied to the finite element model (FEM) to build an accurate simulation model.

Next, the finite element-based software, Altair Radioss 2021 was used to simulate the quasi-static and dynamic loading analyses on the nautilus shell bio-inspired thin-walled structure without corrugated grooves. The Belytschko-Tsay shell element was used because it can easily capture bending and buckling behavior without the need for volumetric mesh refinement, resulting in lower processing needs [13–15].

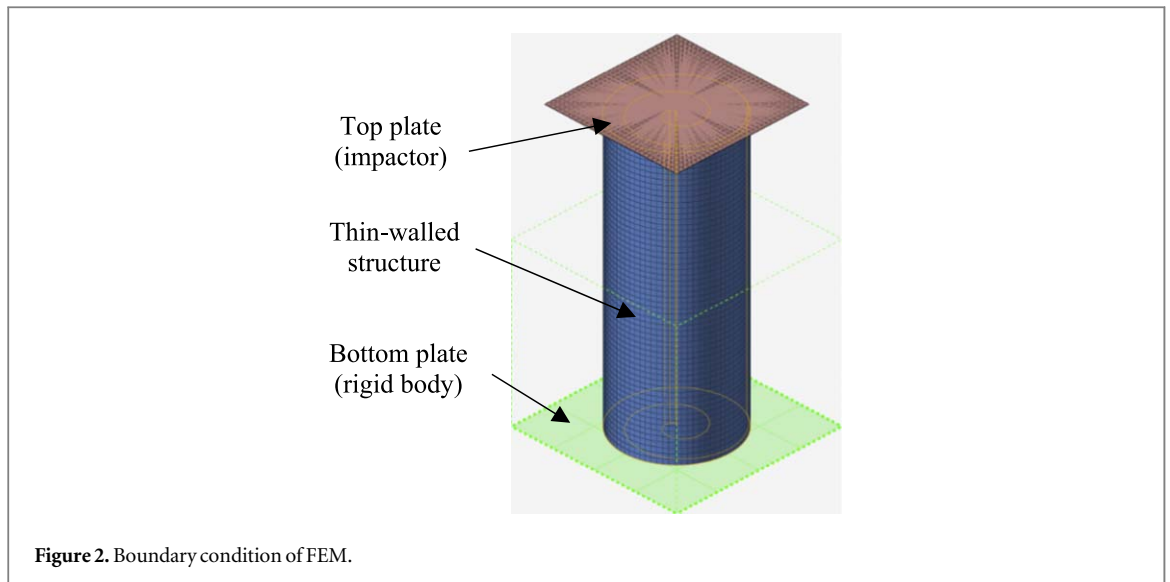


Figure 2. Boundary condition of FEM.

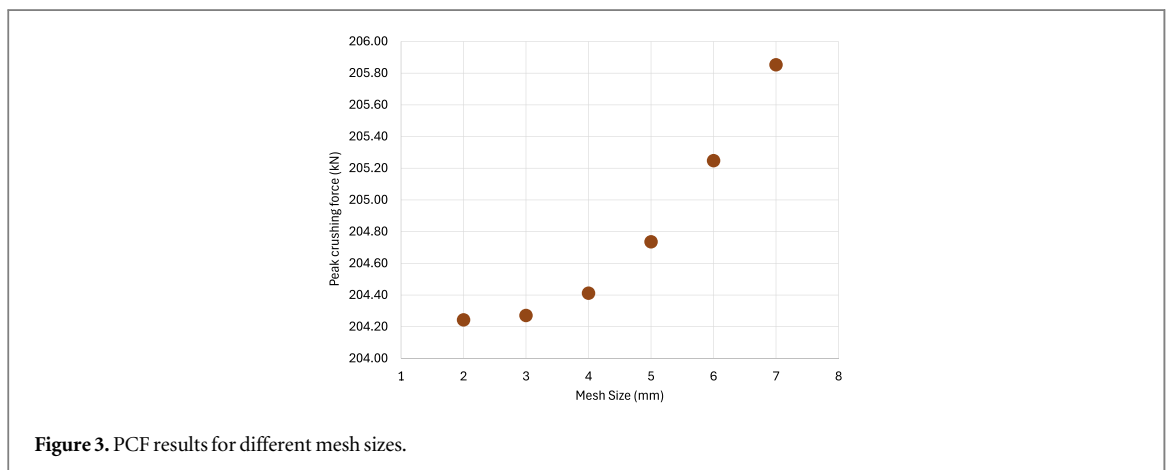


Figure 3. PCF results for different mesh sizes.

