

Experimental investigation on flexural properties of self-healing composites reinforced by shape memory strip

H. Ghanbari^a, S.M.R. Khalili^{b,c}, R. Eslami-Farsani^d, S. Khalili^{a*}, and P. Mahajan^c

^a Department of Mechanical Engineering, South Tehran Branch, Islamic Azad University, Tehran, Iran

^b Centre of Excellence for Research in Advanced Materials and Structures, Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran

^c Department of Applied Mechanics, Indian Institute of Technology, New Delhi, India

^d Faculty of Material Science and Engineering, K. N. Toosi University of Technology, Tehran, Iran

Corresponding author: S.M.R. Khalili smrkhalili2017@gmail.com

Abstract

In this article, the flexural properties of self-healing smart composites reinforced by shape memory alloy strips are investigated experimentally using mechanical flexural tests. 5 groups of specimens consist of specimen without shape memory alloy (SMA) strip, specimen with one SMA strip without pre-strain, specimen with one SMA strip and 4% pre-strain, specimen with three SMA strips without pre-strain and, specimen with three SMA strips and 4% pre-strain. Short hollow glass fibers (SHGF) are embedded in all the mentioned specimens. The 25 wt. % of SHGF containing the resin and hardener were randomly distributed in the epoxy resin and the fibers/epoxy specimens were fabricated using hand layup technique. In order to determine the healing efficiency of the smart composites, the specimens were damaged initially and then subjected to flexural tests after a certain period of healing time. The influence of some effective parameters including healing time and the presence of SMA strip(s) on the healing efficiency of the smart composite was investigated. The healing efficiencies of 43.18% and 71.5% were achieved after three and seven days, respectively, for the specimens with embedded three SMA strips.

Keywords: Flexural properties, Self-healing, Shape memory alloy strip, Short hollow glass fiber (SHGF), Smart Composite

1. Introduction

Degradation, damage, and failure are natural consequences of material applications. Engineering research has been focused traditionally on either the design of new materials with increased robustness or the development of nondestructive evaluation methods for material inspection to any of the above deficiencies, yet all engineered materials eventually fail. The mentioned problems lead researchers to investigate self-healing materials which have the ability to repair damage. There are three steps in the process of self-healing materials. The initial response is triggered by injury. The second response is transport of materials to the site of damage and the third response, analogous to matrix remodeling, is the chemical repair process. Hollow glass fiber (HGF) healing system is one of the existing healing methods that can make the fiber reinforced polymer composites healable. These HGFs are made using drawing technique of hollow glass in glass workshop [1, 2]. A typical HGF self-healing approach used within composite structures could take the form of fibers containing a one-part resin system, a two-part resin and hardener system or a resin system with a catalyst or hardener contained within the matrix material [3]. Storing the healing agent in hollow fibers in composites is more advantageous than storing it in microcapsules [4, 5]. Dry [6] investigated the use of hollow glass fibers as healing agent for the first time. She used millimeter-diameter HGF filled with two-part epoxy system as healing agent. Trask et al. [7] considered the placement of self-healing HGF plies within both glass fibers/epoxy and carbon fibers/epoxy composite to reduce damage occurrence and restore mechanical strengths. They investigated the effect of embedded HGF on the host laminate's mechanical properties and also the healing

efficiency of self-healing HGF after exposure of the laminates to quasi-static impact damage. They found that a significant fraction of flexural strength can be restored by the self-repairing effect of a healing resin which is stored inside hollow fibers.

Pang et al. [8] developed a new generation of fiber reinforced plastics employing biomimetic approach carried out self-repair and visual enhancement of impact damage by a bleeding action from filled hollow fibers. Their results showed that for the lay-up investigated, a significant fraction of flexural strength lost after impact damage, could be restored by the self-repairing effect of a healing resin which is stored inside hollow fibers.

Hucker et al. [9] manufactured hollow borosilicate glass fibers from tubular preforms with a variety of internal and external diameters corresponding to arrangement of hollowness values. In all cases, the resultant hollowness was reduced from that present in the preform state, regardless of drawing rate or furnace temperature. It was revealed that temperature plays an important role in controlling fiber hollowness due to the interaction between glass viscosity and surface tension effect.

Due to the special mechanical properties, the SMA materials are considered as an engineering topic for research in the last four decades. Shape memory effect and pseudo-elasticity are the two unique characteristics of SMA. Embedding shape memory alloy in composites affects the mechanical properties of host composite. Roger et al. [13] investigated for the first time the same topic and come up with an improvement in low velocity impact performance. Gupta et al. [14] reported an increase of approximately 30% in longitudinal compressive strength of shape memory alloy hybrid composites. Shokrieh et al. [15] studied the effect of shape memory alloy wires on the enhancement of fracture behavior of epoxy polymers. The experimental results in their study showed an enhancement of 67% in the changes in the crack growth resistance for 1% pretrained SMA reinforced epoxy sample. This

value is reported 38% and 16% for 2% and 4% pre-strained specimens, respectively. Khalili et al. [16–18] studied the elastic properties of randomly oriented shape memory alloy discontinuous wires reinforced epoxy resin. They reported a 20% improvement in elastic modulus of composites reinforced by wires with aspect ratio of ($l/d \geq 35$) in comparison with composites reinforced by wires with lower aspect ratio ($l/d \geq 5$). They also obtained a 12% enhancement in elastic modulus for composite reinforced by 4% pre-strained SMA. In the case of dynamic loadings, they also found that using embedded SMA wires in the composite plates, enhance the behavior of the composites against low velocity impact of the projectiles [19].

