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Experimental and Numerical Study of Smart Polymeric Composite Beam Embedded with Ni-Ti Shape Memory Alloy

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Abstract

Recent advances in materials engineering have given rise to a new class of materials known as active materials. These materials when used appropriately can aid in development of smart structural systems. This research presents the smart composite beam study in experimental and numerical by ANSYS V.15. In the present research, shape memory alloy NiTinol wire as fiber was used with a linear low density polyethylene (LLDPE) as host matrix. Nitinol wire high temperature is about 80°C±10°C full annealed, (2 mm) with a straight shape, black color, it consists of (Ni-55%, H-0.001%, O-0.05%, N-0.001%, C-0.05%, Ti-Balance). The model consists of four NiTinol wires, each one with 180 mm length and 2 mm diameter, the distance between them is about 10 mm. In the experiment, the model was subjected to a bending load with speed 500 mm/min and displacement 30 mm. After unloading, the composite backed upward (spring-back) by a displacement about 13 mm and stopped. But, the spring back in finite element modeling was about 12.5 mm, the error percentage between the experimental and finite elements results is about 3.8%. Recovery stress is sufficient to return the composite beam to the original shape and position. The factors play the important role in the recovery composite beam are recovery stress, rigidity of host matrix, interfacial bonded force, pre-strain and activation temperature. The temperatures distribution is same on the surface of smart composite beam model in the middle line in both cases, finite elements modeling and experimental work. The pre-strain 4% is enough to recover the composite model after activation. The chosen polymeric host is very significant, because through activation of NiTinol wire, the host material becomes flexible.

Keywords: Shape Memory Alloy, NiTinol Wire Smart Composite Beam, Finite Element, Activation, Recovery Stress.
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1. Introduction

Composite materials are used in aerospace and other industries. With high specific modulus, high specific strength, and the capability to be designed and fabricated with greater flexibility, composite materials have these advantages compared to traditional materials. However, it is well known that fiber-reinforced polymeric composites are vulnerable to transverse loads such as low-velocity impact, which can result in extensive delamination and multiple matrix cracking. Such internal damage can cause significant reduction of the load-carrying capacity of composite structures. Fiber reinforced polymer (FRP) composites have been widely used as load carrying members due to their light weight and versatility [1].

Shape memory alloy based smart structures are fabricated with reinforced composite materials, with SMA fibers being embedded either into the matrix material or as in a laminated fiber reinforced composite structure, as shown in figure (1). Changing the temperature beyond the point of phase transition, the shape and material characteristics of the SMA and hence the shape and global mechanical characteristics of the smart structure are changed too [2].

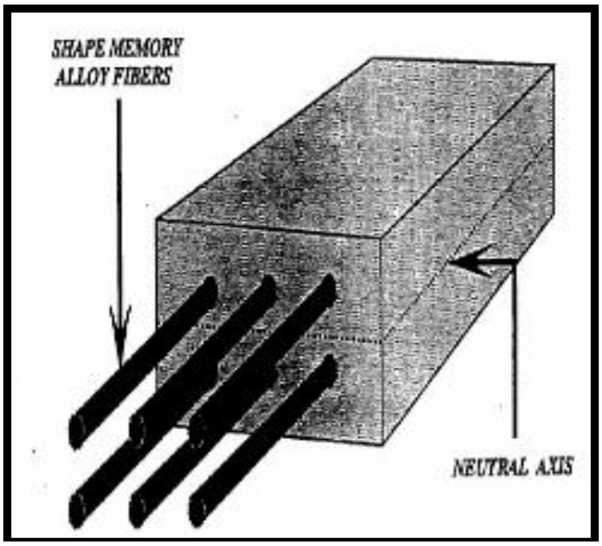


Figure (1): Shape memory alloy based smart structure [2]

D. Bollas et al. (2007) studied the stress generation in two cases, the first case when the NiTinol wire is 3% pre-strained and the second case is without pre-strained. They used composite materials consisting of epoxy resin as matrix embedded with NiTinol wire (0.15 mm diameter) and (29) Kevlar fiber. The results showed that the NiTinol wire with pre-strained 3% achieved stresses up to 450 MPa, while the NiTinol wire without pre-strained achieved stresses about 350 MPa [3].

