New Methodology for Prestressing Fiber Composites

Abdul Kareem F. Hassan[1,*], Osama A. Abdullah[2]

[1]Mechanical Engineering Department, College of Engineering, Basra University, Iraq
[2]Marine College, Arabian Gulf Academy for Maritime Studies, Iraq

Abstract The development of composite materials is characterized by the improvement of their mechanical properties (stiffness and strength) which have widened their application for structural fields like automobile, aerospace, and naval industries. The mechanical properties of composite materials can be upgraded during the manufacturing process by applying an appropriate load on the fibers and curing the corresponding matrix at certain temperature. For that purpose a machine was designed and built to exert load and heat on a composite of carbon fiber mat or glass fiber mat and matrix. The result is a rig agreed with horizontal tensiometer that can be called a prestress machine. This machine holds a certain tension on the fibers while the matrix is being cured. The main parts of the prestress machine are the mold, pulling crosshead, oven and sensors. This paper presents the steps of constructing and using this machine. Experimental investigations were carried out to determine the complete set of stiffness characteristics E_{ij}, G_{ij}, ν_{ij} and strength characteristics $\sigma_{i,n}$, $\varepsilon_{i,n}$. The outcome results show that this machine can produce prestressed composite materials with much better mechanical properties comparing to those properties of the non-prestressed composite materials.

Keywords Prestress, Composite Material, Mechanical Properties, Electric Jack

1. Introduction

The use of composite materials is advantageous due to the cost saving and weight reduction. A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone [1]. Composites that containing fibers such carbon and glass fibers contain high strength-to-weight and stiffness-to-weight ratios, they are thermally and electrically conductive and exhibit fatigue resistance, these fibers made by woven unidirectional, plain weaving or twill weaving style which can be cut accordance with ASTM standards or ISO equivalents in order to cover the determination of mechanical properties test methods.

This machine built for matrix composite materials reinforced by high-modulus fibers, the composite material forms are limited to continuous fiber-reinforced composites in which the laminate is balanced and symmetric with respect to the test direction. Samples for ASTM standard test methods like D 3039, D 790 and D 7136 were made by this machine, these samples were cut to the required test specimens in the standard tests, such type of specimens have suitable geometry design for the machine's mold spacing which was limited by 260×200×8 mm.

2. Materials

There are many different kinds of fibers that can be used to reinforce polymer matrix composites and then prestressed to hold residual stresses. The most common are carbon fibers and glass fiber. Carbon fibers are conductive, have an excellent combination of high modulus and high tensile strength and offer good resistance to high temperatures. There are five categories of carbon fibers generally used in composites and they are; low modulus (tensile modulus of less than 210 GPa), standard modulus, intermediate modulus, high modulus and ultrahigh modulus (tensile modulus of greater than 500 GPa), while steel has a tensile modulus of 200 GPa [2]. While carbon fibers and fiberglass are the most common reinforcements in composites, there are other options that offer beneficial properties like toughness, compressive strength, light/difficulty machining, brittleness, insulating, or high-temperature properties. Such fibers are; Aramid fibers, Boron fibers and Ceramic fibers [3].

The most common matrix are known as polyester, epoxy, vinyl ester, phenolic, polyimide, polyamide, polypropylene, and others. Fiber volume fraction variations in the range of approximately 0.40 – 0.70 and various methods have been developed to reduce the resin content of the composites. The characteristics of manufacturing quality of the composites can be controlled during several processing including; curing, fiber/matrix distribution, fiber volume fraction, fiber orientation, porosity and fiber waviness [4]. In this study, epoxy resin was mixed with 0.5 volume fraction of continues unidirectional fabric carbon fibers to produce the required

composite laminates. A low temperature furnace was used to obtain an optimum curing cycles for this mixture under different fiber prestressed levels.

3. Fiber Prestress Methods

Prestressing fiber composites requires a certain rig to apply a predetermined prestress during curing process. The following methodologies are reported for the asymptotic design:

a. Dead-weight method [5, 6]. Prestressed composites can be prepared by applying a suitable load to the fiber ends at room temperature curing process. Upon applying this methodology is difficult to obtain a uniform fiber distribution through the width of the composite.

b. V-slot mechanical fastening method [6, 7]; An aluminium plates with two V- slots machined at the ends, The composite is cured in a hot-press at 125°C during prestressing . The pre-strain was achieved by pushing the fibers toward the V-slot and by the thermal expansion of the aluminum plate. This method can be used to apply only one prestress level. Also Brittle fibers like glass and carbon cannot be prestressed using this technique because the kinking of fibers in the V-slots will result in numerous fiber fractures leading to an uneven stress distribution.

c. Filament winding [8, 9, 10]; Filament winding is a fabrication technique mainly used for manufacturing open or closed end cylinders. The process is under tension over a rotating mandrel. The most common filaments are glass or carbon and are impregnated in a bath with resin, once the mandrel is completely covered to the desired thickness, the resin is cured. In this method it is difficult to determine the prestress released to the composite and the fiber volume fraction is large and constant.

d. Hydraulic cylinder prestress rig [11]; Different levels of prestress can be made on composites using hydraulic cylinder which drags the movable loading rod of the laminate on a horizontal frame. Heated platens of hot press are used to cure the resin. It was found that slippage occurred between the ply and loading rod surface at high fiber prestr jmkess levels.

e. e. Horizontal tensile testing machine [12]; Fiber prestress could be achieved by using a horizontal tensile testing machine. The electric motor provides the mechanical energy and rotates a drum, which pulls the fibers in one direction. The load applied could be monitored by a load cell. A U-shaped mold was used to prepare composites. However, this method restricts itself to room temperature.

f. f. Flat-bed prestress methodology [7]: It is a basic principle of using a load screw to apply the prestress. Two blocks are used; of which one is fixed to a base plate and the other is movable, the moving block slides on guide bars. These guide bars are used to align the clamps of the moving and fixed blocks. Prestressed composites were manufactured by laying up a unidirectional prepreg laminate, and pre-curing the ends with aluminum tabs attached. But this design used locking bolts to lock the movement of the moving block by clamping it to the base plate after loading, i.e. the load and extension at curing and after loading cannot be quantified, which it might be a source of calculating the residual stresses. Also Krishnamurthy [7] applied only 100 MPa as a maximum prestress to the fibers.

