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Experimental Investigation of Flexural Properties of E-glass Fiber/Epoxy Grid Composite Structures Filled with Self-Healing Materials

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Abstract
Self-healing materials are a class of smart materials that have the structurally incorporated ability to repair damage caused during mechanical usage. In the present study, E-glass/epoxy anisogrid composite structures filled with self-healing materials were fabricated. Self-healing system includes a number of hollow glass fibers containing room temperature curing epoxy resin and related hardener as healing agents. The effect of self-healing materials volume percentage (5%, 8% and 11%) on the healing efficiency of maximum load-bearing capacity of resultant specimens after quasi-static damage, was experimentally investigated. The results of flexural tests showed that introduction of self-healing materials affected the maximum load-bearing capacity of the specimens. The maximum healing efficiency (84%) of flexural load-bearing capacity was observed in the sample containing 8Vol% self-healing materials. In the samples containing 5Vol% and 11Vol% self-healing materials, lower healing efficiency was observed than the maximum value, respectively due to shortage of healing agents and excess of structural discontinuities caused by hollow glass fibers.

Keywords: *grid composite structures- self healing- flexural testing- hollow glass fiber- anisogrid lattice pattern*

Introduction

Since the advent of composite materials, influence of these materials in various industries is undeniable. Aerospace industry is the main consumer of these materials. However, due to economic costs, use of these materials are not universal but the need for high efficiency and lower weight lead to greater use of these materials. Therefore, while the structure must withstand the loads, it should be as light as possible. In other words, they should have a high strength to weight (specific strength) and stiffness to weight (specific stiffness) [1, 2].

Grid composite structures due to their high specific strength and stiffness, high energy absorption and damage tolerance as structural elements have been widely used in different aerospace applications such as airplane wings, ballistic adaptors, etc [3].

The main components of the grid composite structures are ribs and skin. In these structures, the ribs are the main load-bearing members which are surrounded by skin. These structures due to their ribs have good reliability and efficiency [4, 5]. Mass efficiency and reliability of these structures are derived mainly from the unidirectional nature of the ribs [6].

When all of ribs made from unidirectional fibers, it doesn't make any mismatch in properties. So the possibility of delamination occurrence in these structures is very low. As an open composite structure, grid structure should avoid corrosion of the structure due to permeating moisture and it is very convenient for partial inspection of the structure, monitoring and repairing of damages [7].

Different types of lattice patterns comprising triangles, hexagons, and diamonds can be formed by choosing suitable types of ribs and their relative locations.

Predicting the load-bearing capacity is an important parameter in the design of grid structures. However, this is due to the complexity of mechanical and structural properties in these materials, this matter is very complicated. These structures have different failure modes which include partial destruction of the shell and stiffeners and also general destruction of grid structure. Failure of grid composite structures has several mechanisms. Fracture of ribs, buckling of ribs, cracking of ribs and skin, delamination and the combination of above are example of failure mechanisms that may occur in these structures [8].

The development of cracks in composites and polymer materials is a major problem during their service. The growth of micro-cracks and incorporation of them together, can lead to failure and catastrophic failure. In this field the use of self-healing materials can be a good choice for long term-application. Self-healing can be defined as the ability of a material to recover damages automatically and autonomously, that is, without any external intervention [9, 10].

According to the methods of healing, the smart materials are classified into two categories: (i) intrinsic self-healing ones that are able to heal cracks by the polymers themselves, and (ii) extrinsic in which healing agent has to be pre-embedded, in which case the use of microcapsules and hollow fibers are common.

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As compared with microcapsules which accommodate less healing agent and also because of the high amount of healing agent needed for healing process, utilizing hollow fiber is the best choice for use in self-healing composites, and also there will be repeatability for the healing process [9, 11 & 12].

As shown in Fig.1, after the hollow fiber is damaged and the first delivery of healing agent occurs, the network may be refilled by an external source or from an undamaged but connected region of the vasculature. This refilling action allows for multiple local healing events [13]. So far, lots of research on self-healing materials is presented that involve the use of hollow fibers or microcapsules containing a healing agent, which is released into a damage site upon fracture [14-19]. Williams et al. [14, 15] demonstrated that inclusion of HGF in carbon/epoxy composite, leading to 97% recovery in flexural strength of composite.

