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Fabrication, Testing and Analysis of Composite Lattice Panels Under Three-Point Bending Load

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Abstract: Thanks to their high strength-to-weight ratio, lightweightness, and excellent energy absorption, composite lattice panels can be used in the aerospace, marine, automotive, and other industries. These structures can be used as an alternative to string-reinforced structures, honeycomb (core) sandwich panels, and aluminum grid structures. In this paper, a composite lattice panel is first fabricated from glass/epoxy by hand lay-up method using a silicon rubber mold. In this method, a Kagome composite lattice panel with twelve layers of resin-impregnated fibers was fabricated during a continuous process. After fabrication, the test panel was shown under three-point bending and failure modes. Also, a numerical simulation of three-point bending was performed in ABAQUS software. Then, the simulation results were compared with those of the experimental test, indicating a good convergence between the experimental test results and the finite element ones up to the point of failure. Due to changes in directions of force, these structures have a high ability to withstand damage, and therefore, continue to withstand the load after the failure of one or more ribs. Also, there is no sudden and sharp drop in the load-bearing capacity of the structure despite the force being maximized, which can be attributed to the high energy absorption of such structures. Instead, the force decreases slowly with fluctuations, and the structure continues to absorb energy until final failure. Therefore, such lightweight structures can be used in applications where energy absorption is of great importance.

Keywords: Composite Lattice Panel, Glass/Epoxy, Numerical Analysis, Three-Point Bending Test

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Research paper

1 INTRODUCTION

The properties of composites depend on various factors, such as the type and percentage of ingredients, the shape and arrangement of the reinforcement, and the connection of the components to each other. Thanks to benefits such as high specific strength, lightness, and corrosion resistance, composite lattice structures are widely used today in the aerospace, missile, and marine industries. A lattice composite structure is created by connecting the composite ribs that form a continuous two-dimensional (or plate-like) or three-dimensional (or spatial) set. This set of ribbons (or ribbons) turns a structure into a lattice, consisting of continuous, tough, rigid, and strong fibers. Therefore, composite lattice structures have more applications than metal structures due to their high strength, lightweight ratio, and design flexibility. The main part of lattice structures is the lattice part, which is made of a series of very thin strips called ribs. The fibers in the ribs must maintain their strength and cohesion. Also, the layers in the ribs should not lose their alignment. Composite lattice panels can be used in structures where stiffness, strength, lightness, and energy absorption are important [1].

For example, composite lattice panels can be used in the bed of solar cells, most of which are now made of aluminum honeycomb with graphite/epoxy coating [2]. Solar cell panels must meet the minimum structural stiffness requirements. The natural frequency is usually considered to be greater than the given value to ensure that the panel vibrations do not lead to a resonance phenomenon on the satellite. Isogrid composite panels are predicted to be more rigid than honeycomb structures at a certain weight [2]. Unlike honeycomb structures, isogrid structures do not have an intermediate core that prevents heat from flowing along the depth of the panel; Therefore, the temperature difference along the depth of isogrid lattice panels is much smaller than honeycomb panels [2]. Composite lattice panels can be used in applications where energy absorption is considered as an important parameter, including car doors and roofs [1] and [3]. For example, it is used on the roof of a Ford Tire ("Fig. 1").

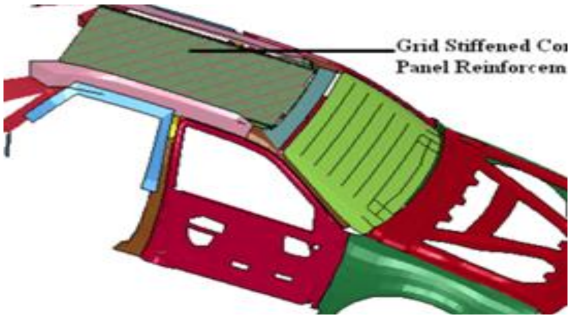

Fig. 1 Simulated car with composite lattice roof [3].

Thomas Kim (2000) [2], [4] investigated the method of construction and behavior of cylinders as well as composite lattice plates under compressive force. The results showed that ribs play a vital role in the buckling of these structures, which can withstand structural damage and also remain resistant to compressive forces following the failure of one or more ribs due to multiple load paths. Heibrich et al. [5] proposed two methods for constructing composite lattice structures using developed molds.