In this crash scenario, the thin-walled structure will be axially crushed by the top and bottom plates, as shown in figure 2.

The top plate is designed as an impactor and will be fixed in all degrees of freedom except the vertical direction (translational motion in the z direction) to crush the thin-walled structure. For quasi-static FEM, the impactor velocity was set to a constant velocity of 100 mm min^{-1} instead of 10 mm min^{-1} , as in the experimental compression test, to speed up the simulation process [12]. Meanwhile, the FEM was subjected to dynamic loading (impact load).

The impactor was set with an initial velocity of 18 m s^{-1} (64 km h^{-1}), which followed the Euro NCAP testing standard, with an impactor mass of 500 kg [16–18].

Besides, the bottom plate was fully fixed. Node-to-surface contact was set between the impactor and the structure. To avoid unrealistic self-penetration of the structure, the same type of contact was used for the structure [15].

The values of ρ , E , and ν were set for the thin-walled structure. The plastic behavior of the material was characterized using piecewise linear elastic-plastic, which was fitted with effective plastic stress–strain table data obtained from tensile tests.

Furthermore, a mesh-dependent study was carried out by systematically altering element sizes from 7 mm to 2 mm in order to determine the best element size. The PCF has been selected as an indicator for the mesh-dependent study. The PCF findings indicated that the mesh size converged at 3 mm . As illustrated in figure 3, the 3 mm mesh size had modest variances in PCF value compared to the other mesh sizes, showing convergence.

Table 2 provided specifics on the proportion of variances, which further supported the 3 mm element size's acceptability. Therefore, a total of $8,344$ elements were used to mesh the nautilus shell bio-inspired thin-walled structure without corrugated grooves.

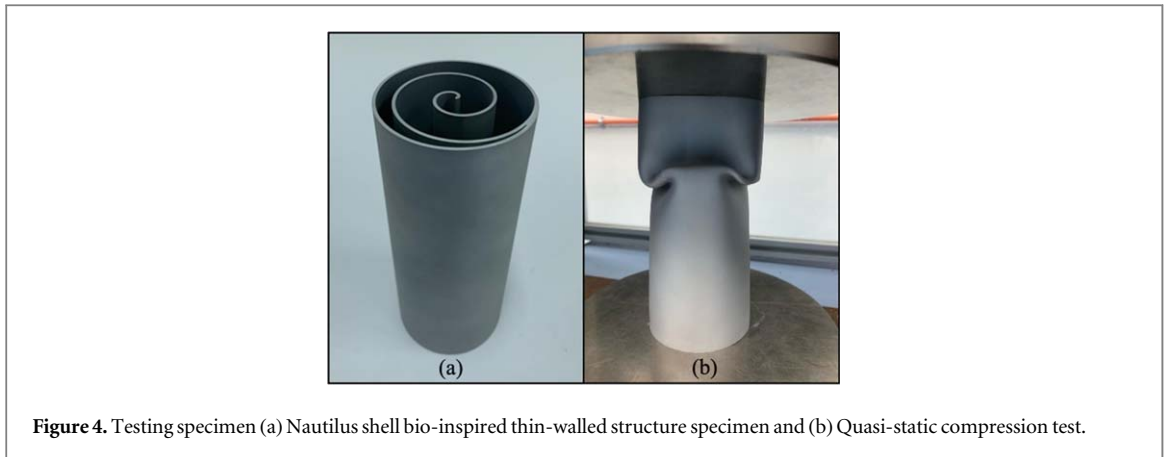


Figure 4. Testing specimen (a) Nautilus shell bio-inspired thin-walled structure specimen and (b) Quasi-static compression test.