In this study, the influence of incorporating hollow glass fiber on flexural properties recovery of GFRP grid composite structures with anisogrid lattice patterned reinforcement, formed by helical and longitudinal ribs was experimentally investigated. Self-healing agent (resin + hardener) was stored in hollow glass fibers. Hollow glass fibers contain self-healing agents at different volume percent (5%, 8% and 11%) were placed inside the ribs. To investigate the effect of self-healing materials on recovery of mechanical properties, after damage occurrence, samples were healed for 7 days in room temperature.

Materials

ML-526 epoxy resin (bisphenol-F) was selected because of its low viscosity and extensive industrial applications [20]. The low viscosity of the resin causes that the resin is easier injected into the hollow fibers. The curing agent was HA-11 (polyamine). ML-526 epoxy resin and HA-11 polyamine hardener were supplied by Mokarrar Engineering Materials Co., Iran. Properties of resin based on company datasheet are given in table 1.

Table 1: ML-526 epoxy resin properties [21]

Density (gr/cm^3)	Viscosity (Centipoise)	Flexural strength (MPa)	Flexural modulus (GPa)
1.11	720	96	3.6

E-glass woven fabric supplied by LinTex Co., China, was used as the reinforcement of skin. Product density of fabric is $400gr/m^2$. Unidirectional E-glass fiber (E-glass roving) supplied by LinTex Co., China, was used as the reinforcement of ribs. Properties of glass fiber based on company datasheet are given in table 2.

Table 2: Properties of unidirectional glass fiber

Type of Fiber	Roving Tex (gr/km)	Mean Fiber Diameter (μm)	Type of Sizing
E-Glass (ASTM D578-98)	2400	12	Silane

Sample preparation

First, with the use of CNC machine, template of anisogrid structure was created in PVC sheet. For making mold, silicon molding RTV-03325 was used. This is a two-component silicone molding and by adding hardener (6H) at a ratio of 100:4 to silicon, is capable of curing at ambient temperature. Silicon molding was poured on templates and was cured for 3 hour at room temperature.

In order to fabricate the anisogrid composite specimens, manual filament winding method was used. First a set of HGFs (resin + hardener) bonded together (as shown in Fig. 2) was placed in the center of grooves. Resin and hardener in a ratio of 100 to 15 are mixed together at room temperature. In the next step, the surface of fibers impregnated with resin. Using a sharp tool, the air trapped inside the fibers was removed. A small amount of resin was poured into grooves of mold and 8 layers of fibers were inserted into the grooves. Next, the surface of mold was impregnated by resin for laying up the skin using 4 layers of E-glass woven fabrics was carried out. Fabricated specimen between 2 to 3 hours was held in the room temperature until curing process of resin was accomplished.

The fabricated specimens are shown in Fig. 3 and Fig. 4. The specimens were characterized by length of 300mm, width of 125mm and thickness of 7.8mm. The cross-section area of all ribs was a quadrangle with the area 6×6 mm^2. Different set of samples as shown in table 3 were fabricated to study the effect of self-healing agent on flexural performance of E-glass/epoxy anisogrid composite structures.

Table 3: Characteristics of fabricated specimens

Sample Code	Content of Self-healing agent (Vol %)	Content of glass fibers (Vol%)	Content of glass fabric in skin (Vol%)
SH0	0	30	48
SH5	5	30	48
SH8	8	30	48
SH11	11	30	48

Damage procedure

Endamaging to the specimens was performed using a Hounsfield tensile testing machine during which bending test was performed on samples with a constant rate of 2mm/min. When the displacement of specimens was attained to the amount of 5mm, loading was stopped. In the process of damaging, some cracks were formed on the outer surface of ribs where the hollow glass fibers were placed intentionally exposed to damage. After endamaging to the specimens, they were left at room temperature for 7 days. During a damage occurrence, some of these hollow fibers fracture and the healing agent is released and infiltrates the damage zone (cracks) and also prevents further damage propagation.