A major issue in composite technology is matrix microcracking due to loading in various conditions which may severely limit service lifetimes of composite parts. Self-healed structures are nowadays strike the mind of researchers in the field of structures to increase the integrity and lifetime as well as the behavior of composite structures. In this work, short hollow glass fibers are used for self-healing mechanism and remarkable levels of healing of damage are obtained using shape memory alloy (SMA) strips to close transverse or longitudinal cracks in woven glass fiber-reinforced polymer plates. Thermal actuation of SMA strips stacked to glass fiber composite plies introduces compressive loads to the cracks. Hence, significantly greater degrees of healing than so far reported could be achieved.

The focus of this research work is dedicated on the influence of presence of SMA strips and the effect of filled short HGF on healing efficiency and the response of flexural properties of composite structures. The combination effect of SHGF and SMA strips on flexural behavior of composite materials has been never studied earlier by any researchers.

2. Materials and experimental procedure

2.1. Materials

2.1.1. Resin epoxy 828

To fabricate self-healing composite specimens, resin epoxy 828 (Appendix A) was used as matrix and also healing agent. Resin epoxy 828 is a medium viscosity liquid epoxy resin produced from bisphenol A and epichlorohydrin. It contains no diluent and provides good pigment wetting, good resistance to filler settling and a high level of mechanical and chemical resistance properties in the cured state. TETA (Triethylenetetramine) 10% was used as resin epoxy hardener component. Resin epoxy 828 resin epoxy is the most common resin used in the last decade as matrix in self-healing composites where the physical and chemical properties are represented in Table 1 [10].

Table 1. Physical and chemical properties of resin epoxy 828 [10].

Physical state	Liquid
Color	Pale yellow
Boiling point	>200 °C
Vapor Pressure	<0.01 Pa @ 20 °C
Density	1160 kg/m ³ @ 25 °C
Dynamic viscosity	12 poise
Flash Point	>200 °C
Auto-ignition temperature	>300 °C

2.1.2. Woven textile glass fibers

Woven textile glass fibers (Figure 1) are chosen as reinforcing element inside composite matrix. Type E-Glass fiber has the density of 400 g/cm³. These fibers have tensile strength of 2400 MPa and special weight of 2.56 g/cm³. High strain values, high wettability, high adherence with matrix, proper final cost and the possibility of ordering different densities are

the reasons for choosing the woven textile glass fibers. In order to fabricate specimens, the textile is cut into different sizes using special scissor.



Figure 1. Woven textile glass fibers.

2.1.3. Short hollow glass fibers

To store healing agent (resin and hardener) in this study, short hollow glass fibers (SHGFs) (Figure 2) were used. These SHGFs are made from Pyrex glass (Borosilicate). Hollow fibers are hand-made in glass workshop of K. N. Toosi University. Hollow glass fibers with 0.8 m length, 400 μm average outside diameter and 320 μm average inside diameter which results in a hollowness ratio (internal area to total area) of 65% are manufactured in a constant drawing rate and controlled temperature. High hollowness ratio results in fibers with low thicknesses. In this system, soda-lime silicate, amber tubing glass and borosilicate glass can be utilized as the hollow glass fibers. In the present experiments, in order to achieve high healing efficiencies due to sufficient brittleness of the fibers, Pyrex (borosilicate glass) hollow glass tubes from bulk material was chosen [19]. In constant strain, the Pyrex glass needs lesser loads for damaging in comparison to other tested glasses. More details could be found in [20].

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Figure 2. Hollow glass fiber.

2.1.4. SMA strip

NiTi SMA strips (Figure 3) with high strain tolerance and recovery stress ability are used in this study to closure cracks mechanically. Super-elastic and shape memory effects are the two significant thermo mechanical properties of these alloys. Adding SMA wires to matrix reduce the strength of composite. To fix this issue, in this work, the SMA wires are replaced with SMA strips with flat faces. SMA strips used in this study have width of 0.03 in. and thickness of 0.01 in. as shown in Figure 3. Physical, chemical and mechanical properties of these strips are given in Table 2 [11]. The SMA strips used in this research work are in martensitic form at room temperature and their shape memory effect is considered.

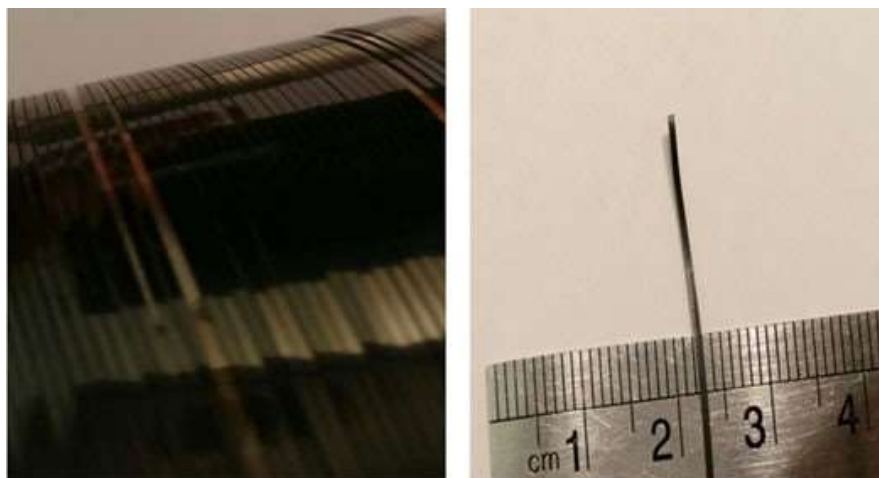


Figure 3. SMA strips used in the present study.

