Heliyon 8 (2022) e11280

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Research on lightweight laminate for car body with excellent cushioning and energy absorption characteristics

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ARTICLE INFO

Keywords:
Fiber metal laminate
Corrugated-core panel
Finite element simulation
Flatwise compression test

ABSTRACT

With the development of the economy, car ownership is increasing day by day. In the context of energy shortage and environmental pollution, it is very important to study lightweight and ensure car safety. In this paper, a lightweight fiber metal laminate (FML) with excellent cushioning and energy absorption characteristics for car body is proposed by studying the deformation and energy absorption mechanism of ordinary groove plate under flat pressure. The FML is made up of an M-shaped aluminum alloy sandwich plate and two carbon fiber reinforced composite outer panels. By means of experiment and finite element simulation, it is proved that this structure had good cushioning energy absorption effect. Under the same conditions, the peak force of the M-shaped corrugated core FML with 2.5 mm groove depth is 46.3% of that of the traditional trapezoidal corrugated-core FMLs. Besides, the energy absorption capacity of the M-shaped corrugated core FML with 2 mm groove depth is 1.62 times of that of the traditional trapezoidal corrugated-core FMLs, before the top plate of sandwich unit touches the bottom plate. And cushioning energy absorption mechanism of M-shaped corrugated core FML is further explained by simulation.

1. Introduction

Under the background of increasing car ownership and energy conservation and emission reduction, automobile lightweight technology is in a very important position. It is of great significance to environmental protection and energy supply [1]. Using lightweight materials is the most effective and direct means of reducing body mass [2]. Common lightweight materials include aluminum alloy, magnesium alloy, high strength steel, high strength fiber composites, etc. Among them, aluminum alloy and carbon fibre reinforced plastics (CFRP) are the most widely used due to their low density and high strength [3, 4, 5]. Lightweight metals such as aluminum alloy have stability and plastic behavior, and can absorb energy during the deformation process [6], but it is easy to deform too much and squeeze the living space of the occupant. Fiber reinforced composites, such as carbon fiber composites have high strength and fatigue resistance. However, the disintegration of the body caused by brittle fracture threatens the lives of occupants in the car. Therefore, fiber metal composite (FML) came into being. It makes metal sheets and fiber reinforced composite materials into composite materials, so that the advantages of the two complement each other, so as to achieve high specific strength, specific stiffness, good fatigue resistance, fracture toughness and high energy absorption capacity [7, 8].

In the study of FMLs, its sandwich structure has attracted much attention. Feng Xiao et al. [9] reviewed the research status of laminated plate structure. The positive influence of laminated plate structure on energy absorption has been proved [10, 11, 12]. At present, corrugated sandwich structure, honeycomb sandwich structure and foam core structure are widely used [13, 14]. Among them, the cross-section shapes of corrugated structures are diverse, mainly including trapezoidal, triangular and sinusoidal waveforms. Various cross-section forms of corrugated structures are used in beams, webs, and embedded panels. Compared with the flat plate, the corrugated structure can increase the buckling stress under the same plate thickness, it can provide a larger out-of-plane stiffness. The existence of the corrugated structure also improves the ductility of the component, increases the overall energy dissipation capacity, and reduces the overall mass. Zaid et al. [15] found that corrugated core structure has higher shear strength than foam core structure and square honeycombs core structure in the longitudinal direction. What's more, corrugated sandwich structure has more space to be designed. Some scholars [16] had proved that the corrugated structure has a good buffer energy absorption capacity. This is very consistent with the purpose of lightweight and improving mechanical properties of this topic. Therefore, this paper starts from the groove (trapezoidal)

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https://doi.org/10.1016/j.heliyon.2022.e11280
Received 17 April 2022; Received in revised form 11 July 2022; Accepted 21 October 2022

corrugated structure, optimizes the design of the middle interlayer, and improves its buffer energy absorption characteristics.

At present, there are many productive sandwich structures improved from corrugated sandwich panels [17, 18]. Li et al. [19] proposed a novel Kirigami modified corrugated core, which reduced the rear plate deformation of the corrugated sandwich laminate by 48% [19]. Cao et al. [20] has proposed a graded multilayer sandwich panel with corrugated cores and explored the influence of the property gradient. Yang et al. [21] proposed a modified truncated square pyramid (TSP) folded structure. And the TSP unit cells had better performance in energy absorption. The deformation was more stable. Meng et al. [22] designed a new bio-inspired corrugated core structure based on the microstructure of cybister elytra and proposed an analytical formulation with a much higher accuracy. A novel sandwich structure with bi-directional corrugated core was proposed in the work of Ge et al. [23], which owned better compression properties than the single-corrugated core. However, most of these sandwich structures focus on the higher strength and less weight. And less researches pay attention to the buffering property of the laminate in the early stage.

