Studying the Tensile and Buckling for PMMA Reinforced by Jute Fibers for Prosthetic Pylon

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ABSTRACT

The main objective of this research is studying the tensile and buckling of Jute fibers reinforced composite by varying the number of Jute fibers layers and fibers angle (±45° & 0°/90°). Vacuum bagging technique was adopted for the preparation of laminated composite specimens that made from PMMA as matrix and Perlon layers with different number of Jute fibers layers as reinforcement materials. Also the finite element method (ANSYS-15) was used by creating a model of prosthetic pylon and applied compressive load at heel strike step from gait cycle to know the critical buckling stress. The results showed that the best laminated composite specimens have three Jute fibers layers at (0 ° /90 °) fibers orientation relative to applied load. Where, the critical buckling stress, tensile strength, and modulus of elasticity were (442MPa, 61MPa, and 3.75GPa) respectively, while, the percentage elongation was (2.1).
Keywords: Prosthetic pylon, Jute fibers, tensile, buckling.

دراسة الشد والانبعاج لـ PMMA المقوى بألياف الجوت للساق الاصطناعي

الخلاصة

الهدف الرئيسي لهذا البحث هو دراسة الشد والانبعاج لمادة متراكبة مقواه بألياف الجوت بتغيير عدد طبقات الياف الجوت وزاوية الالياف (°0/°90 & °45±). تقنية الحقيبة المفرغة من الهواء هي الطريقة المعتمدة لتحضير عينات المواد المتراكبة الطبائقية المصنوعة من البولي مثيل ميثا اكريليت كمادة اساس وطبقات البرلون وعدد مختلف من طبقات الياف الجوت كمواد تقوية.

طريقة العناصر المحددة (ANSYS-15) هي الطريقة المستخدمة لخلق موديل للساق الاصطناعي وتسليط حمل انضغاط عند خطوة ضربة الكعب من دورة المشي لمعرفة اجهاد الانبعاج الحرج. اظهرت النتائج بأن أفضل عينات المواد المتراكبة الطبائقية هي التي تمتلك ثلاث طبقات الياف الجوت باتجاه الياف (°0/°90) نسبة للحمل المسلط. حيث ان جهد الانبعاج الحرج, مقاومة الشد , ومعامل المرونة هي (442MPa, 61MPa , and 3.75GPa) على التوالي, بينما نسبة الاستطالة هي (2.1).

INTRODUCTION

Natural fibers as a replacement to synthetic fibers in a polymer matrix is the focus of many scientists and engineers. The reason for chose the natural fibers reinforced polymer matrix is because of its low cost, low effect on environment and also its shows good mechanical properties compared to polymer resins. Natural fibers reinforced composites are advantageous over the metals when excellent corrosion resistance is required [1&2]. In Baghdad center for prosthetic limbs, there was a manufacturing of (777) of lower and upper of artificial limbs only in (2013). Therefore, this large number of amputees with different economic situation led to towering to economic materials to manufacturing artificial lower limb [3]. The researchers are studied in this field, *Shasmin*, comparison between two types of pylons, the first from stainless steel and the other from bamboo. The results indicate that there was no

significant effect to gait properties, cadence, and stride velocity for two types but the benefit from the use bamboo pylon in mass and cost from stainless steel pylon [4]. *Shasmin*, studied the developed low priced pylon by replacing the conventional materials that used in pylon such as Ti, St.St., and Al to bamboo. The mechanical properties for this pylon such as (flexural, tensile, and compression) shown the bamboo had the strength and modulus are adequate, the former being stronger than aluminum pylon [5]. *Prasanna*, development a new prosthetic design for the socket and adjustable pylon have a light weight (especially for children), ease of fabrication, and low cost (in countries with people having low socio-economic status). The new prosthetic design have adjustable pylon made from nylon and polypropylene was economically than conventional pylon [6]. *Albert E.*, included the design and development for artificial lower limb (knee joint, adjustable shank, ankle joint and foot) by using FEM to determine the max. Von-Mises stresses, shear stresses, and max. total deformation. The adjustable shank contains from two parts, the upper made from aluminum and the lower part made from beach wood. The results of upper and lower part of adjustable shank are shown the max. Von-Mises stresses and shear stresses occur at the edge of contact of the upper part with the support and the total deformation occurs at the end of the lower part of the adjustable shank [7]. *M. Pitkin*, studied the flexural strength of two pylons (composite pylons containing a solid titanium core with drilled holes surrounded by a porous sintered titanium shell) and (pylons composed of the porous titanium a lone). The results show the composite pylons have a flexural strength and stiffness greater than that of pylons composed of the porous titanium alone [8].