4. Design the Prestress Method

In order to apply and hold the tension on the fibers while the matrix is being curing, there was need to design a horizontal tensiometer machine with furnace for the composite laminates, in order to apply preloading on the fibers under different temperatures.

This machine is designed to create changes in the fiber composites mechanical properties by absorbing residual stresses during prestressing and curing processes. The residual stresses are then to be quantified experimentally based on an understanding of the situation of the sensors at the final extension and applied load. The determined residual stress will be used to explain the changes in the mechanical properties of the composites.

In the next section a new approach to prestressing the fibers using an electric methodology is presented. This method is evaluated to conclude all the above design criteria mentioned in section 3.

4.1 Electric- jack Prestress Rig (EJPR)

In this work, an Electric-jack Prestress Rig (EJPR) was designed and constructed. The basic principle is to use a dc electric jack to apply prestress in horizontal rig which is supplied also with an electric oven for curing.

As shown in (Figure 1), this machine consists of three main parts; prestress assembly, pulling-jack and low temperature furnace. Each part consists of several pieces and the whole parts are mounted on structural frame.
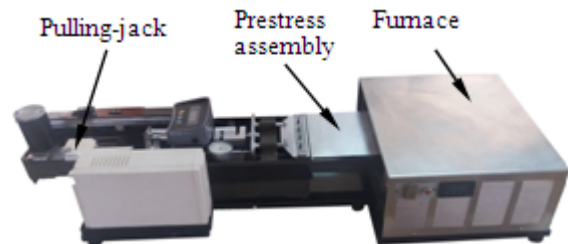

Figure 1. Photograph of manufactured Electric- jack prestress rig.

4.1.1. Prestress Assembly

As shown in (Figure 2), the prestress assembly consists of

260×200×4 mm steel plate (No.1), which is used as a mold to manufacture the composite materials. Aluminum plate was examined in this part, but considering a temperature more than 100C° inside the oven, deformations occurred as a result of deferent thermal expansion coefficient (α). Hence, a mold of steel was used in this assembly because aluminum has about twice the value of α for steel.

One end of the fiber laminates is to be fixed by a base plate (No.2) in (Figure 2) by using four M6 bolts (No.3) which carry the applied preload, and the another end of the fiber laminates is to be clamped with the moving assembly (No.4). For accuracy, this adverse end of the fiber laminates will be mounted with a fastening plate to the moving assembly (No. 5) using four M6 studs with nuts (No.6).

These assembly moves on two guide bars (No.7) as in (Figure 2) by mean of a cross head (No.11). The guide bars

are used to align the moving parts, which are connected to a load cell (No.8). Load gauges (No.9) and dial gauge (No.10) were mounted to display the generated load and extension on the fibers respectively.

The moving assembly was designed to have a maximum free movement of 14 mm, and the load cell can hold maximum load of 500 kgf (4903 N) which can be exhibited on the digital gauge (No.9). The steel plate with the dimensions 260mm length, 200mm width and 4mm thickness was used to produce molded thin flat strip of composite materials. Common continuous carbon fiber and glass fiber composites under the required conditions mainly was used in this rig to produce samples for tensile, flexural and impact tests in order to achieve an experimental study on the mechanical properties of pre-stressed composites.
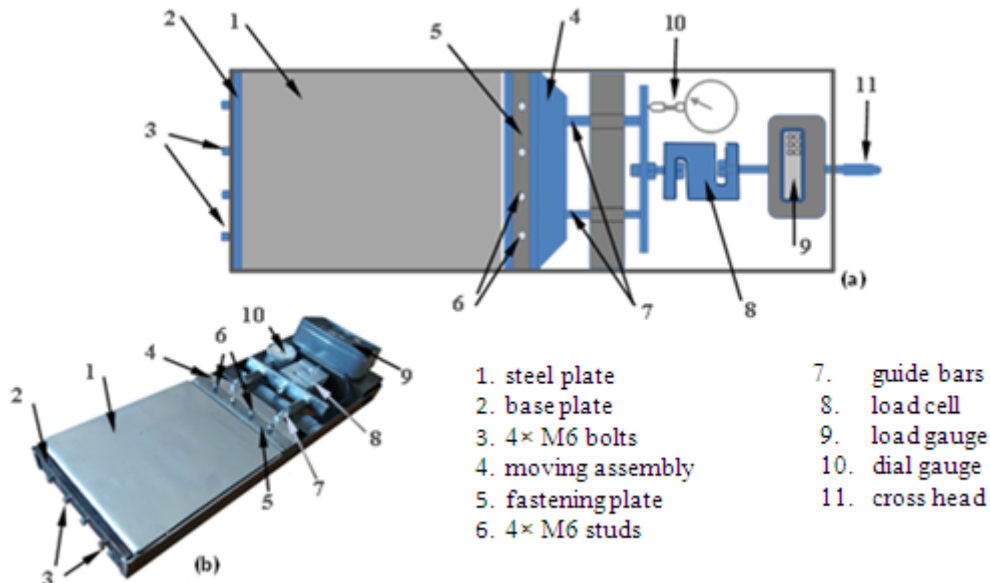

1. steel plate
2. base plate
3. 4× M6 bolts
4. moving assembly
5. fastening plate
6. 4× M6 studs
7. guide bars
8. load cell
9. load gauge
10. dial gauge
11. cross head