The methods of experiment and finite element analysis are frequently used in optimizing composite sandwich plate. He et al. [24] researched on low-speed impact behavior of trapezoidal corrugated sandwich structure with aluminum alloy cores and CFRP faces sheet by the method of finite element analysis and drop hammer impact test. The effective mechanical properties of an orthogonal corrugated core sandwich structure have been investigated numerically and analytically on the work of Zhu et al. [25], Cheng et al. [26] found that the transverse impact resistance behavior of the U-type corrugated core sandwich panel was better than the longitudinal behavior by numerical simulation and drop hammer impact test. However, there is little difference between the drop weight area and the unit area in the study. When the impact area is larger than the area of the sandwich unit, the flat pressure test will be a better choice. Yang et al. [21] used the way of theory analysis and the flat pressure test to explored the best geometrical configuration of modified TSP folded structure. Ge et al. [23] used the flat pressure test and finite element method to investigate the compression performance of the new bidirectional corrugated core sandwich structure. In this study, the lightweight design of auto body structure is developed to use in auto hood, auto side doors and trunk and other auto body panels. And it is locally equivalent to applying a flat compression load on the unit, because the impact area is often much larger than the unit area of the body panel. The flat pressure test is a simple and feasible way that make it an effective method to investigate the cushioning property and energy absorption effect of FMLs. Therefore, this study used the flat pressure test as one of the research tools. At the same time, finite element simulation was also used to further investigate the deformation process. And the influence of the cell geometry on the laminate was also explored.

To improve the plank of lightweight car body and buffer energy absorption capacity further, this research set out from the traditional trapezoidal corrugated-core FMLs, which was made of aluminum alloy and CFRP. Then, a M-shape corrugated laminated board structure was developed. In this shape, not only the plastic deformation is offered by aluminum alloy but also the car body will not be easily destroyed because of the high strength of CFRP. In addition, different from traditional troughs corrugated board structure, the M-shape corrugated structure has better cushioning properties.

2. Method

2.1. Materials

In the production process of composite samples, 5052 aluminum alloy sheets with a thickness of 0.5 mm were used, and carbon fiber composites with a thickness of 1.5 mm (CFRP component: T300-3K/epoxy resin) were used. The material properties are shown in Table 1, Table 2 and Table 3, where Liu [27] gave the stress-strain relationship of the plastic segment of 5052 aluminum alloy in his study.

Table 1. Symbol and contrast relation table of material properties (Coordinates are shown in Figure 1).

Material property symbols	Explanatory notes
E_1	Modulus of elasticity of CFRP in x-axis direction
E_2	Modulus of elasticity of CFRP in z-axis direction
E3	Modulus of elasticity of CFRP in the y-axis direction
S_1	Tensile strength of CFRP in x-axis direction
S_2	Tensile strength of CFRP in z-axis direction
S_3	Tensile strength of CFRP in the y-axis direction
G_{23}	Shear modulus of CFRP in the YOZ plane
G_{13}	Shear modulus of CFRP in the XOY plane
G_{12}	Shear modulus of CFRP in the XOZ plane
E	Modulus of elasticity of aluminum alloy
Et	Aluminum cutting line modulus
σ_y	Yield strength of aluminum alloy

2.2. Test samples and simulation models

The test sample and simulation model are sandwich structure, as shown in Figure 1(a) and (c). The upper and lower floors of the sandwich structure are made of 1.5 mm CFRP, and the dimensions of the upper and lower floors are 30 mm × 100 mm. The material of the middle interlayer is 5052 aluminum alloy, and the specific unit size is shown in Figure 1(b) and (d). The sandwich structure is made of three-layer plates. Considering that the adhesive is a secondary influence for the optimization of the structure, the three plates was lapping in the study with no adhesive. Then, the finite element simulation result would more easily to fit the experiment result well.

2.3. Flatwise compression test

When a large object impacts the plate surface, the contact area can be regarded as the plate is subjected to a certain speed of flat pressure, so this study explores the mechanical response of the laminated plate through the flat pressure test. The flat compression test is mainly applicable to the sandwich plate structure with thin skin. The sample used in the test is 30 mm × 100 mm, as shown in Figure 1(a) and (c). Four groups of samples were tested for each model. According to the ' GB/T1453-2005 sandwich structure or core flat compression performance test method ' criterion, the WDW-200D microcomputer-controlled electronic universal material testing machine was used to perform quasi-static flat compression tests on different sandwich plates [28], and the loading speed was 1.75 m/s. The experimental instrument is shown in Figure 2(a) and (b).