Wambura Mwiryenyi Mwita (2010) studied the effect of embedded NiTinol wire (1 mm diameter) into polyurethane matrix in a silicon mold, pre-strain technique was employed to stretch the wire by 3%. Pull-out test and four-point bending test were performed. Increasing in flexural stiffness (EI) and fracture stress intensity factor (K_{IC}) of the composites plate was deduced. It shown that the deboned force decreased when activating SMA [4].

L. Horny et al. (2011) investigated the effect of NiTinol wire (0.1 mm diameter) embedded into silicon rubber matrix on the inflation-extension behavior of NiTi-elastomer composite tube. They used a stent containing (36) wires with wound angle (±58°) to create a composite tube. NiTinol wires were tested within simultaneous inflation and extension. It was proved that the viscoelasticity of elastomer (silicon rubber) reduced by NiTinol wire reinforcement [5].

H. N. Bhargaw, et al. (2013) investigated NiTinol wier (0.508 mm diameter) when activated above the transformation temperature (finish temperature) to use as actuator. Different parameters were studied and their relationship for example, recoverable strain, temperature hysteresis and electrical resistance difference under different stress levels. It was found that the NiTinol wire was heated (activated) in a current value about 680 mA for 796 secs under natural air convection. Strain recovered is 4.33% and the corresponding change in resistance is 11.2% at 43 MPa of stress [6].

The ability of these materials (shape memory alloys) (SMAs) to generate large recovery stresses when thermally activated has been recently used for the development of functional structures or composites, in which SMA elements are embedded in a polymeric matrix [7, 8].

In the present research used shape memory alloy NiTinol wire as fiber was used with a linear low density polyethylene (LLDPE) as host matrix. The goal of this study is retuned the deformational composite model after activation NiTinol wires.

2. Experimental Work

The experimental work is divided into two parts, the first part is manufacture the injection mold for the composite model, and the second part is preparing NiTinol wire to injection. The testing is classified into two types, the first test is bending test, and the second test is infra-red (IR) test.

2.1 The Used Materials

In this work, a linear low density polyethylene (LLDPE) host material with a density about (0.92-0.93) gm/cm^3 was used [9]. Melting temperature of the host material is about 122.7^0C, which was obtained by DSC test.
Plastic in form of grains was obtained from the Sabic Company in Saudi Arabia; this plastic is illustrated in figure (2).

Figure (2): Linear low density polyethylene used in the present work.

In this research, a high temperature about 80°C±10°C NiTinol wire, a full annealed, (2 mm), with a straight shape, as shown in figure (3).

The main purpose of using the NiTinol wire in composite is to carry the load applied to composite, while the matrix holds and protects the wire, thus distributing the load between them [10]. In this work, the main purposes of NiTinol wire are to reinforce the polymer, shape memory control of host material, and self-heating by current to reach the activation situation. The general properties of NiTinol wire are shown in table (1): [11]

Table 1, Mechanical properties of NiTinol wire.

Property	Value
Color	Black
Primary Fiber Direction	(Unidirectional)
Density (Kg/m^3)	6450
Thermal expansion coefficient ($10^{-6} K^{-1}$)	6.6-11
Resistivity (μΩ cm)	80-100
Thermal conductivity ($W\ m^{-1} K^{-1}$)	10-18
Melting temperature (K)	1573
Heat capacity ($J\ kg^{-1} K^{-1}$)	390
Young modulus (austenite) (GPa)	60000
Young modulus (martensite) (GPa)	20000
Austenite finish temperature(A_f) (K)	343

Figure (3): NiTinol wire Coil used in the present work.

