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Design and strength analysis of glass fiber-reinforced epoxy composite shelter

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1. Introduction

In today's world, automobile lightweight has been the best effective way to solve energy saving and emission reduction problems. Recently, an extensive interest within vehicles industries to develop and make use of lightweight composite materials and structures has been generated by the need of reducing energy consumption. Clear benefits of using fiber reinforced plastic (FRP) composites have been reported within aeronautical, rail, naval and automotive industries [1]. Besides, glass fiber-reinforced epoxy composite (GFRP) application on the shelter can reduce the quality and enhance the strength. The lighter vehicle body means less fuel consumption, more power and higher transport efficiency. The higher shelter strength means more different battle environments and stronger operational ability. Therefore, it is especially important to study GFRP shelter currently.

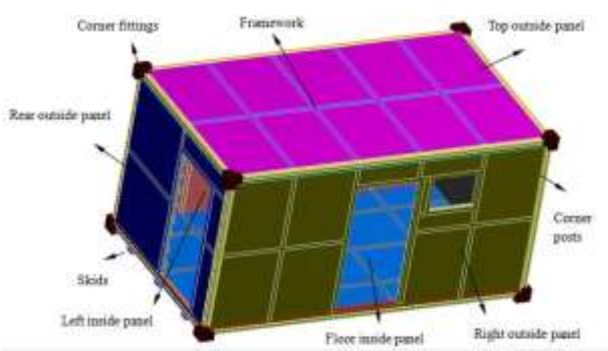
The study object in this paper is the shelter of a special vehicle, whose carriage panel skins were replaced by GFRP laminates incorporating E-glass fibers within an epoxy matrix. But many of the available publications are the study of containers and the application of glass fiber-reinforced epoxy composites. Kevin Giriunas et al. [2] investigated the ISO shipping container's structural strength using finite element computer modeling and the computer simulations demonstrated the effectiveness of the container walls and roof to resist the loads, which were beneficial for the shelter modelling and analysis. Genelin and Salim [3], Borvik et al. [4], and Borvik et al. [5] performed blast load structural tests on actual ISO containers. The available information is relevant and important to structurally define and evaluate performance for the shelter. M.A. Badie et al. [6] examined the effect of fiber orientation angles and stacking sequence on the torsional stiffness, natural frequency, buckling strength, fatigue life and failure modes of composite tubes, which incorporates hybrid carbon/glass fiber with an epoxy matrix, and the results obtained in this article could provide the reference for GFRP shelter study. Craig W. Hudson et al. [7] made use of carbon fiber-reinforced composite for rail vehicle floor panels, it was concluded that the use of lightweight material could indeed get a lot of weight loss.

Table 1 shows the overall dimension of the shelter studied in this paper, which conforms to ISO [8] and national standards [9]. Structural components and framework (details are shown in Table 2) of the shelter are seen from Fig. 1. In the article, the structural strength analysis of various aluminium shelters using FEM was performed firstly to select the optimal structure model for GFRP shelter design. Then, the impacts of different lay-up design and different fiber thickness of GFRP laminate to the strength and stiffness of the shelter were carried out to find the better lay-up design method based on the shelter lightweight. The loading scenario was choose as the helicopter lifting condition according to ISO [8] and national shelter standards [9], which could determine the ability to withstand over loading ability of the shelter.

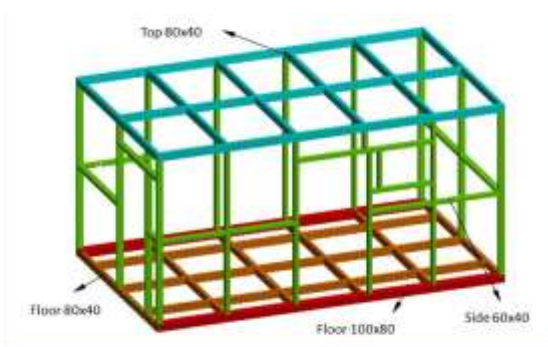
Table 1

Typical specification for a standard CAF35 shelter

ID codes	Length *L*, mm	Width *W*, mm	Height *H*, mm
CAF35	350	2100	1900



a



b

Fig. 1 CAF35 shelter model: a - structural components, b - structural framework

2. The shelter computer model information

The material properties of the plates of the shelter were analyzed with classical lamination theory [10] and designed by laminate lay-up design points [11]. Sandwich panels utilize flexural strength of a system composed of outer stiff skins spaced by a softer core of low density. Spacing between skins is increased to improve flexural resistance, thermal insulation, and minimize relative slip from shear transfer. Softer foams can be better insulators and will generally result in better continuous strain transfer, minimizing de-bonding failure [12].