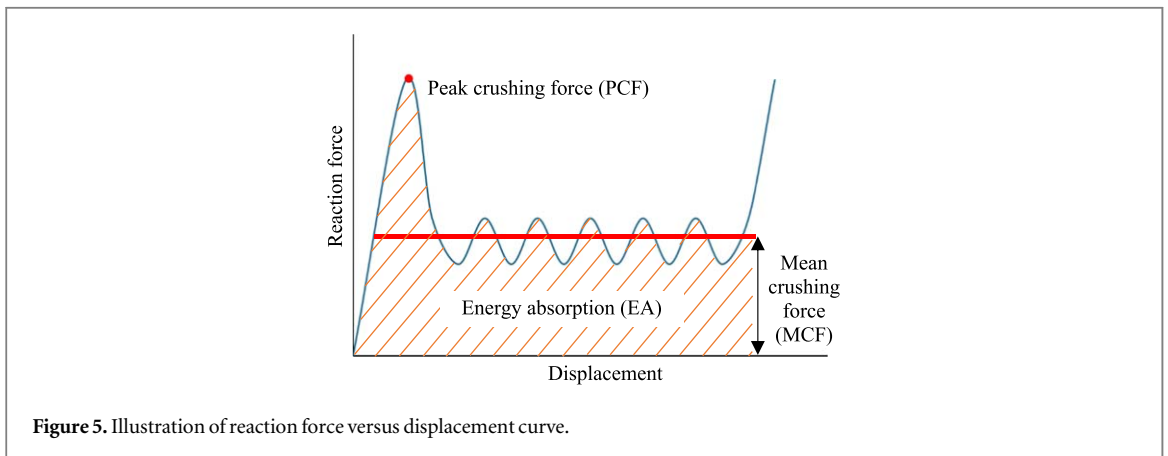


Figure 5. Illustration of reaction force versus displacement curve.

Table 2. Mesh size comparison.

Mesh Size Comparison (mm)	Difference (%)
7–6	0.29
6–5	0.25
5–4	0.16
4–3	0.07
3–2	0.01

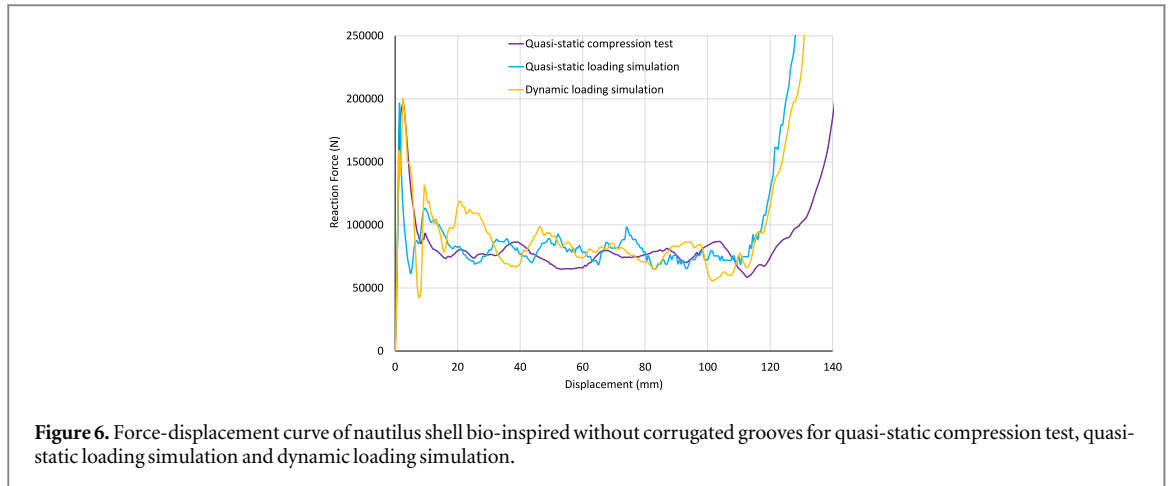
Concurrently, the prototype of the proposed bio-inspired design thin-walled structure without corrugated grooves design was fabricated by using the wire electro-discharge machining (WEDM) process as shown in figure 4(a) and then compressed under quasi-static loading by using the UTM machine as shown in figure 4(b) with a constant velocity at 10 mm/min speed rate to validate the FEA result [7, 16].