Three-point bending test

Three-point flexural test was performed to investigate the flexural properties of grid composite structures with and without self-healing materials. Hounsfield test machine with a capacity of 25KN, and a special fixture (as shown in Fig. 5) designed and manufactured for bending of structures were used for testing specimens. Loading rate of the machine was chosen 5mm/min. The tests were performed based on the requirements of ASTM D7264. During the loading, load versus the displacement curve for each specimen was recorded in the Hounsfield testing system. To ensure the test results, each test was repeated at least 3 times. Figure 5 shows the grid composite specimen under flexural loading. Results of maximum flexural load bearing of specimens (control and self-healing composites) are given in Table 4.

Table 4: Maximum flexural load-bearing capacity of fabricated specimens

Sample Code	Max Load (N)	Max Load after 7days of Healing (N)	Healing Efficiency (%)
SH0	1465	-	-
SH5	1203	902	75%
SH8	1141	958	84%
SH11	964	656	68%

Results and discussion

For all of the grid composite structures (panel type) with anisogrid lattice pattern used in this study, three-point bending test was performed from the skin side. It should be noted that under flexural loading, samples from the skin side were under compressive loads and from the rib sides were under tensile loads. The information of the maximum load bearing of the control grid composite sample and grid composite samples filled with self-healing materials (without damage and 7 days after healing) are given in table 4. It can be mentioned that under flexural loading, longitudinal ribs of grid composite panel along with skin sustain the maximum applied load. Therefore, grid composite panels with anisogrid lattice pattern due to having two longitudinal ribs show higher flexural strength than the isogrid panels. According to the obtained results from three-point bending test, it is clear that the presence of hollow glass fibers in longitudinal ribs as a result of discontinuity creation in their tensile properties causes a significant reduction in maximum load-bearing capacity of ribs and this can lead to reduction of tensile strength in ribs. Results from the maximum flexural load-bearing capacity of grid composite specimens filled with self-healing materials after 7days of healing indicate that two main factors including volume percent of self-healing materials and structural discontinuity caused by the presence of hollow glass fibers in longitudinal and helical ribs, have opposite effects on the mechanical properties of the structures. Increasing the amount of self-healing materials leads to improve healing efficiency and recovery of maximum load-bearing capacity, conversely as volume percentage of hollow glass fibers increases in ribs, load-bearing capacity of the specimens decrease. Figure 6 shows the maximum flexural load-bearing capacity of undamaged and healed specimens containing 8Vol% self-healing materials after three-point bending test. In can be concluded that in the sample containing 8Vol% self-healing materials and 30Vol% reinforcement fibers, the positive effect due to the amount of self-healing materials overcomes to the adverse effect of the hollow glass fibers on tensile strength of the longitudinal ribs, and as a result, this sample shows the maximum healing efficiency of load-bearing capacity. In the sample containing 5Vol% self-healing materials, although the structural discontinuities do not decline the tensile strength in ribs considerably, due to the shortage of healing agents, the healing efficiency is not as much as the maximum value. Also in the sample with 11Vol% self-healing materials, appropriate amount of healing agents cannot counteract the intensive structural discontinuities in ribs which caused by hollow glass fibers, so that the healing efficiency is much lower than the maximum value.

Conclusions

In the current study, the incorporation effect of self-healing materials in different volume percentages on recovery ability of maximum flexural load-bearing capacity of grid composite structures with anisogrid lattice pattern reinforced with glass fibers was investigated experimentally. Experimental results are as follows:

1- Increasing the volume percent of hollow glass fibers in longitudinal and helical ribs and nodes leads to reduction in maximum flexural load-bearing capacity of structures.

2- Healing capability of damaged specimens increase with amount of healing agents. But healing efficiency of maximum load-bearing capacity of specimens is influenced by a combination of the two above factors.

3- In sample containing 8Vol% self-healing materials, the maximum healing efficiency of load-bearing capacity was observed.

4- In samples containing 5Vol% and 11Vol% self-healing materials, respectively, as a result of shortage in healing agent amount, and mechanical discontinuities caused by excess volume percent of hollow glass fibers, the healing efficiency of maximum load-bearing capacity declined considerably.

