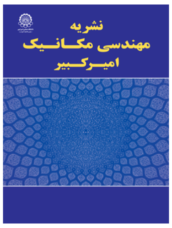

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Design and analysis of mechanical behavior of a novel lattice auxetic structure based on rigid rotating mechanism

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ABSTRACT: Auxetic materials with negative Poisson's ratio, as a group of metamaterials, attracted significant attentions among researchers due to their interesting and remarkable mechanical properties. Rigid rotating structures are a subcategory of auxetic materials which can show the same behavior in various directions by tuning their parameters, but due to using rigid rotating blocks their relative density is high. As the rotating blocks are connected by weak joints, stiffness and strength of these structures are low and considering high relative density of these structures specific mechanical properties are even in worse condition. In this research, novel lattice structures based on rigid rotating structures but with remarkably lower relative density were presented. To reduce relative density of these structures, bar elements were used instead of rigid blocks. 3D printing method was used to manufacture samples with these structures and then tensile test was performed on the samples. Poisson's ratios of the samples were measured by recording image of the structures before and during deformation. The behavior of the structures was predicted by finite element method and compared with experimental measurements. Both of the methods showed auxetic behavior of the structures. Then deformation mechanism of the structures and the effect of the structures shape on the auxeticity were investigated.

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1- Introduction

Composite structures demonstrate interesting mechanical properties to weight ratios. This has been the motivation of applying such materials in engineering structures. However, due to the mismatch between the matrix and the reinforcement phase of composite materials, different failure phenomena may occur in these structures during function, such as delamination, matrix cracking, fiber breakage and fiber pullout. These failures are basically due to crack initiation and propagation in the composite structure.

An important source of crack initiation and propagation in such structures is related to impact loading and/or thermal shocks. These kinds of loadings lead to initiation of microcracks in the material, where the propagation on these microcracks may cause catastrophic failures in the structure. Thus, online and offline health monitoring of composite materials by acoustic emission, thermography and X-ray is an essential procedure in industrial applications of such structures. However, consistent monitoring, replacing and/or repairing of the composite parts of the engineering structures are costly [1].

An alternative solution is to take advantage of composite materials with self-healing behavior. Self-healing composite materials are divided into two groups, intrinsic and extrinsic self-healing composites. The extrinsic behavior is achieved by taking advantage of an external agent which is stored at the fabrication procedure in hollow fibers, micro capsules or a vascular network. After a damage is introduced to the composite material, this external agent is delivered to the damaged area and causes some kind of repair mostly on a chemical reaction basis. A comprehensive review on the concept and applications of self-healing composites is presented by Zhang et al. (2021) [2]. In addition, several researches have been published on evaluating the effect of self-healing behavior on the restoration of mechanical behavior due to different failure mechanisms such as delamination, matrix cracking, fiber breakage and fiber pullout; for example, the researches of Dry et al. can be outlined [3-5].

As mentioned, composite materials are vulnerable to impact loading and the idea of taking advantage of self-healing behavior in repairing the damaged impacted area has been studied by researchers. The main stream of these researches has been the evaluation of the recovery of the mechanical properties of the composite material after being damaged by low velocity impact and being healed by the external agent [6-8].

In general, the healing process is a time dependent process. Furthermore, as described, the basis of the extrinsic healing behavior is a chemical reaction of the external agent. This external agent is mainly consisted of a low viscosity resin combined with a proper hardener, where the combination reacts with the composite elements and leads to the restoration of the microstructure of the composite. This

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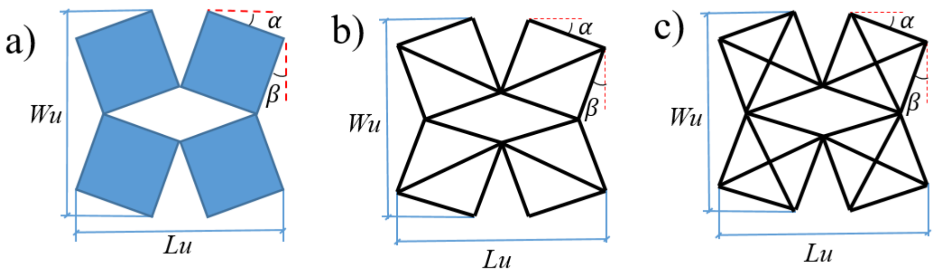


Fig. 1. Creating auxetic structures inspired by structures with rotating blocks: a) a unit cell of the structure with rotating blocks, b) construction of a unit cell with similar behavior in two directions, c) a unit cell with completely identical properties in two directions.