Figure 2. (a) Schematic drawing of the Prestress Assembly, (b) Photograph of manufactured prestress assembly.
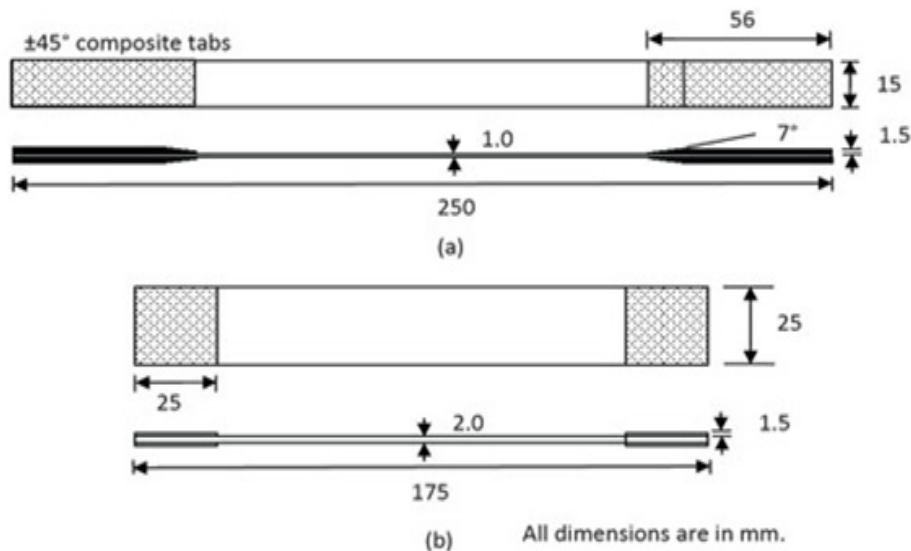

All dimensions are in mm.

Figure 3. Composite tensile test specimens (a) ASTM D 3039 for 0 °and (b) ASTM D 3039 for 90°.

ASTM standards were strictly implemented to define the requirements for specimen shape, dimensions, and tolerances, e.g. a strip of dimensions 260mm×80mm×1mm was adequate to make five tensile test specimens ASTM D3039 for 0° (Figure 3-a) and strip of dimensions 180mm×130mm×2mm to make five tensile test specimens ASTM D 3039 for 90° (Figure 3-b). For flexural properties, the prestress assembly was suitable to produce molded shapes for ASTM D 790 standard specimens, though a strip of dimensions 135mm ×130mm ×3.2mm was proper to cut five desired finished dimensions, see (Figure 4). And for impact test, this machine was used to produce molded shapes with the dimensions 150mm×100mm×5mm for ASTM D 7136 standard specimens for measuring the damage resistance of a fiber-reinforced matrix composite (Figure 5).
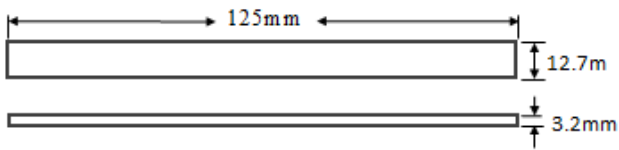

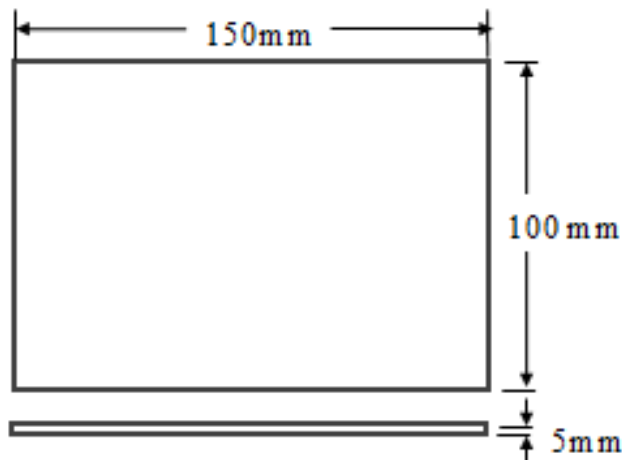**Figure 4.**   ASTM D 790 Specimen for 3-point bending test.

Figure 5.   ASTM D 7136 Specimen for Impact test

4.1.2 Electric Pulling-jack

12v dc electric jack operator was used in the electric- jack prestress rig (EJPR) to apply the necessary tensile force for generating the required prestressed settings. It has been chosen to create maximum load of 1.1kN. Electric jacks require less effort for operation, therefor this pulling jack has small electric motor of 0.6W which powered by 12 dc volt electricity supplied directly from a rechargeable battery. The electric motor transmits this power via worm gear to a piston which pinned to a second class lever to make use of the ideal mechanical advantage of a lever as the length of the effort arm divided by the length of the resistance arm see (Figure 6). The ratio between the effort arm and resistance arm selected as 4, i.e. since there is little loss, this jack can produce 4.46kN which is almost agreeing to the capacity of the load cell (5kN) as illustrated below:

For torque equilibrium:

$$F_r/F_e = L_e/L_r \qquad (1)$$

Where F_r is the resistance force, F_e is the effort force, L_e is the length of effort arm and L_r is the length of resistance arm.

It was found that the worm gear feeds the jacks piston by 0.05m in 93sec, and if the maximum power is 0.2W, therefore:

$$V_e = 0.05m/ 93s = 5.376 \times 10^{-4} \text{ m/s} = 32 \text{ mm/min} \qquad (2)$$

$$F_e = W_e / d_e = (P_e \times t)/ d_e = (0.6 \times 93)/ 0.05 = 1116 \text{ N} \qquad (3)$$

Where W_e is the jack work, P_e is the jack power, d_e is the displacement of the piston in 93second (t).
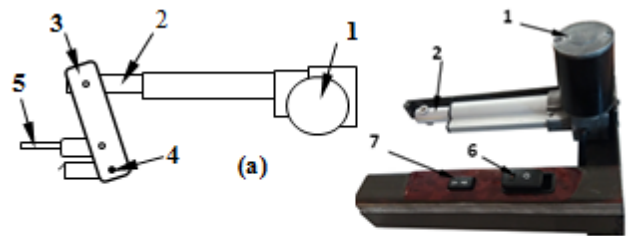
From eq. (1) and for $L_e = 0.1m$ and $L_r = 0.025m$:

$$F_r = (L_e/L_r)F_e$$

or $\qquad F_r = (0.1 / 0.025) \times 1116 = 4464 \text{ N} \qquad (4)$

This is the maximum force that can be transmitted to the cross-head. It can be noted that all the prestress processing carried out at a cross-head speed of:

$$Vr = 32 / 4 = 8 \text{ mm/min} \qquad (5)$$

1. 12v dc motor
2. jack piston
3. Lever
4. pivot
5. cross head
6. power push button
7. up-down push button