Gann and Gibson [6] analytically and experimentally investigated the energy absorption in a composite lattice structure under transverse loading. The results of tests and simulations showed the excellent impact resistance of the mentioned structures and the highest energy absorption after the initial failure. It has also been observed that the maximum amount of force on the shell face is greater. On the other hand, the absorption of specific energy and displacement range is considerably larger if force is applied to the shell-less face. Fan et al. (2007) investigated sandwich panels with a carbon fiber-reinforced hexagonal lattice core [7]. Experimental results showed that the carbon-fiber-reinforced lattice structure is stiffer and stronger than foam and honeycombs. Ribs are required in at least three different directions to achieve shear strength of the lattice structure; Therefore, a hexagonal lattice structure can be considered as an optimal choice. Matiala conducted a comprehensive study on fabrication, analysis, and testing of composite lattice panels [8]. In this study, eight groups of panels were made, including multilayer, three groups of lattice panels with a different number of fiber bundles, stranded dry and then vacuumed, group 5, the sandwich panel with lattice core, group 6, shell-less panel, group seventh, the sandwich panel with a foam core, and the eighth group, foam without a shell. The results showed a higher impact resistance and a much more focused impact area of the lattice panel compared to the other panels. Prakash Jadaw also conducted a series of studies on increasing the performance of composite lattice plates under transverse loads, the results of which were published in 2007 [1]. The main purpose of this study was to optimize the geometry of lattice structures to increase the absorption of specific energy under a quasi-static and dynamic transverse impact. Fan et al. (10) investigated and compared the bending performance of carbon fiber sandwich composites with lattice core [9]. Ahmadi and Khalili (9) also investigated sandwich panels with lattice core under tensile load [10]. Numerical and laboratory results are compared to obtain a more desirable structure in terms of structural strength against bending and tension. Mahmoudi et al. (11) designed, fabricated, and tested lattice sandwich panels [11]. They were subjected to a three-point bending test to investigate their behavior against transverse quasi-static loads. According to the results of the practical test, the lattice core continued to withstand the load even after the procedures were exhausted, and no cracks were observed between the layers and the core due to the adhesion and proper processing of the resin. Also, it was found that the parameter of increased strength is affected by weight, mostly by changing the fiber material of the surfaces from glass to carbon and not by increasing the thickness of the surfaces.

This study first briefly reviews the method of constructing a composite lattice panel with a hexagonal structure. It is followed by a three-point bending test to evaluate the strength of the panel as well as a comparison between the experimental test results and the finite element results.

2 HOW TO MAKE COMPOSITE LATTICE PANEL

Composite lattice structures can be fabricated using different methods, mainly on the type and material of the mold. Silicone molds are one of the best ways to make composite lattice panels because of the high thermal expansion of the silicone and the ability to easily separate it from the part. The silicone used as a silicone mold for the winding of lattice structures is RTV-2, which is a liquid and is baked in ambient air. To mold silicone, a mold is required to cast the silicon. For this purpose, a plexiglass mold was used ("Fig. 2"). It is made by a laser cutting method and has high dimensional accuracy.

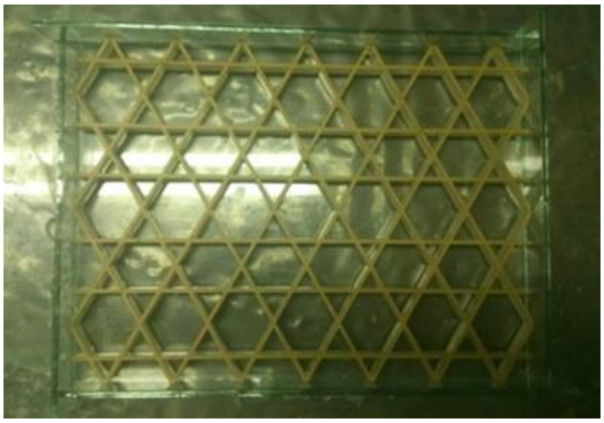

Fig. 2 Plexiglass Molds for molding liquid silicone.

After the mold is ready for silicone casting, the silicone and its hardener are mixed in 100 to 3.5 ratios with an industrial mixer for 10 minutes. Twenty-four hours after casting in a silicone mold, the liquid silicone was cured at room temperature and prepared for fiber spinning. Figure 3 shows the final silicone mold after leaving the plexiglass mold.

Fig. 3 Silicon rubber mold.