The aim of this research is to studying the effect the number of Jute reinforcing fibers (one, two, and three) layers, in additional to the constant number of Perlon fibers layers and Jute fibers orientation angles (±45° & 0°/90°) on the tensile properties and critical buckling stress.

Rule of mixture

The mechanics of materials model uses simple analytical equations to arrive at effective properties of a composite, using simplifying assumption about the stress and strain distribution in a representative volume element of the composite. This approach results in the common (Rule of mixtures) equations for composites, where properties are relative to the volume fraction of the fibers and matrix. The volume fraction of fibers calculated from eq. (1) [9]:

$$\mathbf{V_f} = \frac{Vf}{Vc} \qquad \qquad ....(1)$$

Where:
V_C and V_F = the volume fractions of the composite and fibers respectively.
To describe the mechanical properties of fiber reinforced lamina by assuming as an orthotropic material in its plane (plane 1-2 in Fig.(1), four elastic stiffness properties are needed). In –plane mechanical properties of the lamina are: (E_1, E_2, v_{12}, and G_{12}).
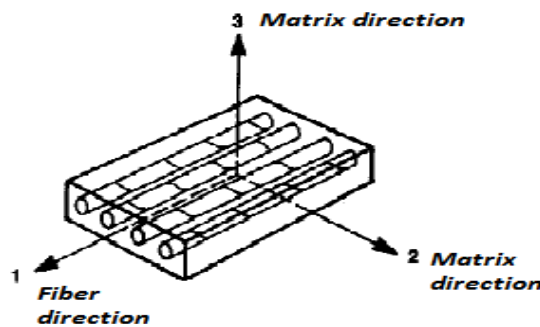

Figure (1): Lamina coordinate system.

The Young's modulus for the lamina composite materials in the fiber reinforcement direction, here the axial strain (isostrain) at the same in the fiber reinforcement and the matrix. E_1 determine according to eq. (2):

$$E_1 = E_f . V_f + E_R . V_R \qquad \qquad \text{....(2)}$$

The Young's modulus of the lamina composite materials in the direction transverse to the fiber reinforcement, with assumption the same transverse stress (isostress) is assumed to be applied to both the fiber reinforcement and matrix. E_2 determine according to eq. (3):

$$E_2 = \frac{Ef . ER}{Ef.VR + ERVf} \qquad \qquad \text{....(3)}$$

Where :
E_F and E_R = Young's modulus of fibers and resin respectively.
While υ is the Poisson's ratio, which is defined as: [$\upsilon = -$(transverse strain)/(axial strain)], from rule of mixture can be determine the Poisson's ratio from eq. (4):

$$v_{12} = v_f . V_f + v_R . V_R \qquad \qquad \text{.....(4)}$$

Where :
v_F, v_R : the Poisson's ratio for fibers and resin respectively.
In the plane shear modulus is determine from eq.(5) [10]:

$$G_{12} = \frac{GR . Gf}{VRGf + VfGR} \qquad \qquad \text{....(5)}$$

Where :
G_F and G_R : the shear modulus of fibers and resin respectively.