2.2 Design and Manufacture of an Injection Mold

The injection mold was designed by Auto CAD software. The mold consists of three parts, upper, middle and lower part. The middle part called cavity part consisting of eight holes and every side has four holes with a distance of 10 mm among them, these holes were produced to pass the NiTinol wire through them. In addition to holes, external side grips exist and used to install the NiTionl wires to prevent their longitudinal movement. Dimensions of cavity are 180 mm length, 40 mm width and 5 mm thickness. The lower part was used to cool the sample model in cavity after the injection process. All parts are made from steel except the lower part is made from aluminum, to speed up the cooling process. The mold design by Auto CAD and the manufactured injection mold are shown in figures (4) and (5), respectively.

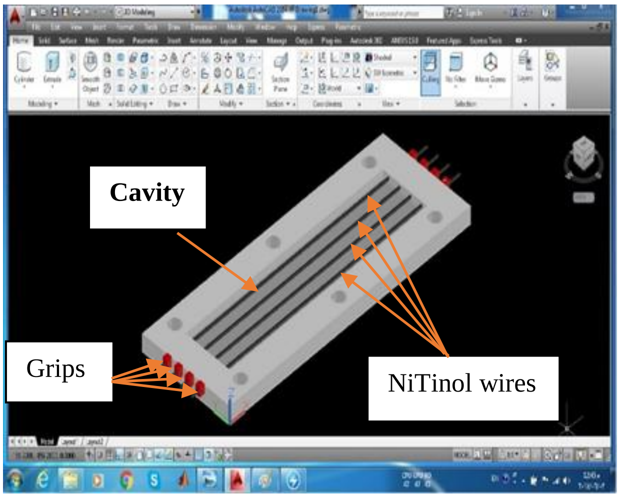


Figure (4): NiTinol wires held in the cavity of mold with grips.

Figure (5): The manufactured injection mold.

3. Smart Composite Beam Model

The model consists of matrix (LLDPE) and embedded unidirectional fiber presented by NiTinol wire having previously mentioned properties. If the matrix embedded with any fiber except shape memory alloys, it is called a conventional composite material, but when embedded with shape memory alloy into matrix (host), it is called a smart composite material, due to shape memory alloys (SAMs) that have unique property; when activated, they return to the original shape.

The host composite must withstand temperatures above the activation temperature of the (SMA) without changing its structural properties, so typically the Tg of the composite polymer must be well above the (As) temperature of the (SMA) wires [12]. Choosing the host is very substantial and should be flexible so that the recovery stress of NiTinol wires after the activation be enough to return the matrix material to the original shape or its position. The model as shown in figure (6) consists of four unidirectional NiTinol wires with 180 mm length and 2 mm diameter, the distance among them is 10 mm and the volume fraction value is 6.28% according to eq. (3.1) [13].

$$V_f = \frac{V_{fiber}}{V_{composite}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

Where;

V_f – Fiber volume fraction

V_{fiber}, $V_{composite}$ –Fiber and composite volume (m^3), respectively.

Figure (6): Smart composite model.

Before injection, model should stretch all NiTinol wires 4% (pre-strain) from length, this step was achieved by a universal tensile machine type (WDW-200E). The Nitinol wires were pre-strained by 4% using Instron

4204 machine [1]. The embedded pre-strained SMA fibers used to strengthen the matrix can absorb the impact strain energy, thereby improving the creep or crack resistance of the material [14].

Pre-straining of the Ni-Ti SMA wires was aimed to induce detwinned martensitic volume fraction in them, hence increasing the transformation strain and recovery force of the Ni-Ti SMA actuator [15, 16]. The aim of this part is the verification of the composite material to become a smart composite material in other words, the composite beam model returns to the original shape after deformation by bending test. The shape of composite beam is controlled by sets of wires of shape memory Nickel-Titanium alloy (NiTinol).