The composite lattice panel was fabricated using S-type glass fibers and Araldite LY556 epoxy resin. For this purpose, the fibers were first impregnated with resin in a resin bath and then guided into silicone mold grooves for threading. Twelve layers of fibers are used continuously to fill the silicone mold. The pins embedded in the four sides of the silicone mold were used in the direction of the mold grooves to guide the fiber path. Figure 4 shows the silicone mold filled with fibers and ready for baking. After the grooves were filled, a Teflon strip was placed on the piece, followed by a heavy steel plate so that the fibers were on top of each other, and the resin was spread evenly [5]. Then, an autoclave was used for baking the panel. The filled silicone mold was placed in the autoclave for baking for 4 hours at 80 degrees and 3 hours at 140 degrees. After baking, the lattice panel was removed from the autoclave. The excess was then cut using a composite saw, and finally, the lattice panel and silicone mold were pulled out.

3 PROPERTIES OF MATERIALS

After the samples were fabricated and tested, the volumetric percentage of fibers was measured using the ASTM D2584 combustion test, which was 39%. After determining the volumetric percentage of fibers and the properties of the fibers and resins used, the longitudinal elastic properties and Poisson's ratio were obtained by the law of mixtures and the transverse and shear properties using the Halpin-Tsai equations. "Table 1" shows the properties of the ribs.

Table 1 The elastic properties of ribs

c (kg/m3)ρ	1638
Vf (%)	39
E1(GPa)	22.05
E2=E3(GPa)	7.63
G12=G13(GPa)	2.37
G23(GPa)	3.13
13ν=12ν	0.29
23ν	0.22

Table 2 Strength properties of ribs

SL+(MPa)	645
SL-(MPa)	2038
ST+(MPa)	54
ST-(MPa)	130
SLT(MPa)	46

Also, the strength of the composite was obtained using the micromechanical method, with the results shown in Table 2. Notably, a higher volumetric percentage of fibers does not necessarily mean higher strength [12]. An increase in the volumetric percentage of fibers leads to increased stiffness, while an increase of more than 35% in the volumetric percentage of fibers leads to decreased strength [12]. The properties of ribs are highly dependent on the parameters of the fabrication process, such as the tensile strength of the fibers, the viscosity of the resin, and the mold used to shape the ribs.

4 QUASI-STATIC TRANSVERSE LOADING TEST

The three-point bending test of the panel was performed using a 15-ton SANTAM universal testing device with an automatic pneumatic jaw. According to “Fig. 4”, the two sidebars are fixed and fully attached to their bases, on which the panel is placed, and the third bar is located in the middle on the panel, connected to the upper jaw of the device, through its base. To provide quasi-static conditions, the movable jaw of the device, to which the center bar is attached, moves downwards at a displacement rate of 2 mm/min. The axis distance between the two supports is 255.86 mm, and the load is applied to the middle of the distance between the two supports.

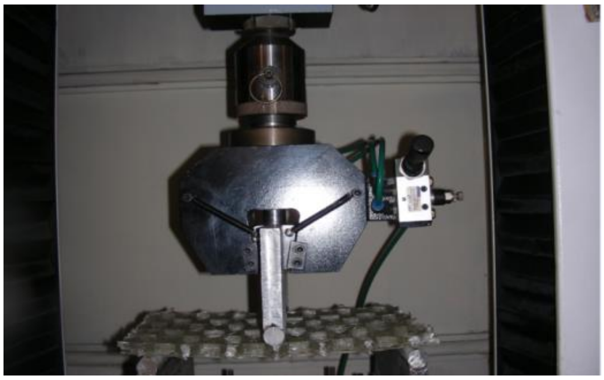

Fig. 4 Three-point bending test of composite grid panel.

5 FINITE ELEMENT ANALYSIS

For the finite element analysis of the composite lattice panel, the SC8R element was used in ABAQUS software, an eight-node linear hexahedral element. The number of elements used is equal to 12640. Figure 5 shows a view of the finite element model used in the analysis.

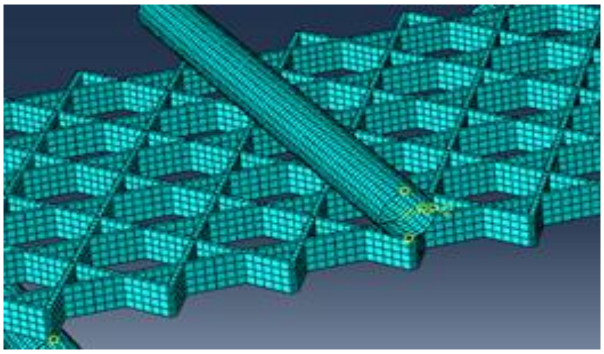

Fig. 5 Finite element model of composite lattice panels in three-point bending.