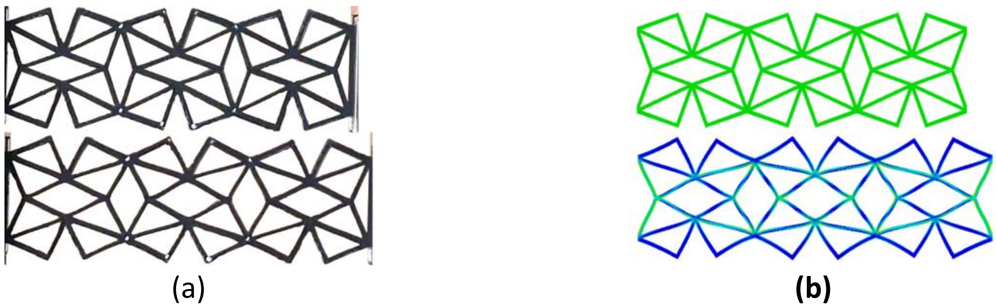


Fig. 2. Comparison of primary structures and structures after strain of 2 % a) experiment (b) simulation

chemical reaction may be affected by introducing thermal cycles into the healing procedure, especially the required healing time. However, reviewing the present literature in this field shows that the effect of thermal cycles on the healing behavior is not studied thoroughly. In addition, the damage is caused by Charpy impact and three-point bending tests to the composite, while in real applications the impact loading is mostly occurred in a form nearly like a drop hammer test.

Based on the above explanation, in this research the effects of healing time and thermal cycles on the healing process of glass/epoxy composites are studied. The investigation is carried out experimentally and the initial damage is introduced to the composite by drop hammer test. The aim is to determine the effect of healing process on the recovery percentage of the

2- Experimental Procedure

Materials: Epoxy resin EPIKOTE828 manufactured by Shell Chemicals combined with an Amine hardener plus E-glass fiber mat with a density of 400 g/m^2 (manufactured by Lintex Ins.) are utilized in fabricating the test samples. ML506 epoxy resin (that has a low viscosity) and HA-11 which is a polyamine hardener are used as the healing agent. In addition, hollow glass microtubes with an outer diameter of 200 micrometers are applied for storing the healing agent.

Fabrication of test samples: 6-layer composite beams are fabricated by hand layup. The resin and hardener of the healing agent are stored in separated microtubes which are joined beside each other. Each set of resin and hardener microtubes are called one healing unit hereafter. Control samples are produced without any healing units. Other samples are produced by 8, 16 and 32 healing units, where this amount of healing units are equal to 0.67%, 1.34% and 2.68% of volume fraction, respectively. Half of the healing units are placed between the first and the second layers and the remaining half are interleaved between the fifth and the sixth layers.

Inserting damage: The damage is introduced to the samples by a 3.1 Kg drop hammer which is released from a height equal to 45 cm. This means that the velocity of the hammer is equal to 2.97 m/s at the impact the impact energy is also equal to 13.68 J.

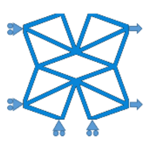
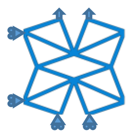
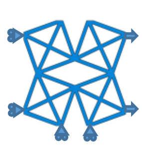
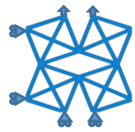
Thermal cycles: Although healing process is a time dependent procedure and is carried out automatically, applying thermal cycles to the damaged samples can accelerate this process. In order to investigate this fact, some damaged samples are placed under thermal cycles directly after impact. The time of each thermal cycle is 120 minutes which includes 60 minutes of heating to 150°C proceeded with 60 minutes slow cooling at room temperature.

Tensile Tests: Tensile tests are carried out on the samples before damage, directly after damage and in periods of 1, 6 and 12 days after damage. In addition, tensile tests are done on the samples which have met thermal cycles 1 day after damage.

Table 1. Poisson's ratio for different values of angle α

Angle value (degrees)	$\alpha = 10$	$\alpha = 20$	$\alpha = 30$	$\alpha = 40$
Poisson's ratio	-0.75	-0.69	-0.38	+0.61

Table 2. Poisson's ratio and Young's modulus among two directions

Unit cell shape and loading direction				
Young Modulus (MPa)	25.3	19.14	24.13	24.51
Poisson's ratio	-0.69	-0.64	-0.83	-0.84

3- Results and discussion

The results for recovery of tensile strength before and after damage as functions of time and thermal cycles are demonstrated in Figures 1 and 2.

The results are also listed in Table 1. As can be seen, applying thermal cycles efficiently accelerates the healing process and increases the recovery percentage as well.

4- Conclusions

In this paper the effect of thermal cycles on the recovery of tensile strength of self-healing composite samples which were damaged by low velocity impact is investigated. The results show that although interleaving the healing units decreases the strength of undamaged samples up to 10%, the healing process leads to a recovery percentage more than 85%. In addition, introducing thermal cycles to the damaged samples accelerates the healing process, as the recovery percentage of damaged samples after 12 days is almost equal to recovery of the samples which have met 7 thermal cycles after 1 day.

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