Before starting the bending test, the model was prepared to this test. At the bending, a series of NiTinol wires was connected by a connecter, the goal from this connected wires is to prevent the wires from shrinking after activation. In this test, three test cycles were applied, the first cycle subjected the model to a bending load with speed 500 mm/min until the maximum displacement becomes 30 mm, and after unloading the spring back value was about 13 mm. The second cycle displacement was 20 mm, and the third cycle was 10 mm. The bending test was done by a universal tensile machine type (LARYEE), as shown in figure (7).

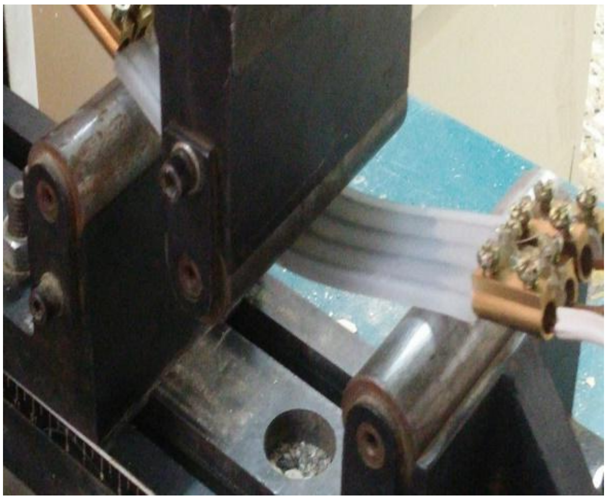


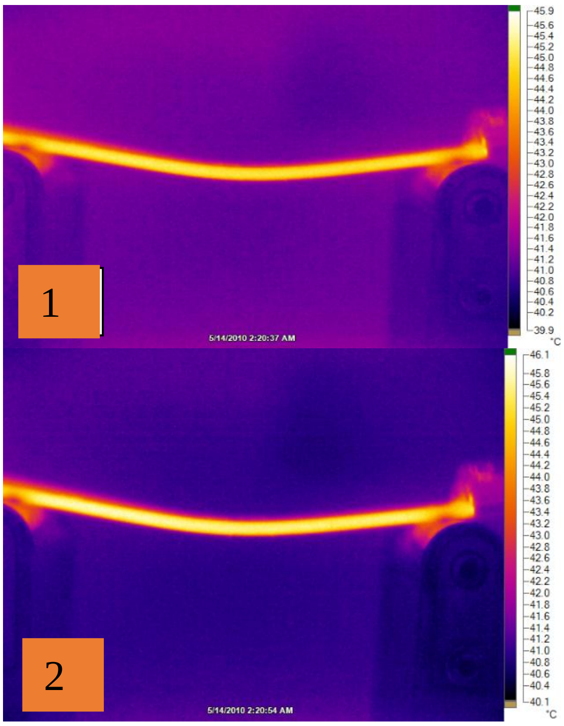
Figure (7): Smart composite beam during first cycle.

After first cycle, a DC current about 8 amperes was applied by a power supply, the aim of this current is to activate the NiTinol wire, the time of activation was about 12 min so as the composite beam returns to the original shape. The second cycle activation time was about 10 min, and in the last cycle, the composite beam returned to the original shape at time about 5 min. All these tests were performed in laboratory where the environment temperature was about 30℃, the springe back for first, second and third cycle was 12 mm, 10 mm and 5 mm, respectively.

All tests were photographed by the infra-red camera type FLUKE Ti32, as shown in figure (8).

Figure (8): Infra-Red camera type FLUKE Ti32.

All infra-red images were saved in memory of the camera, and after finishing test take all taken images were saved in a computer. The stages of composite beam changing from the deformation case to the levelling case are shown in figure (9).