6 TEST RESULTS

Figure 6 shows the force-displacement curve of a three-point bending test of a composite grid panel. The maximum force borne by the structure is 3156 N. At a displacement of about 35 mm, the test was stopped, but the structure continued to absorb energy. In this case, the structure failed to achieve complete failure (i.e., panel splitting).

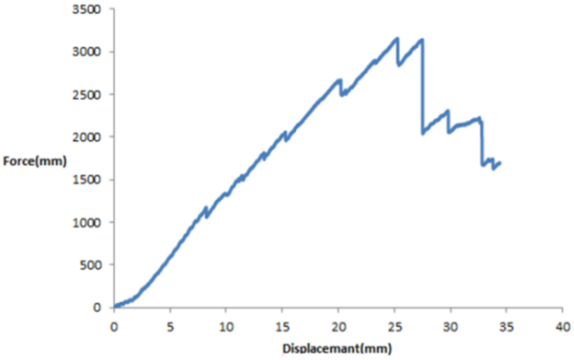

Fig. 6 Force-displacement curve of grid composite panel in three-point bending.

Composite lattice panels without shells have not been fabricated and tested yet. The panels that have been fabricated so far have all been in the form of sandwich structures with two shells and a lattice structure as the core or with one shell on one side of the panel. Deployment of forces on the side of the shell and ribs in these structures induces different behaviors at the maximum tolerable force and also shows the energy absorption of these structures [13]. The maximum force is obtained when force is applied to the shell and not to the ribs, while more specific energy absorption is achieved by applying force to the ribs.

In the bending test of this fabricated specimen, the first crack sound was heard in the structure after a displacement of approximately 20-21 mm, characterized by a small drop in the curve shown in “Fig. 6”. After this small drop, the force curve increased again to a displacement of about 25 mm. However, after this displacement, a sudden drop is observed in a displacement of about 27.5 mm, followed by intermittent oscillations in the curve [6]. Energy absorption continues until the final failure of the structure. As the force increases, the longitudinal tensile stress increases in the underlying layers, leading to their earlier failure compared to other layers (“Fig. 7”).

Fig. 7 Failure in bottom layers.

Failure modes are different in compression mode. This assumption is proved by observing the difference in longitudinal tensile-compressive strength. As shown in “Fig. 8”, the top layers of the panel fail due to the buckling of the fibers due to the longitudinal compressive stress. Nevertheless, the structure has continued to withstand the load after this failure, which occurred in several ribs, due to multiple force distribution paths [2]. Do and Rosen (14) defined the buckling of fibers in the bed of the matrix material as a state of rupture of these materials [14].

Fig. 8 Fiber buckling in the upside layers of the panel.

The final structural failure was not possible due to the limitations of the test device displacement and the maximum force exerted by the tolerance of the fixture.

7 FINITE ELEMENT TEST RESULTS

Figure 9 compares the experimental and finite element test results. As can be seen, there is a good convergence between the finite element test results and the experimental test results up to the point of failure, and the difference in the maximum load tolerance is 5.6%.

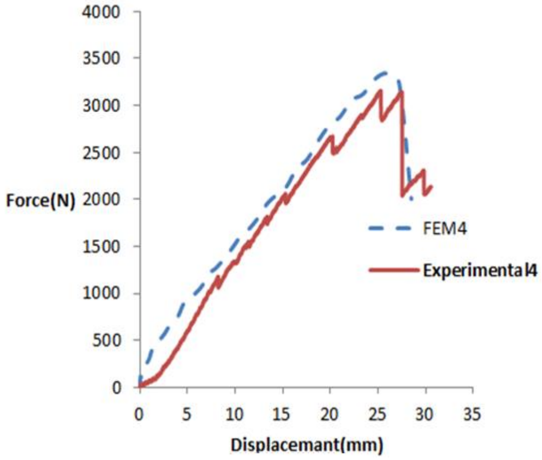

Fig. 9 Comparing experimental tests and finite element curve.

8 CONCLUSIONS

This paper examines composite lattice panels fabricated with S-Glass/epoxy under three-point bending. The main results are as follows:

1. Panels fabricated using silicone molds have very good rigidity and strength.
2. In a three-point bending load, the force decreases slowly and does not decrease sharply at once.
3. The failure process includes the failure of the lower layers of the panel under longitudinal tension and then the buckling of the fibers in the upper layers of the panel under longitudinal pressure. However, the structure continued to withstand the force after the failure of the multilayer fibers. Also, no cracks were observed between the layers.
4. There is an acceptable agreement between the results of finite element simulations and those of experimental tests, indicating the high capability of the software method in bending simulations with damage to the composite lattice structure.

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