Figure 6. (a) Schematic drawing of the pulling jack, (b) Photograph of constructed pulling jack.
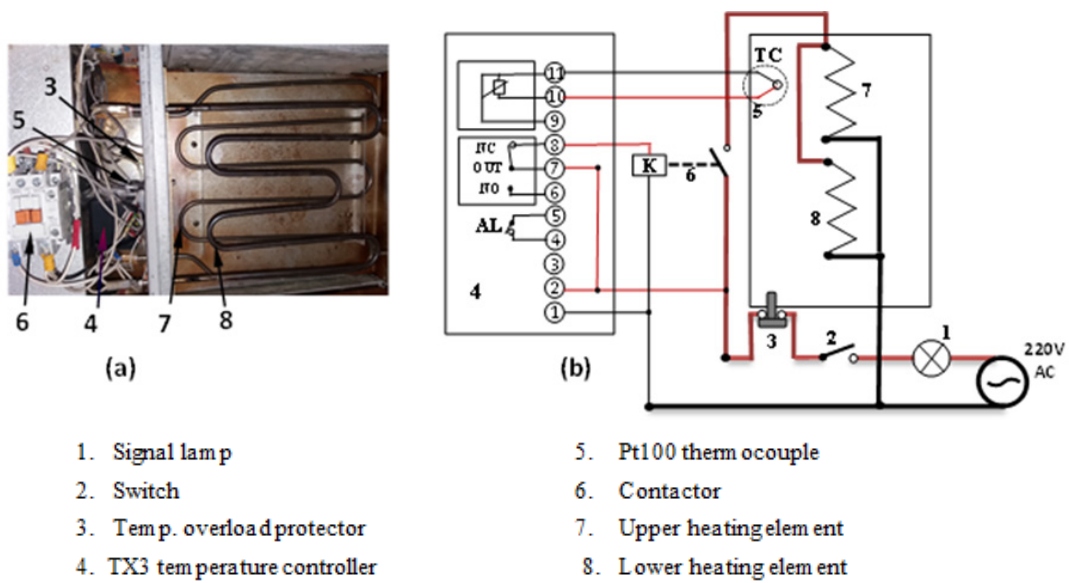
1. Signal lamp
2. Switch
3. Temp. overload protector
4. TX3 temperature controller
5. Pt100 thermocouple
6. Contactor
7. Upper heating element
8. Lower heating element

Figure 7. (a) Photograph of low temp. furnace, (b) Its wiring diagram.

4.1.3. Low temperature furnace

It is found that warming up the resin helps with better mixing of the resin components and also with better wetting of fibers. The mixed resin could be applied directly on the fibers in each experiment, then the sample is inserted inside a furnace. As shown in (Figure 7), a specially designed furnace is used in EJPR to verify the best samples curing, while the fibers have to be tensioned continuously during curing process.

The temperature inside the furnace volume could be displayed and controlled by temperature controller connected to a thermocouple as shown in (Figure 7). Because of dealing with low temperature (not more than 200°C), glass wool was selected as an insulating material for furnace walls. It is synthetic vitreous fiber insulation wool made by melting sand and other inorganic materials, and then physically forming the melt into fires [13].

The oven door is to be installed on the end of the mold and when the prestress assembly is inserted into the oven volume by means of sliding rules, the door which is provided with seal gasket will close the oven entrance to prevent the heat loss from the oven.

At the end of curing process, the oven will be turned off and the laminate will cooled be down to ambient temperature. Normalizing usually took about two hours, then the prestress assembly with the cured laminate drawn out the oven to remove the preloading very slowly. The manufactured laminate samples would be cut and grinded to the required specimens. (Figure 8) shows a photo for some specimens were made by EJPR.
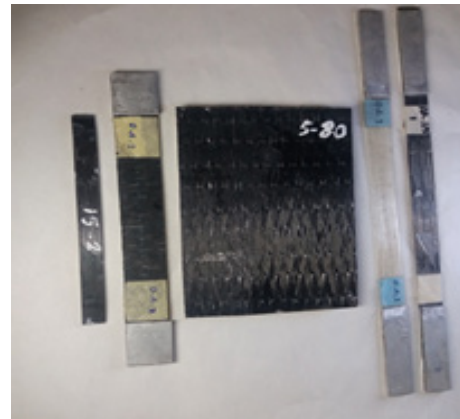

Figure 8. Photograph of standard tests specimens made by EJPR

5. Stress Analysis

Composite materials in the electric jack prestress rig (EJPR) could be subject to three independent loading conditions: preloading the fibers, thermal expansion and resin shrinkage which can be classified also to mechanical and thermal loading.

5.1. Preloading the Fiber

Electrical pulling-jack applied an axial tensile load via a second class lever as a simple mechanical loading condition as shown in (Figure 6-a). This axial load is perpendicular to the fibers cross section areas as illustrated in (Figure 9), which can be considered as a uniaxial normal stress (σ_1).

Such laminate can be treated as orthotropic materials and when loaded in uniaxial tension along of its principal material axes (1) undergoes deformations similar to those of an isotropic material and given by [14]:

$$\varepsilon_{1=\frac{\sigma_1}{E_1}} \ , \ \ \varepsilon_{2=\frac{\nu_{12}\,\sigma_1}{E_1}} \ , \ \ \gamma_{12} = 0 \tag{6}$$
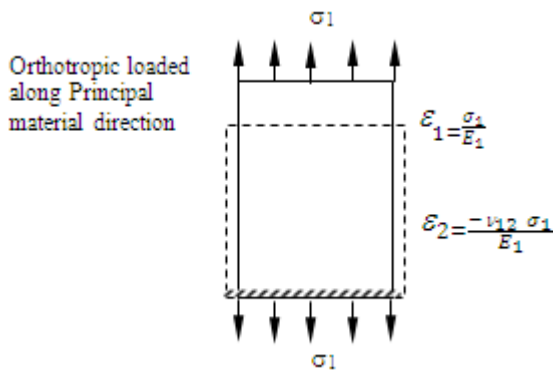

Figure 9. Response of clamped-free laminate under uniaxial loading

where ε_1, ε_2, γ_{12} = Axial, transverse and shear strains respectively, σ_1= Axial stress, E_1= Young's modulus and ν_{12}= Poisson's ratio. Subscripts 1 and 2 denote the longitudinal and transverse directions respectively.