The shelters were modelled and analyzed using the programs CATIA [13] and ANSYS Workbench [14]. CATIA [13] is a three-dimensional (3D) Computer Aided Design (CAD) program used to model 3D objects. ANSYS Workbench [14] is the finite element analysis (FEA) program used to apply a finite element meshing and analyze the meshed shelter models imported from CATIA [13]. Because of the integral bearing characteristic of the stiffener plate, the skeleton and the polyurethane foams were divided by hexahedral elements, and the inner and outer skins of the carriage panels were meshed with quadrilateral elements. Q235 is used for the skeleton, corner fittings and skids, and its main properties are as follow: density is 7850 kg/m^3, elastic modulus is 2100 MPa, poisson's ratio is 0.3 and the yield stress is 235 MPa. However, the skeleton is divided into three kinds of square tubes and the concrete parameters are shown in Table 2. As to the rigid polyurethane foams, its density is 60 kg/m^3, elastic modulus is 10 MPa, and poisson's ratio is 0.3. 2A12 is selected for the aluminum plate, and its properties are as follow: density is 2700 kg/m^3, elastic modulus is 70000 MPa, Poisson's ratio is 0.3. The material properties of selected E-glass/ epoxy composite used in GFRP shelter carriage panel are displayed in Table 3, which are provided by Shenyang Tongchuang FRP company.

Table 2

The material properties of square tube

Material type	Specification, mm			Elastic modulus, MPa	Density, kg/m^3	Location
	H	B	t			
Q235	100	80	4	70000	1204	Longitudinal beams of the floor plate
	80	40	2	65100	1020	Other beams of the floor plate and inner beams of the top plate
	60	40	2	67400	1120	Inner beams of the side plates

Table 3

The material properties of E-glass/epoxy composite used in the laminates of GFRP shelter carriage panels

Parameters	ρ, kg/m^3	E_X, MPa	E_Y, MPa	γ_{YZ}	γ_{XY}	G_{YZ}, MPa	G_{XY}, MPa
Value	1800	34000	6530	0.366	0.217	1698	2433

3. The shelter carriage panel material simulation

In this part, four simplified shelter models were established, which were named M1, M2, M3 and M4. Similar assumptions were made. The rear and right side of the shelter containing the doors, locking assembly, and hinges were replaced by an identical wall used for the other side wall section with similar properties. It was assumed that the rear door and the right door and window assembly could withstand the same loads as the other walls. All of the connections were modelled to represent fully welded connections which could not fail. Therefore, the sandwich panels of M2 include the rigid polyurethane foams compared with M1. The corner posts were added on M3 based on M2. And then the corner fittings were set upon M4 based on M3. Simplified models of the shelter were used to verify model assumptions, and show which components of the shelter could be simplified without sacrificing accuracy. The optimal structure model would be for GFRP shelter design. The GFRP shelter with the initial design [45°, 90°, 0°, 45°, -45°] was named as M5(5). Number 5 in the bracket presented that the laminate of GFRP shelter was designed for five-layers.

Through the linear analysis in ANSYS [14], M4 was the most strength and stiffness, which would be used for the composite simulations. Based on M4, the material of the carriage panel skin was replaced by E-glass fiber epoxy laminate. [45°, 90°, 0°, 45°, -45°] for the laminate was finished by the ACP module in ANSYS. From Fig. 2 and Fig. 3, the maximum deformation of M5(5) was smaller compared with M1, M2 and M3, 0.6 mm larger than M4. Meanwhile, the maximum equivalent stress of M5(5) was the smallest and reduced about 40% than the maximum value. Fig. 4 was the deformation cloud pictures of four simplified shelter models. Therefore, GFRP can be applied on the shelter carriage panel skin to get the lightweight purpose, increase the shelter structural strength and have better carrying capacity.

4. GFRP shelter lay-up design and simulation

The GFRP shelter analysis includes mainly two parts. One is the effects of different lay-up schemes on GFRP shelter strength and stiffness. Giving twelve kinds of lay-up schemes, the laminates were designed with 5-layers in order to find five better lay-up schemes. Another is the impacts of fiber thickness on GFRP shelter strength and stiffness. It can be realized by controlling lay-up scheme the same and changing fiber thickness. Based on five better lay-up schemes, the laminate was designed with ten-layer and twenty-layer.