2.4. Finite element simulation

Using the finite element software to simulate the flat compression test, it is more convenient to simulate multiple models, and observe the deformation process of the model during the test, but also to explore the cause of a peak in the result curve, so the finite element simulation has a great effect on the deformation of the laminated plate. In this study, ABAQUS software was used for finite element simulation, and two models were established and used to simulate sandwich plate under flat compression loading. The specific model size and parameters are shown in Figure 1.

Table 2. 5052 aluminum alloy mechanical properties.

	E	v	E_t	σ_y	ρ
AL-O	70 GPa	0.33	2.5 GPa	80 MPa	2682 kg/m^3

Table 3. Mechanical properties of CFRP (CFRP component: T300-3K/epoxy resin).

	$E_1 = E_2$	E_3	$G_{12} = G_{13}$	G_{23}	v_{23}	$v_{12} = v_{13}$	S_1	S_2	S_{12}	ρ
CFRP	50.5 GPa	8.82 GPa	4.4 GPa	3.2 GPa	0.43	0.336	1975 MPa	74 MPa	45 MPa	1500 kg/m^3

In the finite element model, aluminum alloy plate was characterized by elastic-plastic constitutive model. And CFRP was characterized by elasticity and brittleness. The specific material parameters are shown in Table 1, Table 2 and Table 3. The CFRP roof, CFRP floor and intermediate layer of sandwich structure are modelled using S4R element. In terms of boundary conditions, the CFRP bottom plate was fully constrained. And the roof was fixed with all degrees of freedom except the degrees of freedom perpendicular to the panel. The roof moved downward at a speed of 1.75 m/s in the direction of perpendicular to the panel surface by dynamic analysis step. Contact property adopts normally 'hard' contact and penalty function method is used tangentially to describe friction. The friction coefficient is 0.4.

In the dynamic low-speed impact simulation, a 500 kg mass block was attached to the upper plate. And a velocity field was predefined. The response of the laminate plate under low-speed impact is explored at the initial velocity of 10 m/s. The material parameters, model geometry parameters, contact parameters, mesh parameters, analysis step parameters and constraint mode are consistent with the above quasi-static simulation.

3. Result and discussion

3.1. The proposal of laminated plate structures with excellent buffering properties

This study adopted the method of finite element analysis for trough corrugated structures in different inclination under flat pressure, in which aluminum alloy is in same area. The model with an inclination Angle of 60° and its size is shown in Figure 1(a). And the shape of a trough element is shown in Figure 1(b). The simulation results are shown in Figure 3(a) and (b). Then, by analyzing the force and displacement curve, it is found that there was a shock in the curve of different Angle of trough corrugated broad which suffered by pressing load, with the increase of load displacement (Figure 3(a)). What's more, in the energy dissipation curve (Figure 3(b)), the energy absorption effect of trough corrugated plate was ideal when the inclination Angle was 60°. Therefore, this paper set out from the Angle of 60° trough corrugated board to design a new body panel structure with better energy absorption performance.

The force and displacement of the trough corrugated sandwich board with an inclination Angle of 60° in different load stages are shown in Figure 3(i)–(ix). When the trough structure was subjected to load, the deformation process was the buckling of the roof firstly, which presents a parabolic shape. Then, the side plates began to bend. And the aluminum alloy sandwich element took on the shape of M. This can also be clearly seen in the test deformation diagram (Figure 4(a)–(d)). And due to the slip of the side plate, the side plate of the trough element cannot undergo sufficient plastic deformation to absorb energy. What's more, the peak value of the force and displacement curves was exactly the time when the roof was loaded to the beginning of buckling. Besides, the lowest load state was the process before the roof touched the bottom plate. In addition, after the peak value of the force and displacement curves, where after the trough roof hits the bottom to form two small corrugations, the