Before curing, the stress in the fiber (σ_f) and matrix (σ_m) are:

$$\sigma_1 = \sigma_f + \sigma_m \tag{7}$$

Since the uncured matrix owns negligible stiffness.

$$\sigma_m = 0 \ , \ \text{then} \ \ \sigma_1 = \sigma_f \tag{8}$$

Where $\sigma_f = \frac{F_e}{A_f}$ and F_e is the effort force or the pre-load applied to the fiber and A_f is the cross-sectional area of the fiber.

5.2. Shrinkage and Thermal Expansion

Residual stresses are developed during resin curing due to shrinkage, thermal expansion mismatch between fibre and matrix and mold expansion induced volume changes. The stresses in the fibre and matrix after curing can be written as:

$$\sigma_f^{ac} = \sigma_f + \sigma_f^c + \sigma_T \tag{9}$$

$$\sigma_m^{ac} = \sigma_m^c + \sigma_T \tag{10}$$

Where σ_f^{ac} and σ_m^{ac} are the stresses in the fiber and matrix after curing respectively, σ_f^c and σ_m^c are the curing residual stresses in the fiber and matrix respectively, σ_T is the thermal stress due to temperature change ΔT with respect to the thermal expansion coefficient α of the steel mold and steel modulus of elasticity, i.e, $\sigma_T = E^s \alpha \Delta T$.

Assuming, there is perfect bonding between fiber and matrix with no mechanical stress is applied and the thermal expansion coefficients of fiber and matrix are independent of temperature change.

After curing and normalizing to room temperature the applied load on the fibers is removed. Two forces need to be balanced, the released tensile load and the other is bonding force between fiber and matrix (adhesive force). The result makes compressive stresses to the matrix.

Hence, the resulting stresses in the fiber and matrix after releasing preload can be written as:

$$\sigma_f^{arp} = \sigma_f^c + \sigma_f^t \tag{11}$$

$$\sigma_m^{arp} = \sigma_m^c + \sigma^r \tag{12}$$

$$\sigma_f = \sigma_f^t + \sigma^r \tag{13}$$

Where σ_f^{arp} and σ_m^{arp} are the values of σ_f and σ_m after preload release, σ_f^t is the tensile residual stress, and σ^r is the stress released to the matrix.

From (Figure 9) the principle strain ε_1 denoted only the effect of preloading stress σ_1 on the clamped-free laminate. After curing and releasing the preload the change in laminate strain is:

$$\varepsilon_1 \ - \varepsilon_f + \varepsilon_T = \Delta\varepsilon = \varepsilon_m \tag{14}$$

Where ε_f is the fiber strain after releasing the load, ε_T is the thermal strain due to temperature change ΔT with respect to the thermal expansion coefficient α of the steel mold, i.e, $\varepsilon_T = \alpha \Delta T$. $\Delta\varepsilon$ is the change in strain and ε_m is the matrix strain after releasing the load.

From equations (6) and (14):

$$\varepsilon_f = \frac{\sigma_f^t}{E_f} = \frac{F_e}{A_f E_f} - \Delta\varepsilon + \varepsilon_T \tag{15}$$

Or

$$\frac{\sigma_f^t}{E_f} + \Delta\varepsilon = \frac{F_e}{A_f E_f} + \varepsilon_T \tag{16}$$

$$\varepsilon_m = \frac{\sigma_m^t}{E_m} = \Delta\varepsilon \tag{17}$$

Where σ_m^t is the matrix tensile residual stress.
At equilibrium:

$$\sigma_f^t \times V_f + \sigma_m^t \times V_m = 0 \tag{18}$$

Where V_f and V_m are the volume fraction of fiber and matrix respectively.

Or

$$\sigma_m^t = -\sigma_f^t \frac{V_f}{V_m} \tag{19}$$

substituting eq. 8-14) into(8-12) gives:

$$\Delta\varepsilon = \frac{\sigma_m^t}{E_m} = -\frac{\sigma_f^t}{E_m} \times \frac{V_f}{V_m} \tag{20}$$

substituting eq. (8-15) into (8-11) gives:

$$\frac{\sigma_f^t}{E_f} - \frac{\sigma_f^t}{E_m} \times \frac{V_f}{V_m} = \frac{F_e}{A_f E_f} + \varepsilon_T \tag{21}$$

$$\sigma_f^t \left(\frac{1}{E_f} - \frac{V_f}{E_m V_m}\right) = \frac{F_e}{A_f E_f} + \varepsilon_T \tag{22}$$

$$\sigma_f^t \left(\frac{E_m V_m - E_f V_f}{E_f E_m V_m}\right) = \frac{F_e}{A_f E_f} + \varepsilon_T \tag{23}$$

Or

$$\frac{\sigma_f^t}{E_f} = \left(\frac{F_e}{A_f E_f} + \varepsilon_T\right) \times \left(\frac{E_m V_m}{E_m V_m - E_f V_f}\right) \tag{24}$$

This is the same tensile residual strain in the fiber (ε_f), see equation (10), which can be calculated directly. Then, referring to equations (11) and (12), the curing residual strain

in the fiber (ε_f^c) and matrix (ε_m^c) can be added, hence the strain after preload released in the fiber and matrix (ε_f^{ap} and ε_m^{ap}) becomes:

$$\varepsilon_f^{ap} \;=\; \varepsilon_f^c + \left(\frac{F_e}{A_f E_f} + \varepsilon_T\right) \times \left(\frac{E_m V_m}{E_m V_m - E_f V_f}\right) \qquad 25)$$

$$\varepsilon_m^{ap} \;=\; \varepsilon_m^c + \Delta\varepsilon \qquad (26)$$

The one-dimensional Tsai and Hahn model [15] can be used also to calculate the residual strain development in the fiber and matrix theoretically. And such a thin, unidirectional lamina under a state of plane stress and the composite can be considered as an orthotropic material then the stress-strain relationship expressed in equation (26) could be useful to determine the transverse stress (σ_2).

$$\begin{pmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \gamma_{12} \end{pmatrix} = \begin{bmatrix} \frac{1}{E_1} & \frac{-v_{21}}{E_2} & 0 \\ \frac{-v_{12}}{E_1} & \frac{1}{E_2} & 0 \\ 0 & 0 & \frac{1}{G_{12}} \end{bmatrix} \times \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{pmatrix} \qquad (26)$$

Where G_{12} is the shear modulus.