Figures and drawings

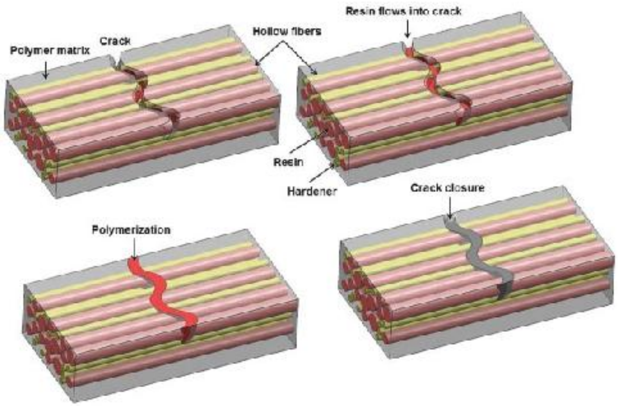

Fig. 1: Schematic representation of self-healing concept using hollow fibers [9].

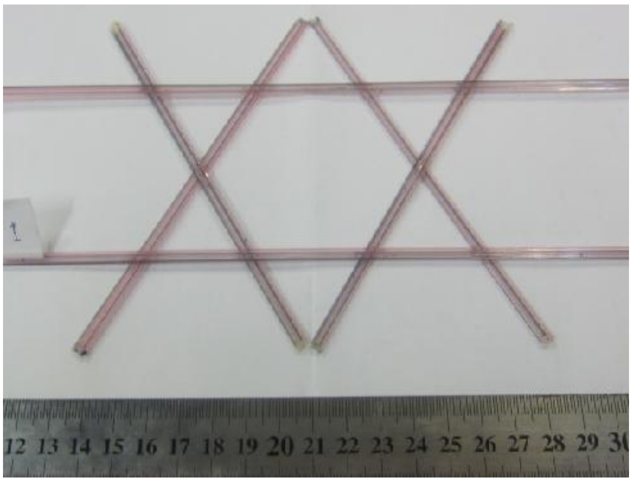

Fig. 2: A set of anisogrid patterned HGFs filled with resin(red) and hardener(green).

Fig. 3: Self-healing specimens containing 5, 8 and 11 volume percent of self-healing materials.

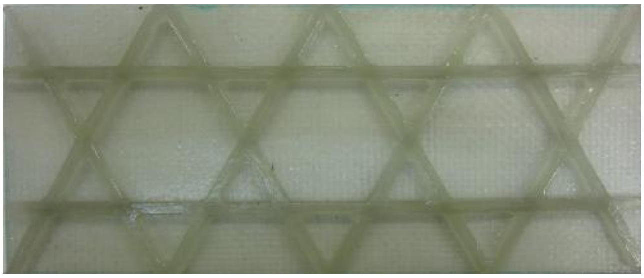

Fig. 4: Control specimen containing 0Vol% self-healing materials.

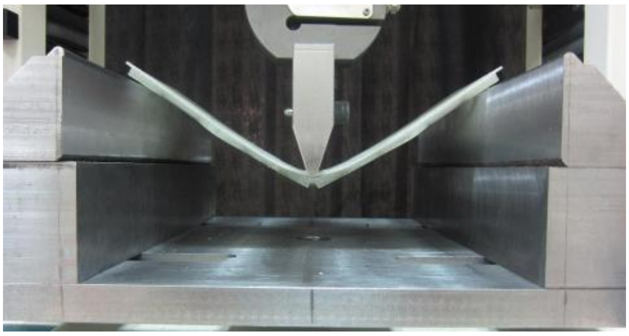

Fig. 5: Grid composite structure specimen under flexural loading.

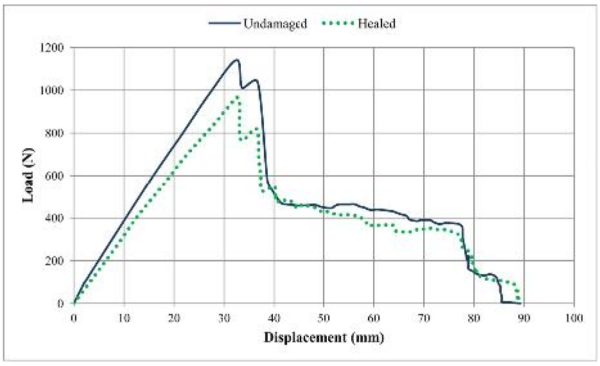

Fig. 6: Load-Displacement curve for self-healing specimens containing 8Vol% self-healing materials under flexural loading.

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