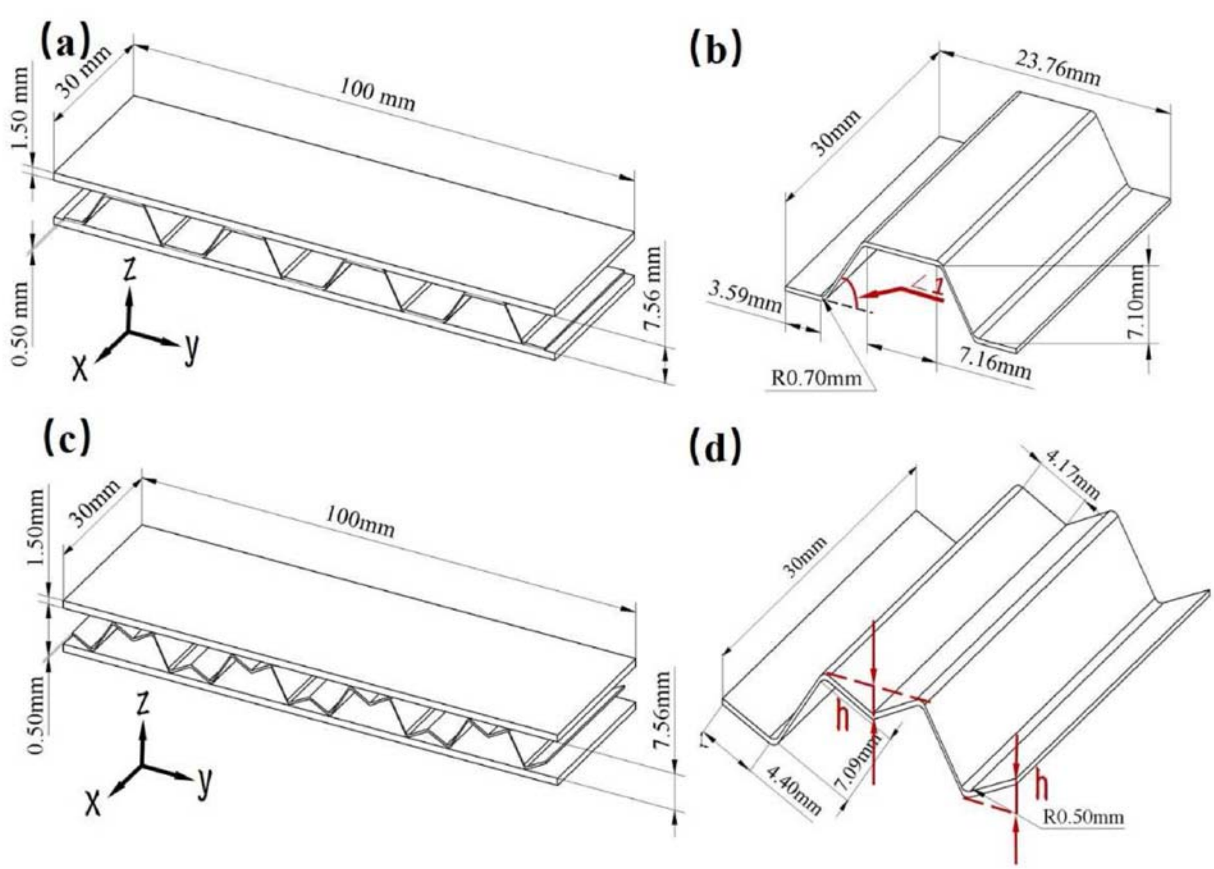

Figure 1. Schematic diagram of ordinary trough sandwich structure (a), schematic diagram of grooved sandwich element (b), ∠1 is the Angle of change, M-shape corrugated sandwich structure diagram (c), the M-shaped element diagram (d), the element is axisymmetric and h is the depth of groove variation.