6. Result and Discussion

In this suction, a case study about the response of a thin flat strip of composite material having a constant rectangular cross section is made by EJPR under certain levels of prestress and curing temperature. The study was carried out within ten hours to record the fiber extension and the direct load in order to calculate the residual stress and residual strain in the composite material after releasing preload.

Three Laminas of unidirectional woven carbon fiber with 50% volume fraction of epoxy resin as matrix were used to manufacture a (260mm×80mm×1mm) laminate sample for this case study.

6.1. Material Characterization

The mechanical properties for fiber and matrix are presented below as registered in origin:
For carbon fibers :
SikaWarp-300, unidirectional fiber fabric.
Arial weight: 300 g/m^2 ± 15 g/m^2
Fabric thickness: 0.166 mm
Fabric density: 1.79 g/cm^3
Tensile strength: 3.9 GPa
Tensile E- modulus: 230 GPa
Transvers tensile modulus: 15 GPa
Shear modulus G_{12}: 27 GPa
Elongation at brake: 1.5%
Poisson's ratio v_{12}: 0.2
Laminate tensile modulus based on 50% volume fraction and thickness 1 mm: 35 GPa
For epoxy resin :
Nitowarp encapsulation resin is a two-part that has a1A: 2B mix ratio by weight.
Resin density: 1.1 g/cm^3
Tensile E- modulus = 3 GPa

Shear modulus; G_{12}: 1.6 GPa
poisson's ratio : 0.35
The volume fraction of fiber V_f= 50% = volume fraction of matrix V_m .

6.2. Experimentally-measured Residual Strain:

This case study was carried out at ambient temperature of 28°C, the applied load to produce prestress of 45 MPa was 182.75 kgf at curing temperature of 115°C. A comparison for the behavior of the laminate during prestress operation can be made between the experimentally readings and the calculated results of the mechanical properties data.

The thermal strain ε_T due to temperature change in the rig includes thermal strain of the carbon fiber, epoxy and steel mold. When starting curing, thermal strain of steel will dominate the composite jell, that is:

$$\varepsilon_T^s = \varepsilon_T^f = \varepsilon_T^m \qquad (27)$$

At normalizing process, the solidified composite can obey the mold steel retraction and releasing its thermal strain ε_T^s as shown in (Figure 10). Thermal expansion coefficient of steel α^s =11.7×10^{-6} C^{-1}, and ΔT = 28-115 = -87 C°, hence:

$$\varepsilon_T^s = \alpha_s \Delta T = -1.018 \times 10^{-3} \qquad (28)$$

While the thermal expansion coefficient of carbon fiber α^f is equal to 4.9×10^{-6} C^{-1}:

$$\varepsilon_T^f = \alpha_f \Delta T = -0.426 \times 10^{-3} \qquad (29)$$

This strain is less than ε_T^s and can be neglected. Experimentally, the laminate's behavior during prestress operation at 45MPa and curing at 115°C, then normalizing and releasing the preload was expressed in (Figure 10) as a variation of the sample's strain with the time. As shown in the figure, after 15 minutes from starting curing the axial strain ε_1 was reduced to 3.48×10^{-3} due to the effect of both curing and thermal expansion. Then, at the next eight hours the composite sample was solidified under only 43.61MPa because of the thermal expansion of steel mold as shown in (Figure 11).

Cooling the sample after eight hours to ambient temperature arises the stain's value to 4.42×10^{-3} .That means, when the thermal effect of ε_T^s was vanished, the steel mold retarded towards the fixed base plate and against the movable base plate, see (Figure 2). Hence, the strain gained about 0.94×10^{-3}, which must be the value of ε_T^s. The difference between the experimental result (0.94×10^{-3}) and that extracted from the reference table of mechanical properties and equation (28) which is equal to (1.018 ×10^{-3}) shows an error of 7.6%.

The variation in the measured value could be due to errors in measuring the following:
i.   The thermal expansions in the steel mold.
ii.   The load cell readings with an increase in temperature.
iii. The temperature by the thermocouple in the oven.
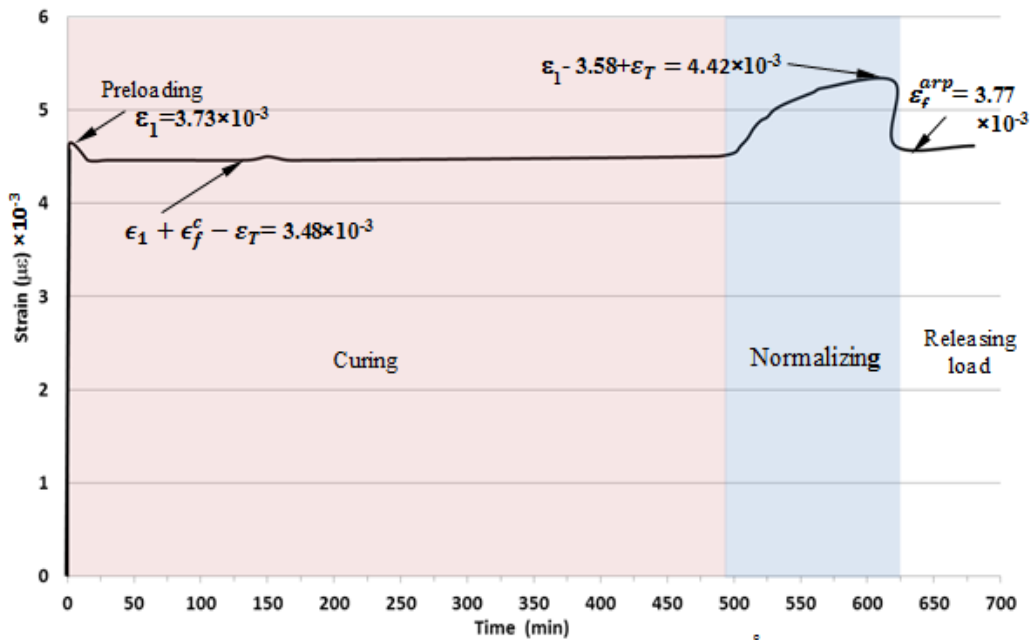iv.   The effect of resin shrinkage on the composite residual strain.