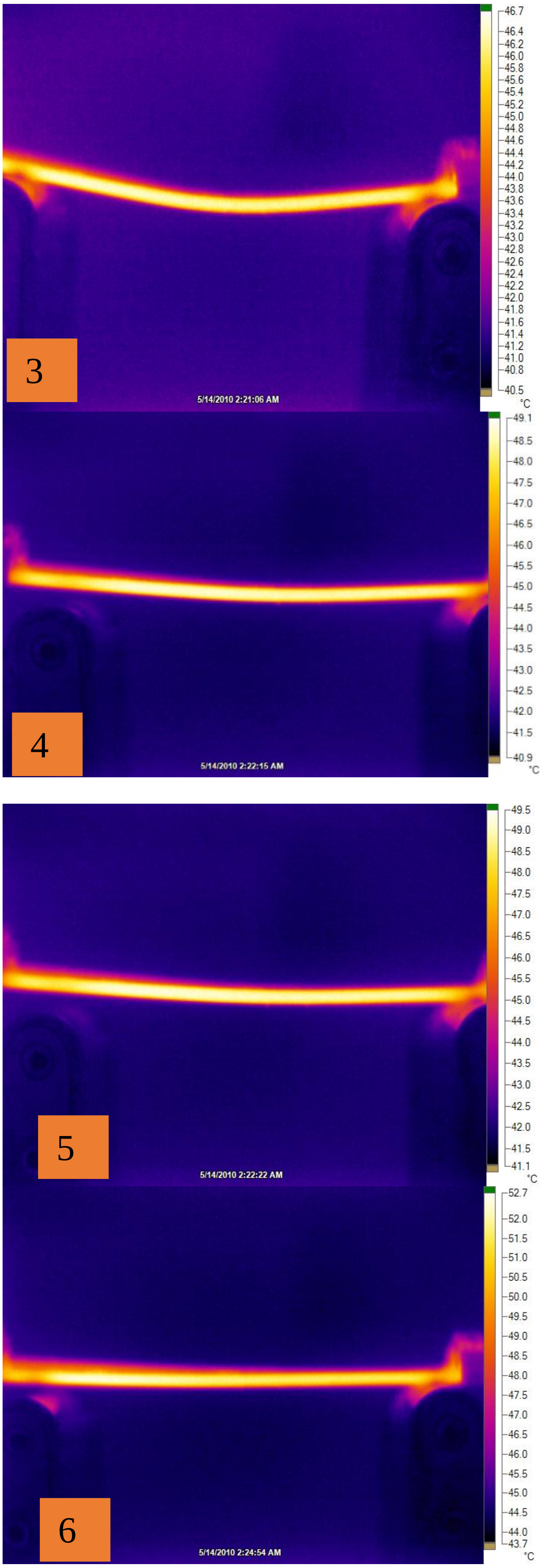


Figure (9): Photo of shape smart composite beam changing stages.

For the smart composite beam after activation NiTinol wires, the heat transferred through the matrix (host material) made the LLDPE more flexible. The smart composite beam in finish activation is shown in figures (10).

Figure (10): Experimentally distribution of temperatures on the smart composite surface beam.

The experimental temperatures distribution on the surface of smart composite beam model in the middle line in is shown in figure (11).

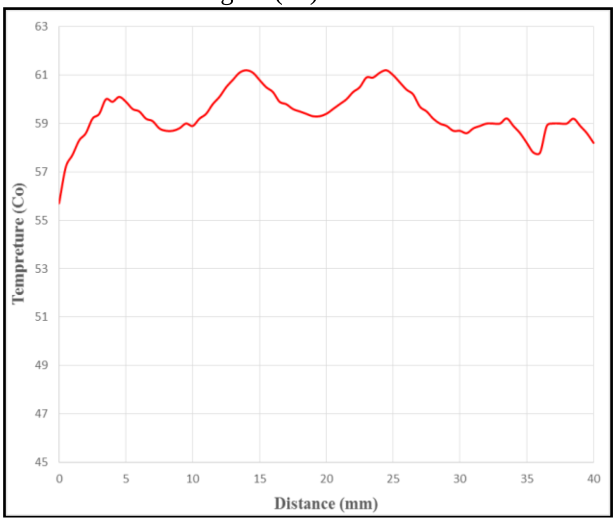


Figure (11): Experimental temperatures distribution in the middle line of smart composite beam.