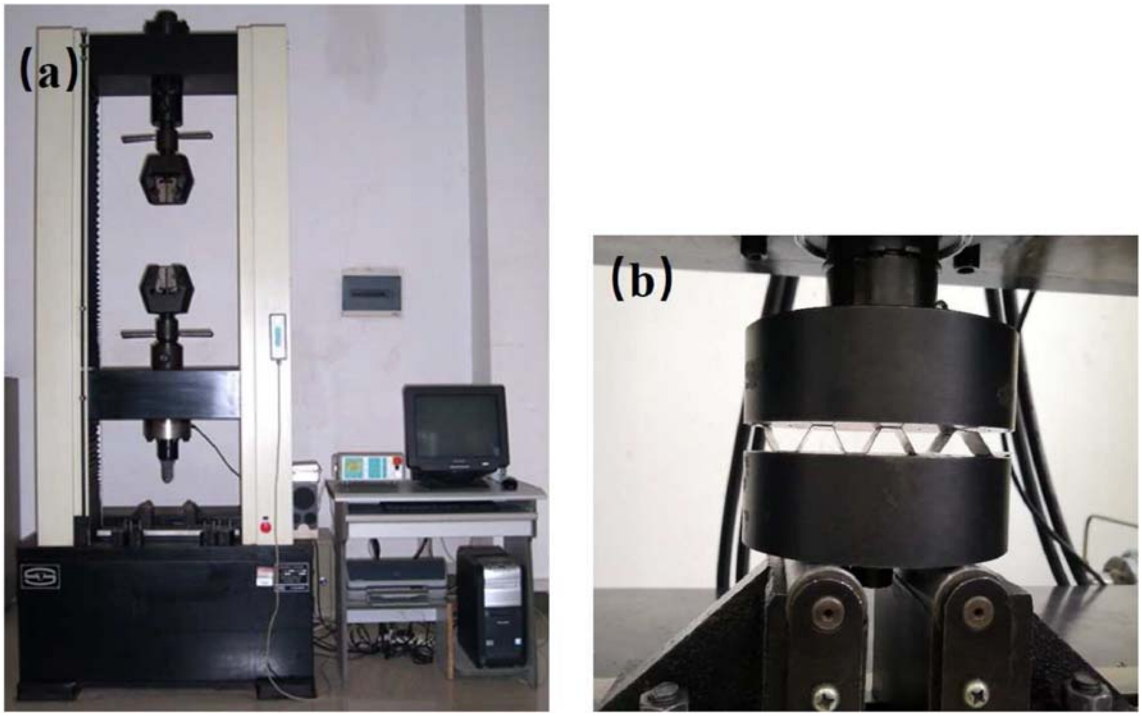

Figure 2. The WDW-200D microcomputer-controlled electronic universal material testing machine [29] (a) and squeeze head device (b).

load was more stable, and the energy dissipation was higher. However, the study found that not every trough could be smoothly into two small corrugated. Thus, there is improved space in buffer and energy absorption capacity of the plate. This study attempts to change the mechanical properties of laminates by changing the structure shape, so that the force is more stable. Therefore, it was believed that the shape of corrugated plate after the peak value could be directly made into laminates to achieve better buffer energy absorption effect.

3.2. Energy dissipation analysis of M - shaped sandwich structure

It was found that when the M-shaped corrugated structure (Figure 1(c)) which like the aluminum alloy shape occurring after the peak value was used as the sandwich plate, the peak value of force and displacement curves could be well avoided, and the sandwich plate entered the latter stage smoothly (Figure 5(a)). To verify the effectiveness of the simulation, the flat pressure test was also used for verification (Figure 5(b)).

Through the simulation results, it is found that the M-shaped structure can effectively reduce the initial peak value and play a role of buffer in the initial stage. According to the flat pressure test results, the force and displacement curve of M-shaped structure was gentler than simulation results, indicating that the M-shaped corrugated plate can play a cushioning role in the initial stage. At the same time, M-shaped corrugated plate structures could enter the overall yield stage faster than ordinary trough structure (Figure 5(a)), and M-shaped corrugated plate can significantly reduce the initial peak value. Comparing the experimental results with the simulation results, the trend and value of the two are roughly the same. Therefore, the above inference is reliable. Then when using M-shape corrugated sandwich laminated plates as the body plate, for the lower peak, the force on the plate was less in the initial stage. Besides, on account of the force transfer, the force located in the plank of vehicle parts and vehicle crew will be reduced accordingly. At the same time, the decrease of the value will reduce the vibration feeling, to achieve the purpose of buffering and improve the comfort. M-shaped plate had certain advantages in energy absorption compared with ordinary groove plate (Figure 5(b)). Before the top plate of the sandwich unit touches the bottom plate, the plastic deformation energy of the trough corrugated core was 2.9 J. The plastic deformation energy of the M-shaped corrugated core with the groove depth of 2.0 mm was 4.7 J. The plastic deformation energy of the M-shaped corrugated core with the groove depth of 2.5 mm was 3.8 J. The plastic deformation energy of the M-shaped corrugated core with the groove depth of 3.0 mm was 3.4 J. The plastic deformation energy of the M-shaped corrugated core with groove depth of 3.5 mm was 2.6 J. Moreover, in the case of low-speed impact, until the middle sandwich was squashed, the plastic deformation energy absorption of M-shaped plate was 2–3 times that of ordinary trough corrugated plate (Table 4). And the proper reasons are as follows. Comparing the deformation process of the two structures (Figure 5(i)–(vi)), it is found that due to the uneven force of ordinary trough corrugated structure, only a few troughs could change into small corrugated shape. Besides, due to the particularity of the M-shaped structure, the grooves of each corrugated plate could become small corrugations under pressure, so that smaller corrugations were formed than ordinary groove corrugations under pressure. In addition, the energy absorption of metal sandwich structure mainly through plastic deformation. The formation of smaller grooves means that more thin-walled pressure bars could enter the stage of plastic deformation to absorb energy after instability and absorb more energy. The side plate of the ordinary trough corrugated element was usually slip. And the deformation was not stable. And the upper plate cannot contribute much. The trough corrugated plate was unable to undergo sufficient plastic deformation.