Figure 10. The variation of fiber strain during prestreesing operation at 45 MP and 115 C° for Carbon fiber -Epoxy laminate (ASTM D3039 Standard)
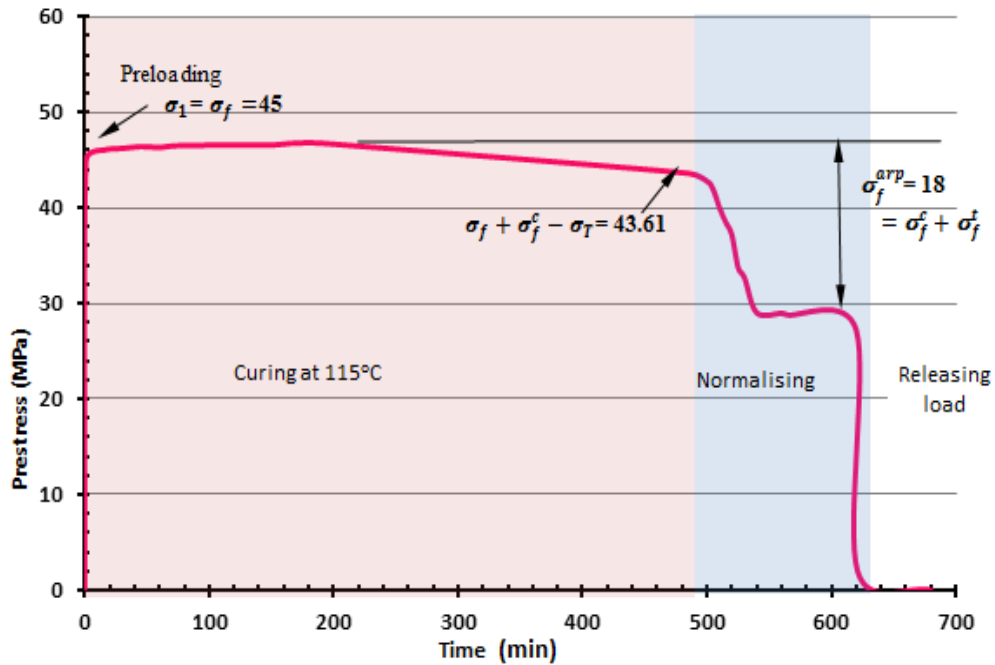

Figure 11. The variation of Prestress value during prestreesing operation at 45 MPa and 115 C° for Carbon fiber -Epoxy laminate (ASTM D3039 Standard).

When the preload was released, the strain arrested at 3.77 $\times 10^{-3}$, i.e. only 0.65×10^{-3} was the final strain of the prestressed laminate. This new value of strain should induced a lot of new mechanical properties for the produced composite, for example the residual stress in fibers became $\sigma_f^{arp} = 18\ MPa$ as shown in (Figure 11) which was absorbed mainly from the initial prestress (45MPa), the tensile residual stress σ_f^t and thermal stress σ_T. Later the last prestressed recorded before releasing preload was 27.18MPa. Hence a new axial modulus of elasticity for the

laminate can be found as flow:

From (Figure 10), the final strain of the laminate is equal to:

Strain before releasing preload - ε_f^{arp}

$$= 4.42\text{-}3.77 = 0.65\ \times 10^{-3} \tag{30}$$

∴ The new E-modulus is equal to:

$$\frac{27.18 \times 10^6}{0.65 \times 10^{-3}} = 41.81\ GPa \tag{31}$$

Referring to the mechanical properties of the laminates illustrated in section 6.1, the ordinary elastic modulus of

elasticity is 35GPa. Therefore, and by mean of this prestressed methodology the improvement of the tensile modulus of elasticity in this case study was 19.5%.

6.3. Improvement in the Tensile Strength

The same 45MPa prestressed carbon fiber composite which described in the previous section was cut into five standard specimens particularly for ASTM standard tensile test method, see (Figure 3-a). The stress/strain curve of one of those specimens was compared with another specimen of non-prestress and cured at ambient temperature, which was made from the same material and tested by the same tensile machine, the results of the two tests are shown in (Figure 12).

The prestressed specimen presented 712.4MPa ultimate stress, while the non-prestressed presented only 434MPa. Hence this level of fibers prestressing at such curing temperature led to improve the tensile strength property to about 64.1 %.