3.1 FE Modeling of Composite Material Model before Activation

Modeling of 3D nonlinear analysis was by finite element in the ANSYS V.15. The model consists of four NiTinol wires, length 180 mm and 2 mm diameter, embedded into host polymer (LLDPE). The distance between every wire is about 10 mm. In this part, finite element modeling of composite model was used by undergoing load displacement about 30 mm by downward motion punch. The goal of this part is to find the spring back of model after removing the load. All procedure steps are listed below:

A) Preprocessor steps:

1- The 3D model is created by a block model having dimensions (L=180 mm, W=40 mm), but the thickness of model is (5 mm), the punch and two supports are also created.

2- Model consists of two materials, two commands are applied in ANSYS, overlap and glued, and all mechanical properties are written.

3-The mesh element of the model is (solid185 3D 8-NODE structural) used for NiTinol wire and polymer (LLDPE), as shown in figure (12).

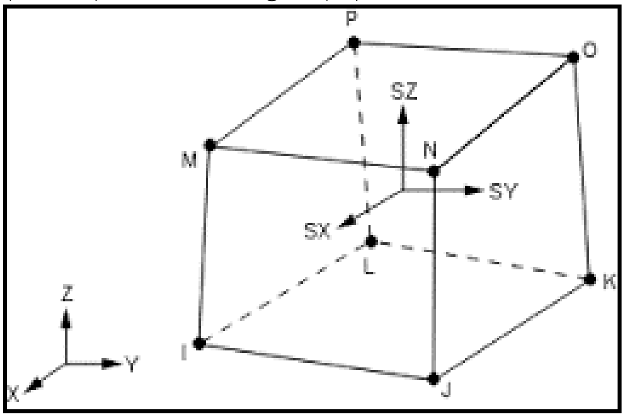


Figure (12): 3D structure solid elements of type solid 185 [19].

SOLID185 is used for 3D modeling of solid structures. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities [17]. The model consisted of 184255 hexahedral elements and 737120 nodes. The meshing type to mesh all the model is shown in Figure (13).

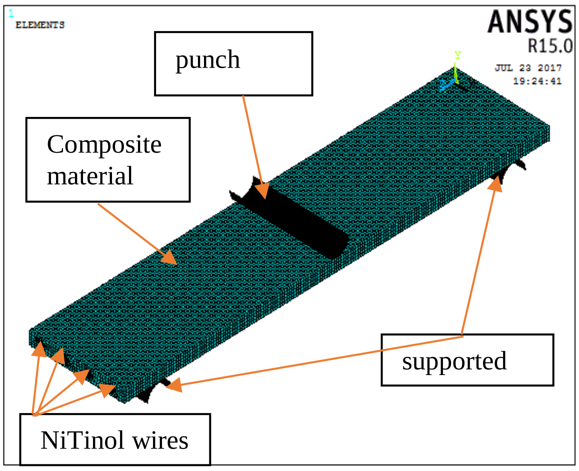


Figure (13): Finite element 3D model of smart composite material

4- In this step, the contact procedure was employed. Contact is performed between the punch and the area below it, and contact between the two supports with the area above them.

B) Solution:

1- The type of solution is transient nonlinear by large displacement.

2- The type of load is displacement applied by punch, the value of displacement is 30. The speed of punch is 500 mm/min.

3- After performing the loading steps, the results of displacement distribution are shown on all model, and the spring-back shape is displayed.

C) Postprocessor:

In this step, the contour of displacement is depicted along the model with the spring-back of composite model, the end displacement and spring back are shown in figures (14) and (15), respectively.