Table 2. Properties of SMA strips [11].

Melting point	1310 °C
Density	6.5 g/cm ³
Modulus of elasticity	28–41 GPa
Electrical resistivity	76 μohm-cm
Coefficient of thermal expansion	$6.6 \times 10^{-6}/^{\circ}\text{C}$
Ultimate tensile strength	1070
Total elongation	≥ 10 %
Ingot austenite finish (A_f)	80 °C to 45 °C
Finished product A_f	30 °C to 50 °C
Nickel (nominal)	55 wt. %
Titanium	Balance
Oxygen	≤ 0.05 wt. %
Carbon	≤ 0.02 wt. %

2.2. Fabrication process

2.2.1. Fabrication of chemical healing agent

Hollow glass fibers are filled with resin and hardener to fabricate self-healing SHGF. A two-part resin epoxy 828 was diluted with the ratio of 1:10 to ease the vacuuming process and

used as healing system. The following equipment is employed for storing healing agent in hollow glass fibers.

Vacuum pump (Figure 4), flexible hose, sealing paste, test tube, special glue (to block the two sides of HGFs) and a caliper for measuring hollow glass fibers in order to cut them into desired length.



Figure 4. Vacuum pump for storing resin and hardener into the hollow glass fibers.

One side of HGFs is placed inside the resin or hardener pot and the other side is placed in flexible hose connected to vacuum pump. Gap between HGFs and flexible hose is filled with sealing paste. Then the vacuum pump is powered on and this process continues until the HGFs are filled with resin and hardener. After the HGFs are filled, the vacuum pump is powered off and two sides of these fibers are blocked using special glue. In the next stage, HGFs are put inside freezer and after four hours, fibers are cut manually with special scissor to 5 mm pieces as shown in Figure 5. Resin and hardener are filled in separate hollow tubes with different colors. The SMA strips are placed and embedded between the third and fourth layers of the laminates. The purchased SMAs are in martensitic phase at room temperature.



Figure 5. Short hollow glass fibers filled with resin or hardener.

2.2.2. Fabrication of self-healing composite

Self-healing smart composite was manufactured using hand lay-up method. The fibers/epoxy composite consists of four layers of woven textile glass fibers, grouped in five categories. During fabrication of specimens, the SMA strips are embedded between the third and fourth layers. SHGF with 25 wt. % are distributed between each two layers. In order to place SMA strips between the layers properly, MDF fixture is used which is shown in Figure 6. Specimens containing SMA strips are manufactured using a simple MDF fixture. The fixture used for strips alignment along the length of the specimens and a 4% pre-strain was applied to them. The strips are placed between the third and fourth layers. Considering the specimen's length and a simple calculations, the 4% pre-strain was applied to SMA strips using a caliper and pliers, and then the bolts screwed to anchor strips, and the process continued until the end.

Self-healing smart composites are fabricated using hand lay-up method (Figure 7) in K.N. Toosi University of Technology. Thus, a weighing scale with 0.01 grams accuracy was employed to weigh mixing ratio of resin and hardener precisely. Woven textile glass fibers are cut into required dimensions for placements as composite layers.

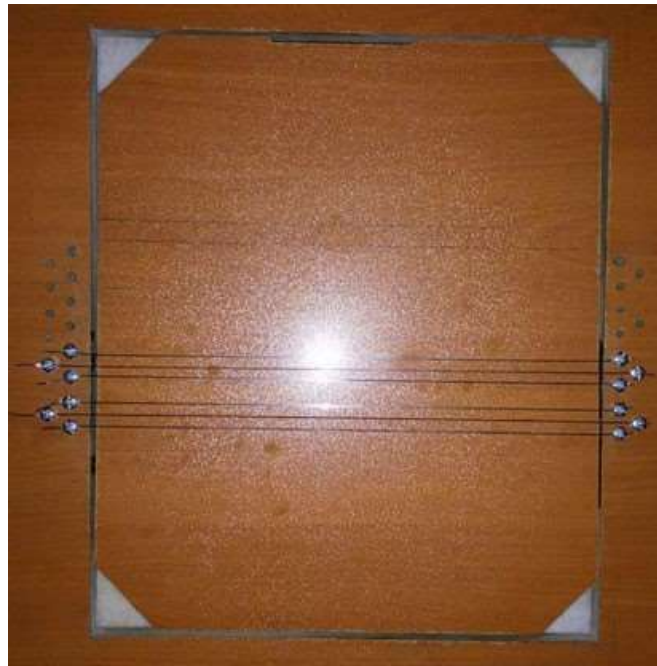


Figure 6. Fixture for placing the SMA strips.



Figure 7. Fabricated self-healing composite.