4.1. The effects of different lay-up schemes

Figs. 5 and 6 correspond to the maximum deformation and equivalent stress of twelve shelter models with different lay-up schemes. The model designed with the lay-up scheme of [-45°, 45°, -45°, 45°, -45°] had the best deformation 1.9697 mm. [90°, 45°, 90°, -45°, 90°] had the worst deformation 2.1791 mm. Maximum stress was between 148 to 173 MPa. According the comparison , we can conclude that [45°, 90°, 0°, 45°, -45°], [45°, 90°, 0°, 90°, -45°], [-45°, 45°, 0°, 45°, -45°], [-45°, 45°, -45°, 45°, -45°] and [0°, 45°, 90°, -45°, 0°] are five better lay-up schemes.

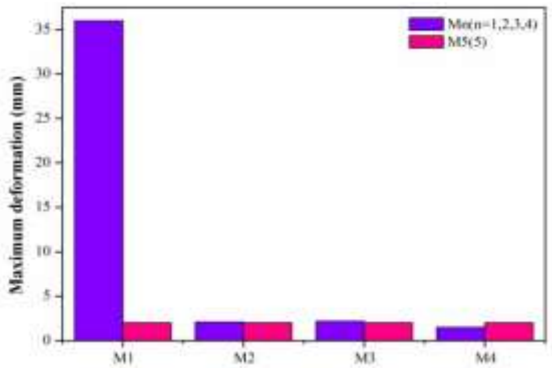


Fig. 2 The deformation of M1, M2, M3, M4 and M5(5)

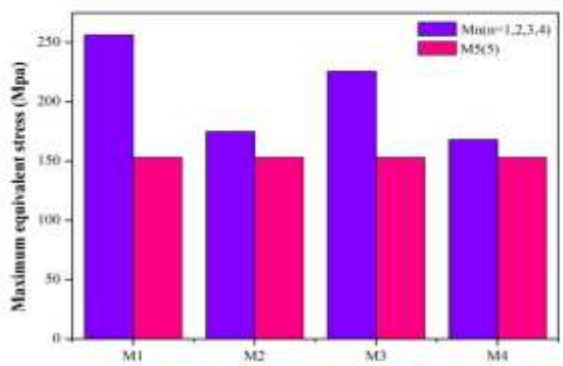
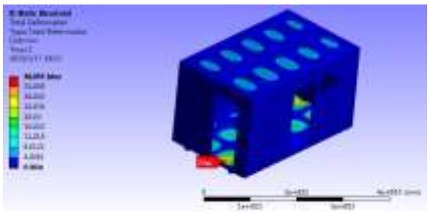
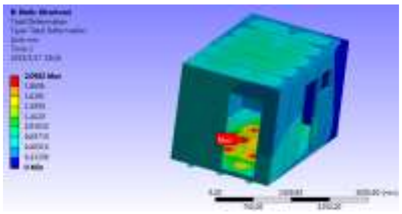


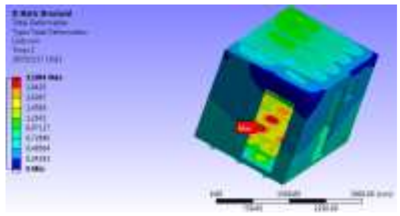
Fig. 3 The equivalent stress of M1, M2, M3, M4 and M5(5)



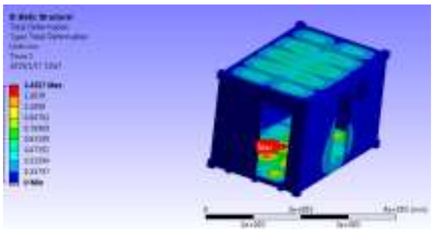
(a) M1



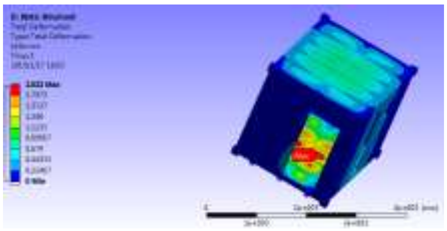
(b) M2



(c) M3



(d) M4



(e) M5(5)