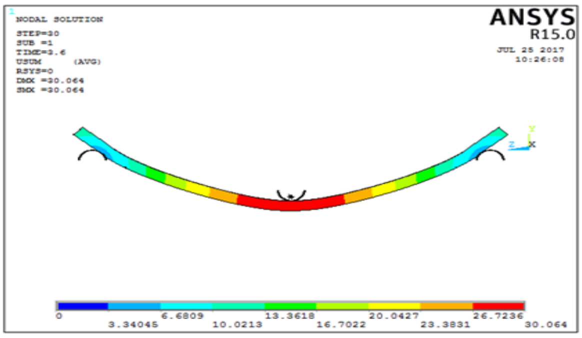


Figure (14): Total displacement of smart composite model.

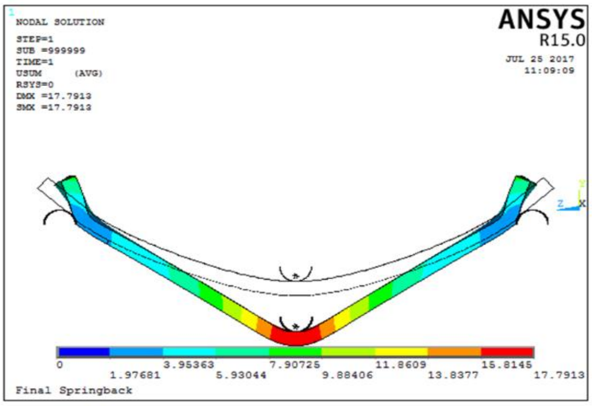


Figure (15): Displacement of smart composite model with spring-back

3.2 FE Modeling of Composite Material Model after Activation

The goal of this analysis is to return the model to zero position after spring-back position, in other words, it returns to the original shape when the shape memory is activated.

A) Preprocessor steps:

1- The 3D is created by the dimensions mentioned in section 3.1, creating block model having dimensions (L=180 mm, W=40 mm), but the thickness of model is (5 mm), the punch and two supports are shown in figure (16).

2. The model element type is a hexahedral element, the meshing type to mesh all the model is shown in figure (17).

B) Solution:

1- The type of solution is transient nonlinear by large displacement.

2- The type of load is coupled field, thermal and structural loads, the first load is the displacement applied by punch, the value of displacement is 30 mm, and second load is thermal loads (temperature and convection). The speed of punch is 500 mm/min.