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At the end of fabrication process, a flat wooden plate is placed on top of the specimens exerting uniform distributed pressure to the surface of the self-healing smart composite to make it bubble-less and make the surface homogenous. This procedure continues until the smart composite sheet becomes cured. Dimensions of each specimen are 100 mm in length, 4 mm in depth and 20 mm in width. Figure 8 shows several specimens for flexural tests. SHGFs distribution and position of SMA strips are shown in Figure 8.

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Figure 8. Specimens prepared for flexural test.

2.3. Flexural tests

The experimental study contains investigation on five categories of test specimens:

1. specimen without SMA strip
2. specimen with one SMA strip without pre-strain
3. specimen with one SMA strip and 4% pre-strain
4. specimen with three SMA strips without pre-strain
5. specimen with three SMA strips and 4% pre-strain

For each one of the mentioned categories, 4 sub-categories including virgin specimens, damaged specimens, healed (3-day) specimens and healed (7-day) specimens were considered. For each case, five specimens were tested and the results are averaged value. The main self-healing composite sheet was cut to proper dimensions according to ASTM D-790-M-93. For testing of undamaged specimens, the loading condition advances up to the failure of the specimen. For the damaged specimens, the specimens are loaded up to 75% of the ultimate flexural strength of the virgin specimen to be damaged. Applied load for damage exertion was specified with a three-point flexural test machine.

2.3.1. Specimens codes

Specimens were coded in order to be easily specified for the testing as well as reporting the results. Figure 9 displays the coding details. "B" letter in the first part stands for flexural or bending test, "S" in the second part stands for self-healing and "C" for the specimens which are damaged but not healed. In the third column of the table in Figure 9, the numbers stand for the number of SMA strips and the fifth column shows the numbers which are indicative of prestrain values of the SMA strips. "W" stands for the specimen with pre-strain. In the sixth column, the first letter (N) indicates that the specimen is tested without any previous damage and letter (D) indicates that the specimens are tested after being damaged. The last column shows the healing time period, where letter (V) stands for virgin specimens and 0, 3, and 7

numbers stand for damaged specimen, healed after 3 days and healed after 7 days, respectively.

Two examples of the assigned codes to the specimens are represented in Table 3.

B	C	0	W	0	N	V
		1			D	0
	S	3		4	D	3
					D	7

Figure 9. Coding of the tested specimens.

Table 3. Two examples of assigned codes to the specimens.

Assigned codes	Number of prepared specimens	Damage	Healing duration (day)
BC-0W0-NV	5	No	0
BC-0W0-D0	5	Yes	0
BS-0W0-D3	5	Yes	3
BS-0W0-D7	5	Yes	7
BC-3W4-NV	5	No	0
BC-3W4-D0	5	Yes	0
BS-3W4-D3	5	Yes	3
BS-3W4-D7	5	Yes	7

2.3.2. Damage exertion to the specimens

Damage exertion is very important in healing efficiency evaluation. If the damage is applied incorrectly, healing efficiency cannot be evaluated precisely anymore. The amount of loading applied to the specimens, to damage them depends on 75% of the ultimate flexural strength of the virgin specimens (NV). All specimens were damaged through three-point flexural test in ambient temperature. Delamination occurs in self-healing composite specimens, if the applied load is higher than the mentioned value. After damage occurred, specimens were heated up to the SMA austenite finishing temperature in an oven for few seconds, so the SMA strips reshaped into their straight initial condition which was happened due to the shape

memory effect. In the next step, the damaged specimens (D group) were tested immediately and the specimens were left in ambient temperature for activation of chemical healing process for three and seven days and then tested, respectively. Figure 10 represents the flexural test using a Hounsfield testing machine.