Moreover, different levels of prestressed conditions were carried by EJPR to produce testing samples for different test methods. The tensile tests were carried by Instron tensile test machine type 5900. Furthermore, some results that extracted by this machine are illustrated in table (1) which displays a worthy improvement in the composite mechanical properties.
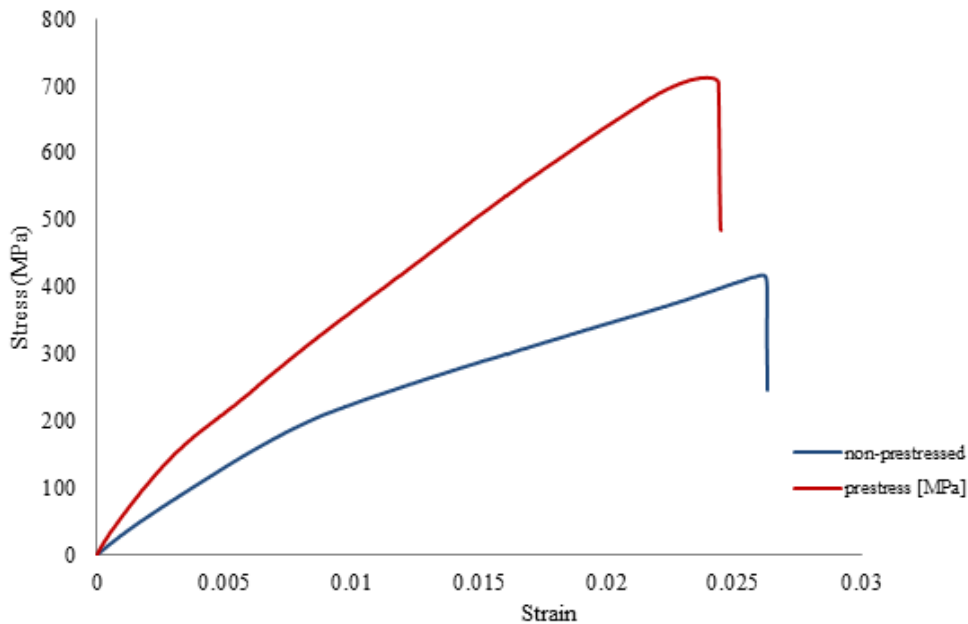

Figure 12. Comparasion between tensile stress- strain curves for non-prestressed carbon fiber composite and 45 MPa prestressedcarbon fiber composite cured at 115°C temperature

Table 1. Expression for the improvements in some mechanical properties of carbon fiber composites manufactured by Electric Jack Prestress Rig

Prestress level (MPa)	Curing temp. °C	Ultimate stress (MPa)	Tensile E-Modulus (GPa)	Improvement in tensile strength %
0	ambient	434	32.3	0
0	80	581.13	41.2	33.9
5	ambient	667.5	37.3	53.8
5	115	724.36	48.3	66.9
10	80	822.5	40.16	89.5
15	115	932.6	56.8	125
20	80	983.82	51.5	114.9
20	115	893.73	59.8	105.9
30	ambient	867.5	38.4	99.9
30	115	770.17	54.6	77.5
45	115	712.4	46.2	64.1
80	150	649.43	51.6	49.6

7. Conclusions

A new methodology of producing prestressed composite materials has been presented. The prestressed rig was designed to pull specimens and to generate heat for curing purposes, where the prestressed ply was either parallel or transverse to the loading axis of the specimen. The major conclusions from this methodology are listed below:

1. The Electric Jack Prestress Rig (EJPR) offers a variable loading levels with the chosen curing temperature to manufacture prestressed laminate. It was designed to apply a unidirectional prestress to continuous fibers.

2. Three main measurements could be read at this machine, they are: the applied load is up to 500 kgf, the fibers extension is up to10 mm and the curing temperature is less than 250°C. These limiting of measurements were found adequate for improving fibers composites manufacturing.

3. The held case study was used also to evaluate the EJPR. From the measured residual strain, it can be concluded that a variation of thermal strain of the mold steel was within maximum error of 7.6%.

4. The prestressing of fibers will increase the tensile E-modulus for composite laminate by (85.1%) at (20MPa) prestress level for 115°C curing temperature.

5. The prestressing of fibers will increase the tensile strength for composite laminate by (114.9%) at the (20MPa) prestress level and 80°C curing temperature.

REFERENCES

[1] F.C. Campbell. Structural Composite materials. 05287G, ASM International. 2010

[2] J. Jacob, O. Lucia, G. Barragan. Flexural strengthening of glued laminated timber beams with steel and carbon fiber reinforced polymers. Master Thesis, Department of Civil and Environmental Engineering, Chalmers University of technology, Goteborg, Sweden. 2007

[3] Composite Learning Centre. Types of Fiber Reinforcement. Automated Dynamic, Research Program AUG 26 2015, Dallas-TX.

[4] H. Thomas Yolken, George A. Matzkanin. Nondestructive Evaluation of Advanced Fiber Reinforced Polymer Matrix Composites. Texas Research Institute, Austin, Texas, NASA/CR-2009-215566. 2009

[5] A. S. Yaser. The Effect of Fiber Pre-Tension On The Static and Dynamic Behavior of Composite Plates. Phd. thesis , University of Technology, Iraq. 2007

[6] K. Shulte, R Marissen. Influence of artificial prestressing during curing of CFRP laminates on interfibre transverse cracking. Composite Science and technology, 44, 1992, 361-367.

[7] S. krishnamurthy. Prestressed Advanced Fiber Reinforced composites. Phd. Thesis, Cranfield University, UK.. 2006.

[8] Y. Huang, P. Frings, E. Hennes. Mechanical properties of Zylon/epoxy composite. Composite: Part B, 33,109-115. 2002

[9] S. Mutasher, N. Mir-nasiri, L. C. Lin. Small-Scale Filament Winding machine for Producing Fiber composite products. Journal of Engineering Science and Technology, Vol. 7, No. 2-156 - 168 ,Taylor's University, Sarawak, Malaysia. 2012

[10] A. S. Hadi and J.N. Ashton. On the influence of pre-stress on the mechanical properties of a unidirectional GRE composite. Composite Structures, 40(3-4), 305-311. 1998

[11] M. E. Tuttle, R.T. Koehler, D. Keren. Controlling Thermal Stress in Composites by Means of Fiber Prestress. Department of Mechanical University of Washington, Seattle, WA 98195. 1995

[12] S. Motahhari. A study of the influences of fiber prestressing on the mechanical properties of polymer ma& composites. PhD thesis, Queen's University Kingston, Ontario, Canada. 1998

[13] International Labour Organization. Code of practice on safety in the use of synthetic vitreous fibre insulation wools", Geneva, page 23. 2000

[14] Isaac M. Danial and Ori Ishai (1994)"Engineering mechanics of composite materials" Oxford university press. pp. 16-54.

[15] S. W. Tsai, H.T. Hahn. Introduction to Composite Materials", Technomic Publications Co., Inc. Westport, CT, ISBN 0-87762-288-4, 402-40.