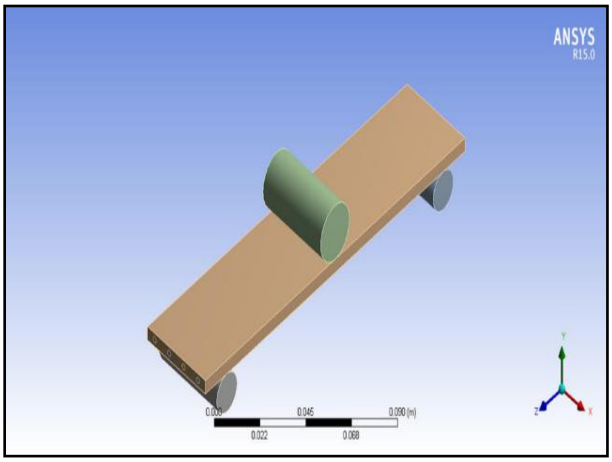


Figure (16): 3D composite material model

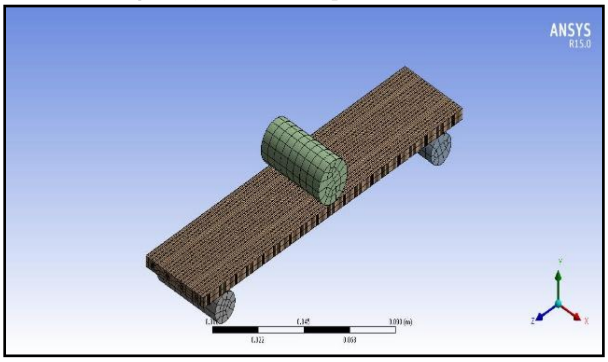


Figure (17): Meshing of composite material model

The experimental and finite element modeling results for smart composite beam showed that after the activation sets of NiTinol wire, the composite beam returned to its original shape and position. The mechanism of composite beam from the primary position and shape passed in four stages, the first stage is the zero position and unreformed shape, this stage prior subjected to load. The second stage is when subjected to bending load and deformation of composite beam, and the third stage is when removing the load and occurrence of the spring-back. The fourth stage is when activation NiTinol wires, the wires tried to return to original shape because the shape memory alloy memorized its shape after the activation.

The temperatures distribution on the surface of smart composite beam model in the middle line in finite element modeling is shown in figures (18). The original shape of composite smart model is shown in figure (19).

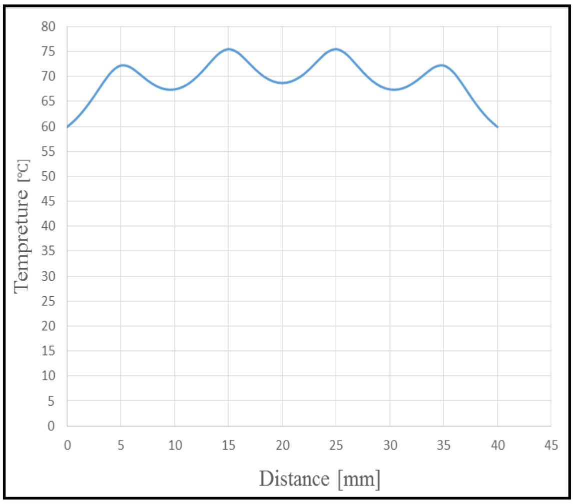


Figure (18): Temperatures distribution in the middle line of smart composite beam modeling in ANSYS

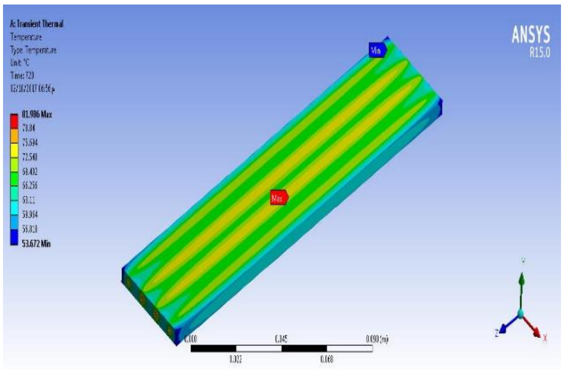


Figure (19): Smart composite model in finish position.

4. Results and Discussions

The model consists of four NiTinol wires, each one with 180 mm a length and 2 mm diameter, the distance between them is about 10 mm. In the experimental, the model was subjected to a bending load with speed 500 mm/min and displacement 30 mm. After unloading, the composite backed upward (spring-back) by a displacement about 13 mm and stopped.

But, the spring-back in finite element modeling was about 12.5 mm as shown in figure (15), and are the error percentage between the experimental and finite element results is about 3.8%.

Recovery stress is sufficient to return the composite beam to the original shape and position. The factors play the important role in the recovery composite beam are recovery stress, rigidity of host matrix, interfacial bonded force, pre-strain and activation temperature. A strong interfacial bond also increases the structural integrity of the final composite [14].

The temperatures distribution close up on the surface of smart composite beam model in the middle line in case finite element modeling and experimental.

5. Conclusion

1. NiTinol wire has a good response to the activation temperature.
2. The composite model is fully returned to the original shape after activation.
3. The pre-strain 4% is enough to recover the composite model after activation.
4. The chosen polymeric host is very significant, because through activation of NiTinol wire, the host material becomes flexible.
5. After deformation of composite material, the NiTinol wire has enough recovery stress to return the composite material to the original shape.

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