Next, the FEM subjected to dynamic loading was carried out on nautilus shell bio-inspired thin-walled structures with corrugated grooves and conventional hollow square crash box structures. The crashworthiness results obtained from the FEA were compared for both bio-inspired structures against the conventional hollow square crash box structure.

The crashworthiness performance of the thin-walled structure can be determined theoretically through the reaction force versus displacement curve obtained from FEA. As illustrated in figure 5, PCF can be directly determined by peak force in the reaction force versus displacement curve [19].

Meanwhile, EA is the area under the graph, which was determined via equation (2) where F is the reaction force and d is the displacement. In the meantime, MCF is an average reaction force, which was determined by dividing EA with d . SEA was determined by dividing EA with structure mass (m), as shown in equation (4), and CFE was identified by dividing MCF towards PCF, as in equation (5) [19–21].

$$EA(d) = \int_0^d F(x) dx \quad (2)$$



$$MCF = \frac{EA}{d} \quad (3)$$

$$SEA = \frac{EA}{m} \quad (4)$$

$$CFE = \frac{MCF}{PCF} \quad (5)$$

3. Results and discussions

Figure 6 shows the results of reaction force versus displacement curves of a nautilus shell bio-inspired thin-walled structure without corrugated grooves design, compressed under quasi-static and dynamic loadings. The results are generated from the quasi-static compression test (experimental), quasi-static loading simulation (FEA) and dynamic loading simulation (FEA).

Based on the results, the quasi-static compression test deviates minimally from both the quasi-static and dynamic loading simulations, indicating that the FEM are accurate and reliable. Moreover, These findings further demonstrate that the chosen AA6061-T6 is insensitive to strain rate, with the difference between quasi-static and dynamic loading simulation results being relatively similar, which is aligned with previous researches where they found that the AA6061-T6 is insensitive to strain rate within 10^{-3} to 10^3 s^{-1} [22, 23].

Besides that, in all cases, the contact force increases dramatically after around 110 mm of displacement, indicating that the structure has densified during this compression length.

The drawbacks of the results are found when the value of PCF was almost 200 kN throughout compression testing and both quasi-static and dynamic loading simulations. High PCF is not ideal for energy-absorbing structures in crashworthiness applications. Low PCF is preferred to minimize excessive force transmitted to the main structures and vehicle occupants that need to be protected [24, 25].

Thus, PCF should be confined to a certain range [26]. To reduce the PCF value, nine corrugated grooves were integrated into the nautilus shell bio-inspired thin-walled structure, as shown in figure 1(c).

Figure 7 compares the reaction force versus displacement curves between the nautilus shell bio-inspired thin-walled structure with and without corrugated grooves and the conventional hollow square thin-walled structure design with similar size and thickness under dynamic loading.

The results show that the nautilus shell bio-inspired thin-walled structure without corrugated grooves design provides a higher PCF than both the structure with corrugated grooves and the conventional hollow square structure.

It is clear that PCF may be reduced by introducing corrugated grooves into the nautilus shell bio-inspired thin-walled structure without significantly reducing overall reaction forces. This is because the corrugated grooves provide more localized zones that may deform and fold independently during the deformation.

Nevertheless, the conventional hollow square thin-walled structure consistently exhibits a lower reaction force than the nautilus shell bio-inspired thin-walled structure with or without corrugated grooves, indicating a weaker resistance to impact collision. The values of PCF, EA, SEA, MCF, CFE and structure mass for these three structures are shown in table 3.

The crashworthiness results reveal that the nautilus shell bio-inspired thin-walled structure integrated with corrugated grooves demonstrated a reduction in PCF of approximately 17.9% compared to the structure