In summary, most of the current research focuses on improving the compressive strength of laminates, while this study focuses on improving the cushioning capacity of laminates. Under the same conditions, the peak value of the force for M-shaped corrugated sandwich laminate with 2.5 mm groove depth is 46.3 % of that of the traditional corrugated sandwich structure. Although this reduces the bearing capacity of the laminate to a certain extent, it also reduces the force transmitted to the car occupant and improves the comfort to a certain extent. Moreover, this study is also committed to improving the energy absorption capacity of laminates. Before the top plate of the sandwich unit touches the bottom

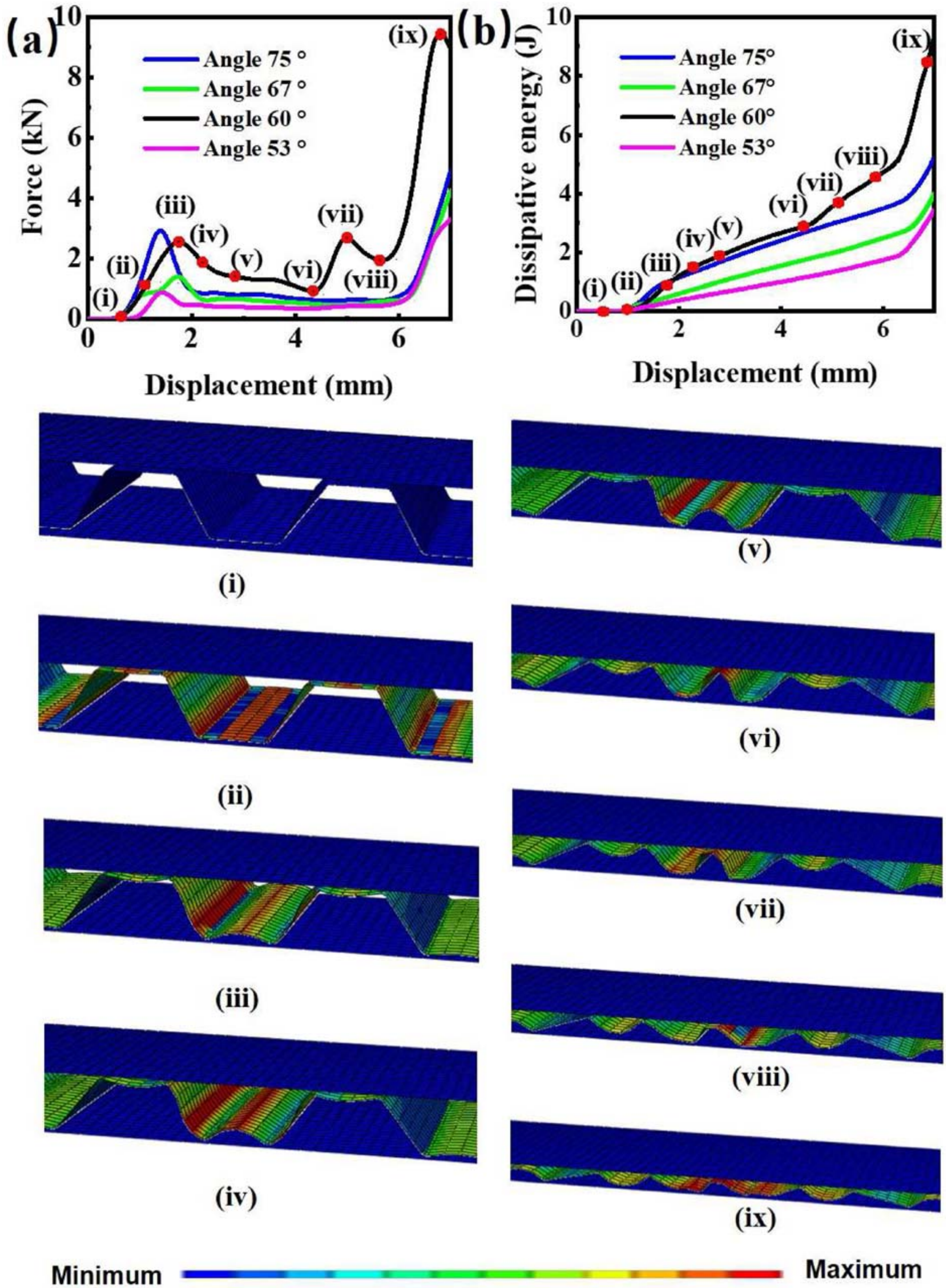

Figure 3. Force and displacement curves (a) and plastic deformation energy and displacement curves (b) of ordinary trough structure with different angles under flat compression, its element deformation shape cloud diagram (i)~(ix) of corresponding stages in the curve (a) and (b).