Fig. 4 The deformation cloud pictures of four simplified shelter models

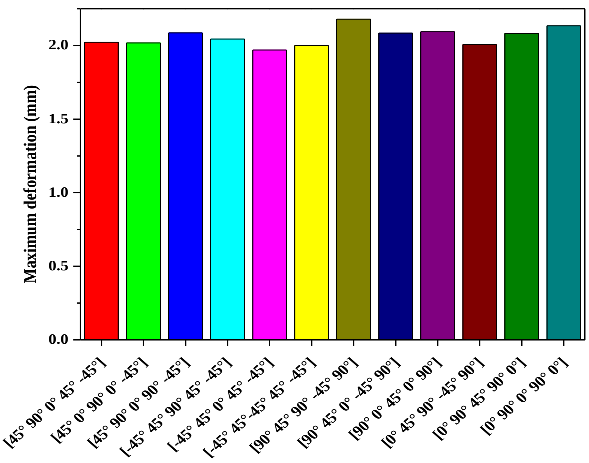


Fig. 5 The deformation of twelve lay-up models

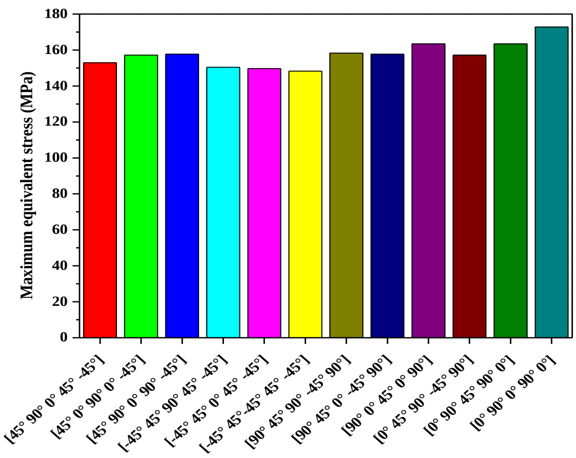


Fig. 6 The equivalent stress of twelve lay-up models

4.2. The impacts of different fiber thickness

Based on [45°, 90°, 0°, 45°, -45°], [45°, 90°, 0°, 90°, -45°], [-45°, 45°, 0°, 45°, -45°], [-45°, 45°, -45°, 45°, -45°] and [0°, 45°, 90°, -45°, 0°], M5(5), M6(5), M7(5), M8(5) and M9(5) were established respectively. Then, ten-layer and twenty-layer design for the laminate were completed and the established models were M5(10), M6(10), M7(10), M8(10), M9(10) and M5(20), M6(20), M7(20), M8(20), M9(20). Just take M5(10) and M5(20) as examples, M5 represents the model with the lay-up scheme of [45°, 90°, 0°, 45°, -45°]. Besides, number 10 in the bracket presents ten-layers design, that is $[45°, 90°, 0°, 45°, -45°]_2$. 20 indicates $[45°, 90°, 0°, 45°, -45°]_4$.

Through the simulation, ten-layer design can improve the GFRP shelter strength and stiffness partly. The equivalent stress of M5(10), M7(10) and M9(10) declined slightly compared with M5(5), M7(5) and M9(5). M6(10)'s and M8(10)'s unchanged. Moreover, the deformation of M5(10), M7(10) and M8(10) decreased a little than M5(5), M7(5) and M8(5). But the deformation of M6(10) and M9(10) increased some than M6(5) and M9(5).

In addition, twenty-layer design can preferably improve the mechanical properties of GFRP shelter. As compared to five-layers design models, the reduced maximum deformation of M8(20) was the least and M9(20) decreased the most. The reduced deformation of $M5_{(20)}$ and M7(20) were respectively 0.0027 and 0.0047 mm. But M6(20)'s deformation increased 0.0012mm. And the reduced range of the maximum equivalent stress is between 0.01 to 0.03 MPa. M6(20) had no changes, M7(20) and M8(20) both fell 0.01 MPa, M5(20) fell 0.02 MPa and M9(20) decreased up to 0.03 MPa. While compared with ten-layers design models, the maximum equivalent stress of M8(20) decreased 0.01 MPa and the other twenty-layer models had no changes. The deformation of M5(20) and M8(20) reduced and the others had some increase instead. Figs. 7 and 8 were the maximum deformation and equivalent stress of different fiber thickness shelter models with five better lay-up schemes.