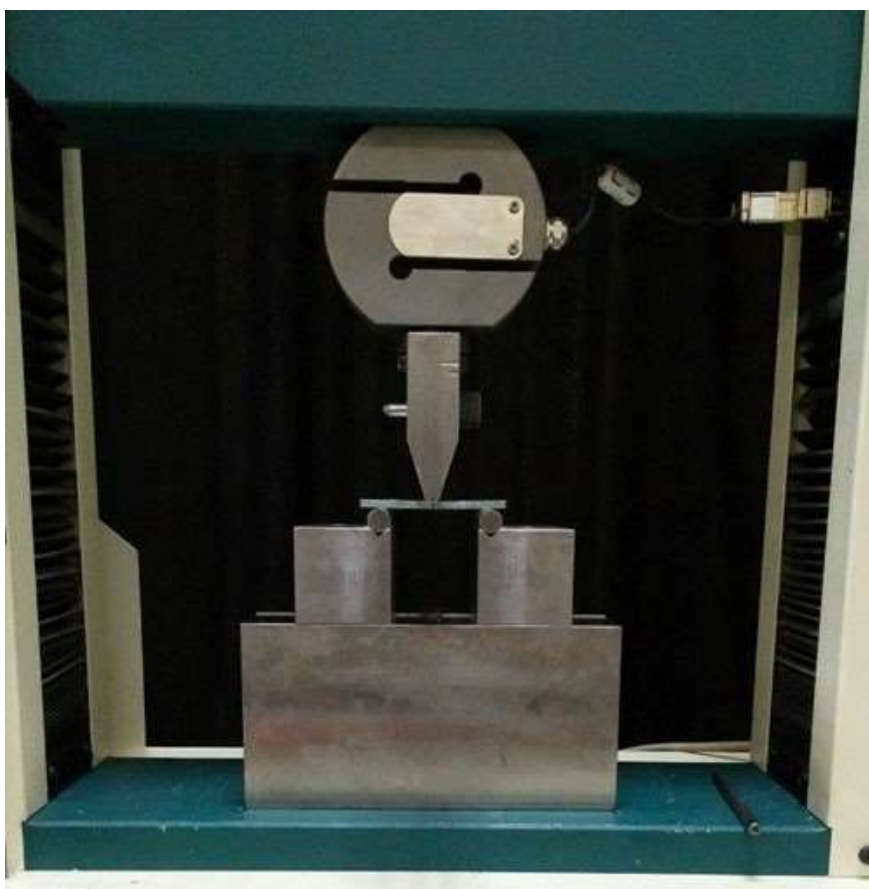


Figure 10. Flexural test of self-healing composite specimens

3. Results and discussion

The results obtained from the flexural test on the specimens with classifications mentioned in 2.3 are presented in form of stress strain diagrams in this section. Each group contains virgin, damaged and healed specimens for comparison purpose, respectively. Flexural stresses and strains are calculated according to ASTM D-790-M-93.

3.1. Specimen without SMA strip

These specimens contain no SMA strip for reinforcement and include virgin, damaged, 3 days and 7 days healed cases. Virgin and damage specimens are those that have not been healed. BC-0W0-NV category are virgin specimens and tested without damage exertion and BC-0W0-D0 specimens are tested immediately after damaged. The stress–strain diagram of these two specimens is shown in Figure 11. In this case, ultimate flexural strength and strain of virgin specimen and damaged specimen were, respectively equal to 363 MPa at 0.0256 and 218 MPa at 0.018.

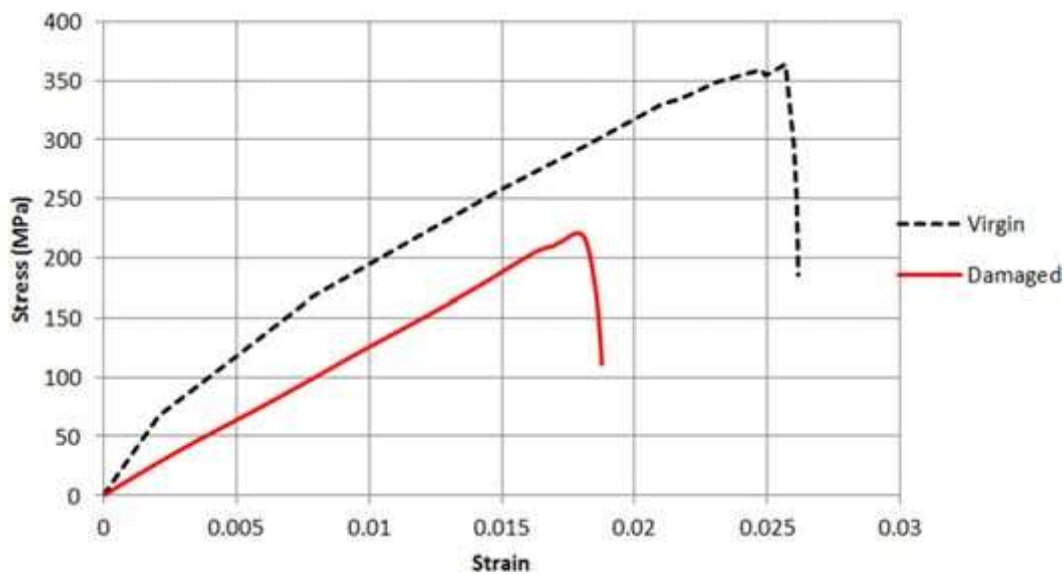


Figure 11. Stress–strain diagrams of the specimens without SMA strip.

As it can be seen from Figure 11, damage causes a 39.9% decrease in ultimate flexural strength of the specimen. Also, damage results a drop in other specimen's properties like maximum strain, area under the curves and the initial slope. The initial slope or stiffness (for less than 75 MPa stress) of the virgin specimen is approximately 33 GPa and the damaged specimen is 13 GPa. It means that a reduction of 60% occurred due to damage to the specimen.

Also, in Figure 11, the area under the flexural stress–strain curves demonstrates flexural toughness or energy absorption of the specimen during bending. The measured areas were equal to 5.8 MPa and 2.75 MPa for the virgin and damaged specimens, respectively. Consequently, damage on specimen causes a 52% reduction in flexural toughness. The maximum strain of the virgin specimen shown in Figure 11 is 0.027 as compared to the damaged specimen with maximum strain of 0.018 which shows 64% reduction.

Healed specimens were damaged and then they were placed in ambient temperature (25 °C) for three and seven days in order to be healed. The only difference between the two healed specimens is in their healing duration time. BS0W0-D3 and BS-0W0-D7 specimens are 3 and 7 days healed specimens, respectively. Figure 12 shows the flexural stress–strain curves for these two specimens. The ultimate flexural strength, strain and toughness, that is, the area under the stress–strain curve are to be considered.