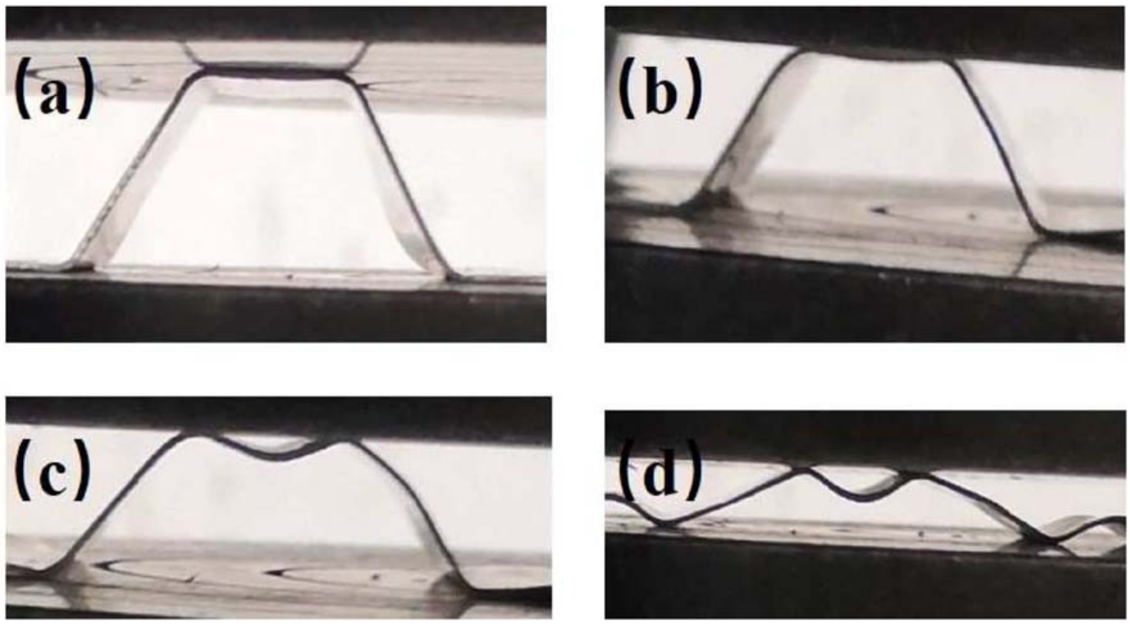

Figure 4. The original trough element (a), the element top plate bending in pressure (b), the element side plate bending in pressure (c) and the element side plate slippage (d).