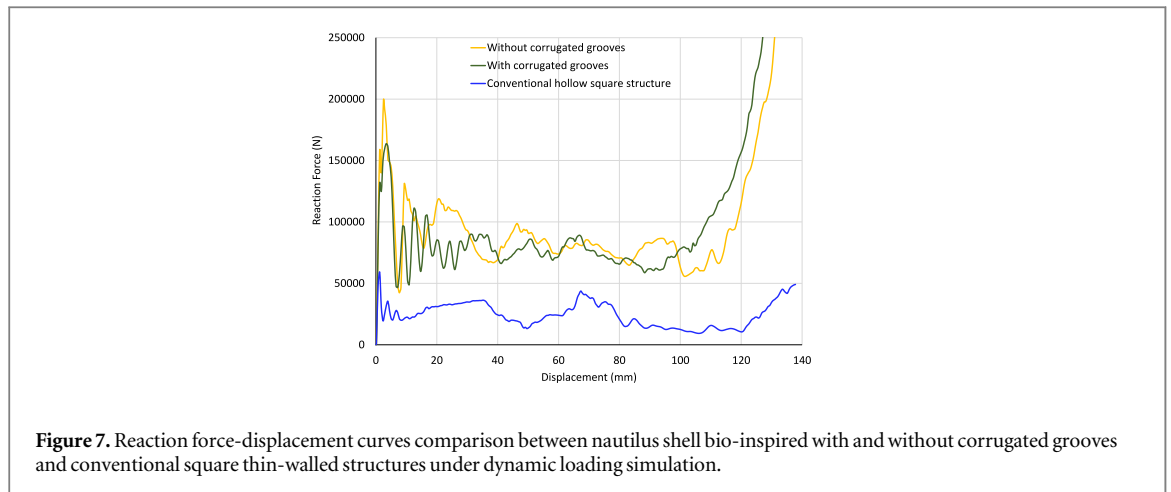


Table 3. Crashworthiness indicators comparison between nautilus shell bio-inspired and conventional square structures.

	Nautilus shell bio-inspired without corrugated grooves design	Nautilus shell bio-inspired with corrugated grooves design	Conventional hollow square design
PCF (kN)	199.17	163.74	59.07
EA (kJ)	8.83	7.82	2.56
SEA (kJ/kg)	26.38	26.72	12.45
MCF (kN)	85.64	82.80	23.29
CFE (%)	43.00	50.57	39.42
Structure Mass (kg)	0.335	0.292	0.205

without corrugated grooves, but it remained 63.9% higher than that of the conventional hollow square structure.

In terms of EA, the design with corrugated grooves showed a slight reduction of around 11.4% compared to the structure without grooves, yet it remained 67.3% higher than the conventional hollow square structure.

Besides that, MCF decreased by 3.3% compared to the structure without corrugated grooves but remained 71.9% greater than the conventional hollow square structure. Furthermore, CFE increased by 17.6% over the non-corrugated design and 22.1% over the conventional hollow structure.

In terms of mass, the corrugated groove structure was 12.8% lighter than its non-corrugated design, but it weighed 29.8% more than the conventional hollow square structure. Although the conventional structure is lighter than the corrugated structure, however, when considering the energy absorption capacity, the SEA of the corrugated tube increases by about 1.3% compared to the structure without corrugated grooves and 53.4% as compared to the conventional hollow tube. Thus, the corrugated tube is proven to be the best structure among the others when involving both lightweight and crashworthiness applications.

Overall, the crashworthiness indicators such as EA, SEA, MCF, and CFE for the nautilus shell bio-inspired thin-walled structure without corrugated grooves outperformed those for the conventional hollow square structure. However, the PCF for the nautilus shell design was relatively high. By integrating the corrugated grooves, the PCF was effectively lowered, while both the SEA and CFE improved, illustrating the efficiency of this design change in improving the structure's crashworthiness.

4. Conclusion

The nautilus shell bio-inspired thin-walled structure integrated with corrugated grooves significantly improves crashworthiness performance. The decreasing of PCF compared to the non-corrugated design is a favorable consequence, as lower PCF is typically preferred for crashworthiness, lowering the impact forces imparted to vehicle occupants during a collision. Despite the reduction, the PCF remained higher than the conventional hollow square structure, indicating increased strength.

Furthermore, the design demonstrated significant improvements in SEA and CFE, implying greater energy absorption and effective deformation control. Although the EA and MCF were somewhat lower than the

non-corrugated design, the structure was generally more crashworthy than the conventional hollow square structure, with an acceptable weight-performance ratio. These findings highlight the advantages of a nautilus shell bio-inspired thin-walled structure integrated with corrugated grooves in increasing energy absorption characteristics, making the design ideal for crash box applications.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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