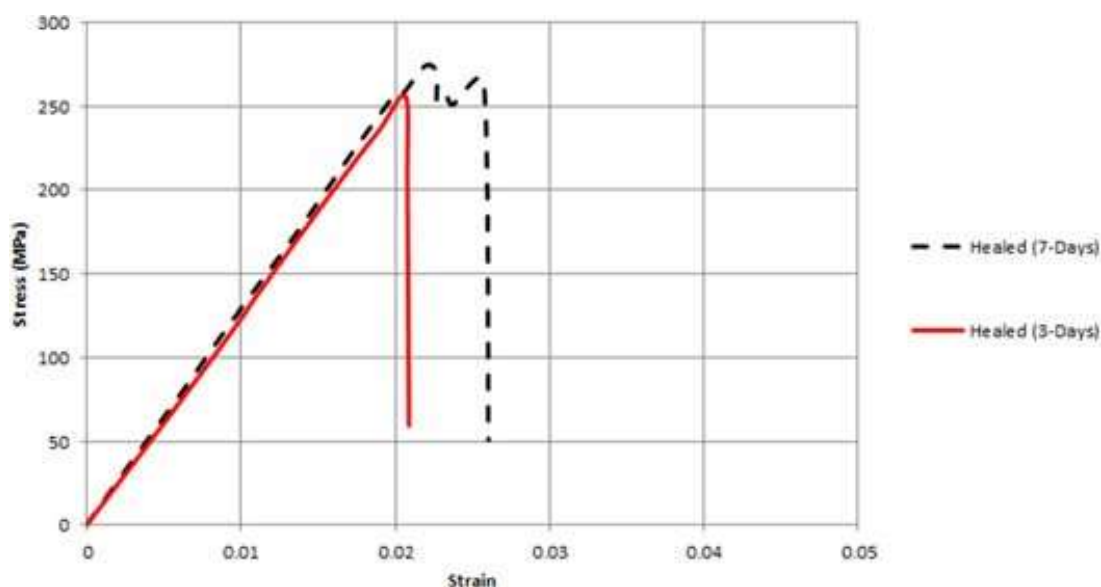


Figure 12. Stress–strain diagrams of the healed specimens without SMA strip.

As it can be seen from Figure 12, the ultimate flexural strength and strain for healed specimens are equal to 273 MPa at 0.0265 for 7 days specimens and 255 MPa at 0.0206 for 3 days specimens, respectively. The measured areas under the stress–strain curves which introduce flexural toughness were equal to 6.38 MPa and 4.27 MPa for 7 days and 3 days specimens, respectively. Consequently, the healing time has a significant role in strength and deformation as well as the energy absorption of the specimens in bending behavior. A reduction of about 33% occurred due to less healing time in flexural toughness. An increase of about 28.6% is achieved in failure or ultimate strain by allowing the specimens for 7 days to heal instead of 3 days. 7 days healed specimen has 6.6% higher strength than the 3 days healed specimen. To calculate the healing efficiency, Equation (1) [12] is applied.

$$(1)$$

In Equation (1), g is the healing efficiency and f is the property that is chosen for healing assessment (e.g. flexural strength). Table 4 shows the average values of ultimate flexural strength and healing efficiency of the specimens without SMA strips.

Table 4. The average values of ultimate flexural strength and healing efficiency of the specimens without SMA strips.

Healing efficiency (%)	Ultimate flexural strength (MPa)	Description	Specimens codes
–	363	Virgin	BC-0W0-NV
–	218	Damaged	BC-0W0-D0
25	255	Healed 3 days	BS-0W0-D3
37.9	273	Healed 7 days	BS-0W0-D7

3.2. Specimens with SMA strips

In this section, the specimens with SMA strips are considered and the same procedure is repeated for all four remaining categories according to Table 5 and the average values of the ultimate flexural strength and the healing efficiency are represented in Figure 13. Comparing the information for healing efficiencies given in Tables 4 and 5 indicates the significant conclusion of combining SHGF and SMA.