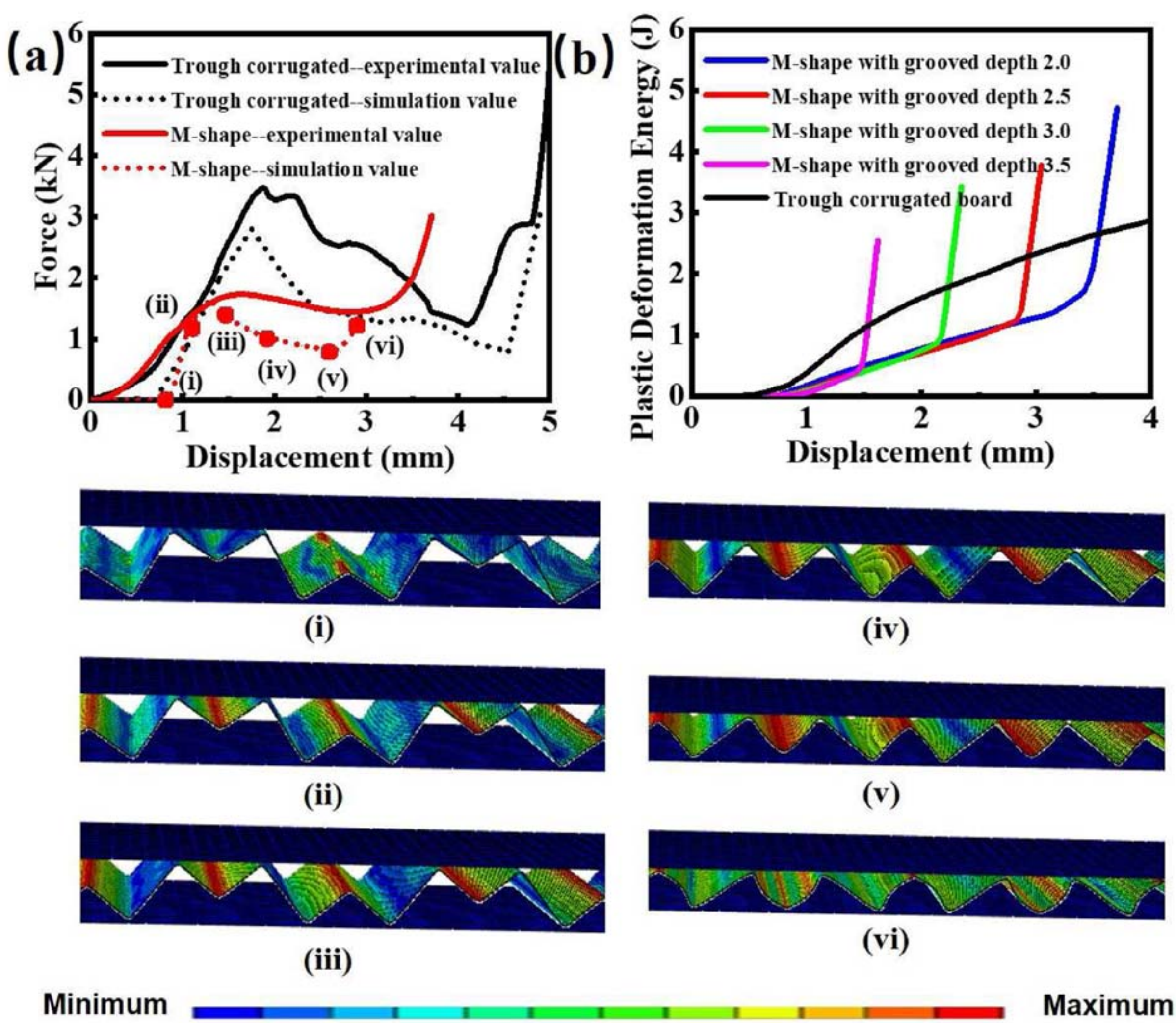

Figure 5. The experimental and numerical force and displacement curve of M-shape structure and common trough structure under pressing (a), the plastic deformation energy curve of the different M-shape structure and common trough structure under pressing until the unit top plate hits the bottom (b), element deformation shape cloud map of corresponding phase in curve (i)~(vi).

Table 4. The plastic deformation energy until the core squashed under low-speed impact.

Corrugated unit type	trough corrugated	M-shape 2.0 mm	M-shape 2.5 mm	M-shape 3.0 mm	M-shape 3.5 mm
ALLPD (J)	27.37	62.67	76.67	86.94	90.73

plate, the energy absorption capacity of the M-shaped sandwich plate with 2 mm groove depth is 1.62 times of that of the traditional corrugated plate, which improves the safety of the car to a certain extent. And in the case of low-speed impact, the energy absorption of the M-shape corrugated core was 2.29–3.31 times of the energy absorption of the trough corrugated core. And under the same area, the same height and the same width, the length of M-shaped corrugated plate is reduced, compering to the length of trough corrugated.

4. Conclusions

A kind of lightweight M-shaped corrugated laminate with excellent buffering and energy absorption characteristics was put forward through flat pressure finite element simulation and experimental analysis against that of ordinary trough corrugated laminate structure. Besides, the application advantages of M-shaped corrugated laminate structure were proved by experiment and finite element simulation. The M-shaped corrugated laminate combines the high strength of CFRP and the advantages of aluminum alloy plastic energy absorption, which not only achieves the purpose of lightweight, but also overcomes the shortcoming of brittle fracture of CFRP body disintegration. At the same time, the M-shaped corrugated laminate structure can reduce the initial peak value of the force compared to that of the ordinary trough corrugated laminate structure under pressure and achieve the purpose of further buffering. The maximum force of M-shaped corrugated laminate with 2.5 mm groove depth was 46.3% of that of the traditional corrugated board sandwich structure under the same conditions. Moreover, compared with the ordinary trough plate, the M-shaped plate can make each unit of the corrugated plate become two small troughs under pressure, so that made the plate into the structure yield as many as possible and increased the energy absorption capacity. The energy absorption capacity of M-shaped sandwich plate with 2 mm groove depth was 1.62 times of that of the traditional trough board until the sandwich unit roof touched the bottom plate. And under the low-speed impact, the energy absorption capacity of M-shaped sandwich plate was 2.29–3.31 times of that of the traditional trough board until the sandwich squashed. There are also limitations in this study that the effect of adhesive in the laminate is not considered. And the effect of adhesive with different mechanical properties and different bonding methods will be investigated in the subsequent study. As a new type of lightweight panel, M-shaped corrugated laminate provides a new idea and design for cushioning and energy absorption, which improve the comfort and safety. And it exhibits a great application potential in the car body like auto hood, auto side doors and trunk and other auto body panels.

Declarations

Author contribution statement

Mengyu Jiang: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Shijie-Liu: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Jiu-mei Xiao: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interest's statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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