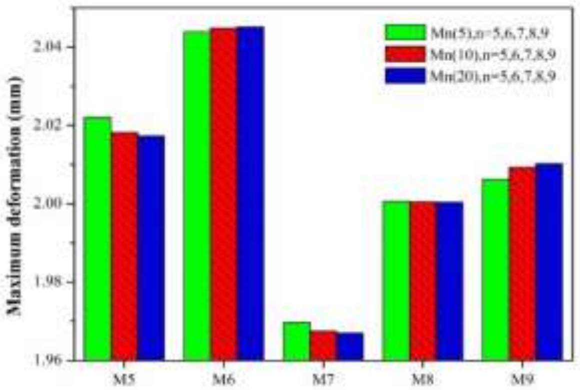


Fig. 7 Deformation of *Mn*(*m*) (*n* = 5, 6, 7, 8, 9; *m* = 5, 10, 20)

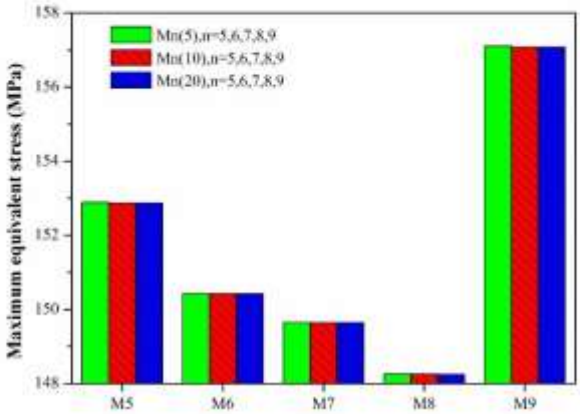


Fig. 8 Equivalent stress of *Mn*(*m*) (*n* = 5, 6, 7, 8, 9; *m* = 5, 10, 20)

5. Conclusions

Following the trend of composite application in the automotive industry, this paper has made use of E-glass fiber epoxy composite in the shelter. Under the helicopter lifting condition, the simulation and comparisons were performed according ISO and industry standards, and the following conclusions have been drawn.

1. Through the analysis of lightweight materials, E-glass fiber composite can be used as the shelter carriage panel skin instead of aluminum in order to achieve the lightweight design. Comparing with the aluminum shelter, GFRP shelter has higher strength and wider carrying capacity.

2. By analyzing the effects of different lay-up schemes on the shelter strength and stiffness, we see that ±45° and 0° are more suitable for the laminate design, and ±45° make the best mechanical performance. ±45° should be put outside of the laminate, and then 0° and 90° could be put inside. With the thickness of glass fiber decrease, more ±45° mean higher strength of the laminate. ±45° and 0° can effectively improve the shelter structural strength.

3. According to the research of the impacts about different fiber thickness on the shelter strength and stiffness, [45°,90°, 0°, 45°, -45°] and [-45°, 45°, -45°, 45°, -45°] are more appropriate for twenty-layer design. [-45°, 45°, 0°, 45°, -45°] and [0°, 45°, 90°, -45°, 0°] are fit for ten-layer design. [45°, 90°, 0°, 90°, -45°] should be designed with five-layer.

4. After using lightweight materials, the quality of the shelter has decreased from 1119.9 kg to 956.5 kg, which has reduced about 14.59%.

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DESIGN AND STRENGTH ANALYSIS OF GLASS FIBER-REINFORCED EPOXY COMPOSITE SHELTER

S u m m a r y

In this study, glass fiber-reinforced epoxy composite (GFRP) plates were applied on the carriage panel skins of the shelter, which substituted the original aluminum plates. The main research objective is to prove that the application of GFRP plate on the shelter can effectively reduce the vehicle equipment quality and enhance the shelter structural strength on one hand, on the other hand is to find the impacts of fiber orientation sequence and fiber thickness to the GFRP shelter strength and stiffness. During the research, the structural strength of four kinds of aluminum shelters was studied in order to choose the optimal geometric model for lateral GFRP shelter design and analysis, which was further investigated using finite element method under the given loading scenario. Finally, the computer simulations demonstrated that ±45° and 0° are more suitable for the laminate design, and ±45° should be put outside of the laminate. With the thickness of glass fiber decrease, more ±45° means higher strength of the laminate. To a certain degree, more 0°, 90° and ±45°can make better stiffness. Besides, the quality of GFRP shelter has reduced 14.59% with using the lightweight material. Therefore, this research provides a reliable guidance for the production and design of GFRP shelter.

Keywords: Glass fiber-reinforced composite; shelter; strength analysis; finite element method; lay-up design; lightweight.

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