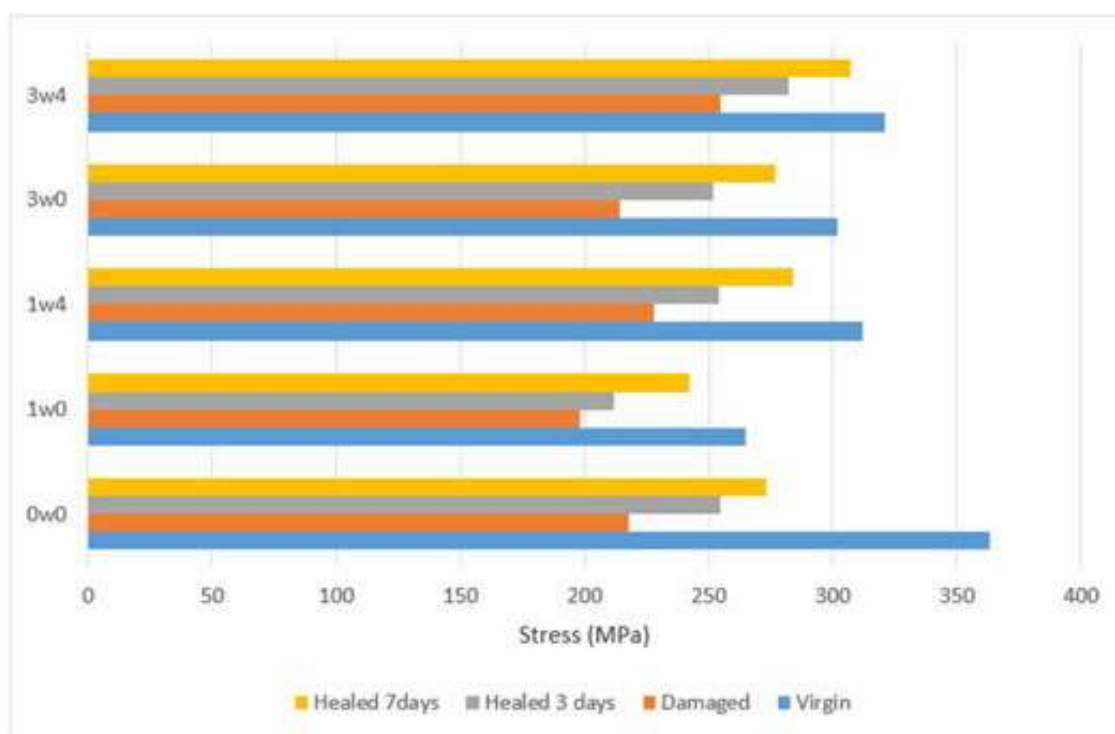


Figure 13. The ultimate flexural strength comparison between virgin, 0, 3, and 7 days healed specimens with and without SMA strips and pre-straining.

Table 5. The average values of ultimate flexural strength of four specimens categories and healing efficiency.

Healing Efficiency (%)	Ultimate flexural strength (MPa)	Description	Specimens codes
—	265	Virgin	BC-1W0-NV
—	198	Damaged	BC-1W0-D0
20.89	212	Healed3days	BS-1W0-D3
65.6	242	Healed7Days	BS-1W0-D7
—	312	Virgin	BC-1W4-NV
—	228	Damaged	BC-1W4-D0
30.95	254	Healed3days	BS-1W4-D3
66.6	284	Healed7Days	BS-1W4-D7
—	302	Virgin	BC-3W0-NV
—	214	Damaged	BC-3W0-D0
43.18	252	Healed3days	BS-3W0-D3
71.5	277	Healed7Days	BS-3W0-D7
—	321	Virgin	BC-3W4-NV
—	255	Damaged	BC-3W4-D0
40.6	282	Healed3days	BS-3W4-D3
78.19	307	Healed7Days	BS-3W4-D7

Comparison of virgin specimen's results in all five categories is shown in Figure 13. As it can be seen, adding one strip results in a decrease in ultimate flexural strength. However, this deficiency decreases by pre-straining strip and embedding more strips instead of one. The reason of this defect could be related to rapid crack growth in the interface with other parts of self-healing composite. Presence of three strips increases flexural strength of composite specimen and also applying pre-straining to the strips causes the specimen to be stress-recover based on shape memory effect. Effect of healing is more predominant in case of the specimens with SMA strips. Figure 14 shows the healing efficiency of the specimens after 3 days.

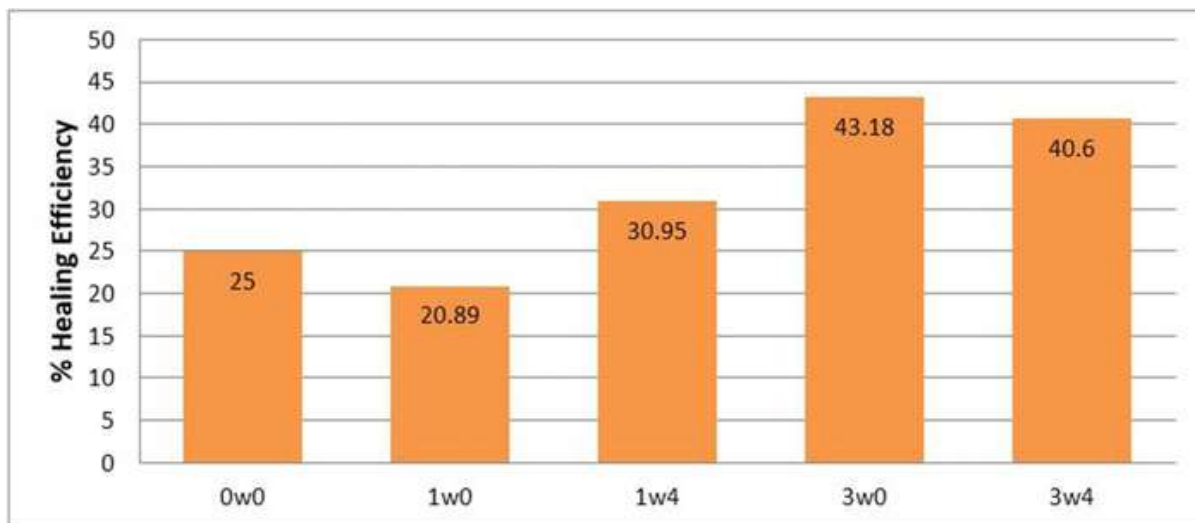


Figure 14. The healing efficiency after 3 days.

As it can be seen in Figure 14, adding a single SMA strip decreases the healing efficiency by 4.11% due to the porosity effect. This deficiency disappears by applying pre-straining and also increasing the number of strips by 10.06% (comparing 1w0 with 1w4) and 22.29% (comparing 3w0 with 1w0), respectively. The increased values mentioned are because of pre strain effect in 1w4 and higher ultimate flexural strength of strips in contrast to matrix which leads to achieve higher healing efficiency. This is mainly because of an increase in ultimate flexural strength of self-healing composite. The maximum healing efficiency of 43.18% after 3 days was achieved using specimen 3w0 which is due to an increase in ultimate flexural strength of healed specimen after 3 days and a decrease in ultimate flexural strength of damaged specimen. This is because of the presence of three strips in normal state. Results of 7 days healing period for specimens are shown in Figure 15.

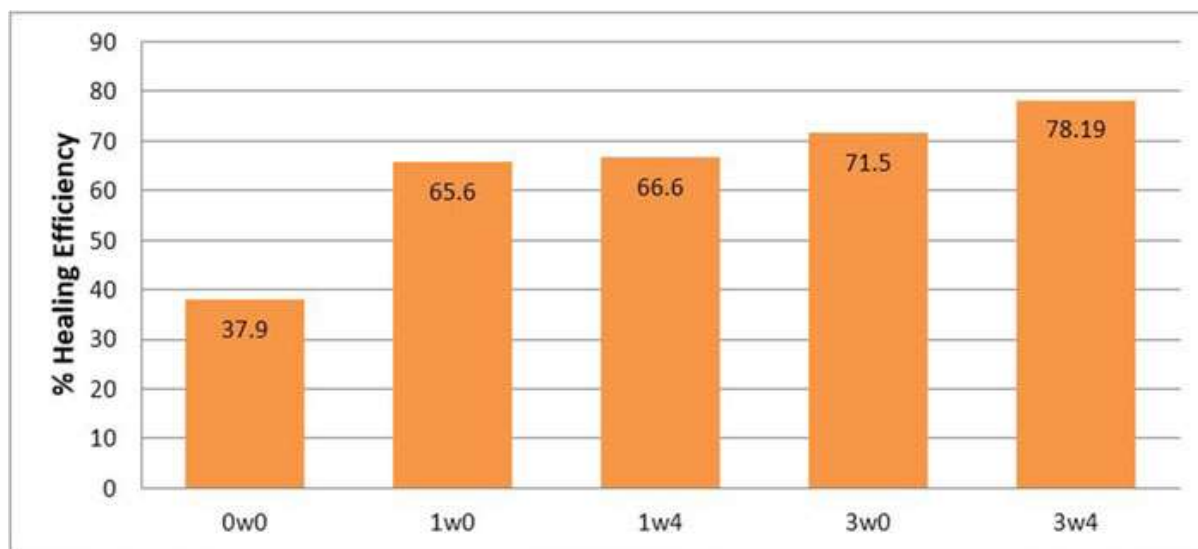


Figure 15. The healing efficiency after 7 days.

As it can be seen from Figure 15, adding a single SMA strip, pre-straining it, and increasing the number of strips to three and pre-straining them, exhibits an increasing trend after 7 days which is due to higher flexural strength of strip compared to other parts of the composite and pre-straining effect which applies a compressive stress to specimens. Also, increasing the number of strips causes a reduction in ultimate flexural strength of virgin specimens. Adding one strip causes a reduction by 98 MPa and similarly adding 3 strips decreases 61 MPa compared to the specimen without strip which is shown in Figure 13. Comparing Figures 14 and 15, shows the importance of healing time duration in self-healing specimens. For instance, the healing efficiency of the specimens with 3 strips without pre-straining effect shows a 28.32% increase after 7 days compared to similar specimen after 3 days.

The improvements in performance and also the healing efficiency of the specimens containing both SHGF and SMA could be due to the effects of crack closure which reduces the crack volume and the amount of healing agent required and also curing of the healing agent

during polymerization at the present of SMA strips, which improves the cross-linking of the healing agents. These effects are higher, by providing pre-straining to the SMA strips.

4. Conclusion

In this article, the flexural properties of self-healing smart composites reinforced by shape memory alloy strips are investigated experimentally using mechanical flexural tests. The approach taken here was to develop a healing system which can recover the baseline material properties after damage creation. In this work, in the presence of SMA strip, short hollow glass fibers were filled with two-part resin epoxy 828 and incorporated in the composite as a novel healing system for fiber reinforced composites. Composites were manufactured using hand lay-up technique. In order to investigate the healing effect, the composite was damaged and after three and seven days were tested and the healing efficiency was calculated with respect to time. By adding a single SMA strip, the final strength was reduced due to delamination and intra-laminar matrix cracking effect. Bonding condition between components of composites plays the vital role in ultimate flexural strength of the specimens. Adding SMA wires to matrix reduce the strength of composite. To fix this issue, the SMA wires are replaced with SMA strips with flat faces. To compensate this deficiency, increasing the number of SMA strips in which improved the amount of ultimate flexural strength due to the higher strength of strips in comparison to matrix and fibers of self-healing composite. Furthermore, applying pre-strain to SMA strips resulted in a significant improvement to ultimate flexural strength and maximum strain and the area under the stress–strain curves due to the ability of SMAs to apply compressive stress to the specimens after damage, which is due to the elastic behavior of SMA strips. A 78.19% healing efficiency has been achieved for specimen with three SMA strips and 4% pre-strain and after seven days compared to 37.9% healing efficiency for specimen with no

strip. The improvements in performance and also the healing efficiency of the specimens containing both SHGF and prestrained SMA are due to the effects of crack closure which reduces the crack volume and the amount of healing agent required and also curing of the healing agent during polymerization at the present of SMA strips.

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