Materials and Method
Jute have different shapes such as continuous, discontinuous, or woven fibers. In this work are used woven jute fibers to obtained (0º/90º) and (±45º) fibers orientation relative to the direction of applied load during test and Perlon fibers or (polyamide 6) fibers are used in orthopedic technology as stockinet [11]. layers as reinforcing materials in PMMA resin, as shown in Fig.(2) and Table (1) illustrate the mechanical properties of these materials.

(A): Jute fibers   (B): Perlon fibers   (C): PMMA resin

Figure (2): Materials that used in this research.

Table (1): The mechanical properties of materials from the company.

Materials	Elastic Modulus(GPa)	Tensile strength(MPa)	Elongation Percentage	Poisson's Ratio
Poly methyl methacrylate	2.24-3.24	48.3-72.4	2-5.5	0.35
Jute fibers	26.5	200-500	1.5-1.8	0.38
Perlon fibers	2.6-3	78	1-30	0.39

Preparation of prosthetic pylon specimens

PMMA resin mixture is prepared by adding hardener at room temperature relative to percentage (80:20). The specimens were prepared by using vacuum bagging technique with capacity (5MPa), the arrangement of fibers layers in specimens as shown in Table (2). After remove composite prosthetic pylon cast entered an oven dryer for (30 min.) at (50°C) to completed the curing step [15], as shown in Fig.(3), then cutting relative to angle of fibers orientation for tensile test.

Table (2): Type of lamentation.

Number of lamination	Type of materials	Arrangement of layers	Number of lamination	Type of materials	Arrangement of layers
--------	**PMMA**	-------			4 perlon layers+ **1 Jute layers +** 4 perlon layers.
Laminate 1	PMMA +	4 perlon layers+ **1 Jute layers +** 4 perlon layers.	**Laminate 4**	PMMA + Jute	4 perlon layers+ **1 Jute layers +** 4 perlon layers.
Laminate 2	Jute layers + Perlon	4 perlon layers+ **2 Jute layers +** 4 perlon layers**.**	**Laminate 5**	layers + Perlon	4 perlon layers+ **2 Jute layers +** 4 perlon layers.
Laminate 3	layers at **(0º/90º)**	4 perlon layers + **3 Jute layers +** 4 perlon layers.	**Laminate 6**	layers at **(±45º)**	4 perlon layers + **2 Jute layers +** 4 perlon layers.

Figure (3): Vacuum bagging technique.

Tensile Testing

The tensile test was used to graph a stress-strain curve for each prosthetic pylon specimens to obtain from this curve several mechanical properties are (Young's modulus, Tensile strength, and Elongation percentage at break). The tensile composite prosthetic pylon specimens prepared according to ASTM (D-638 type IV standard) [16], and then the test was carried out at room temperature by tensile testing machine type is (LARYEE) with capacity load (5 KN) and strain rate about (5mm/min.), the tensile specimens are shown in Fig.(4).
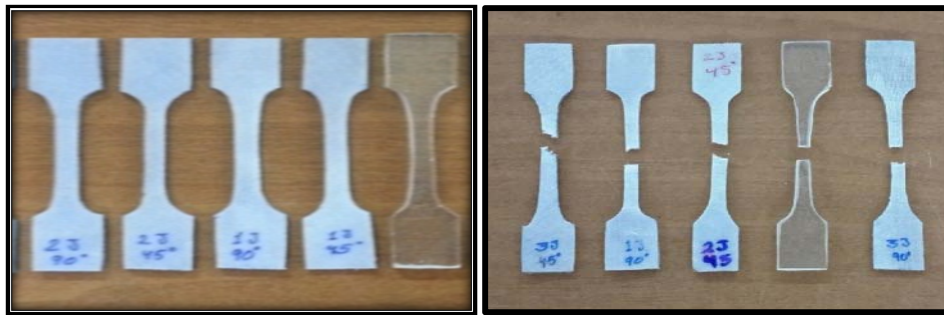
Figure (4): Samples of prosthetic pylon specimens before and after tensile test.

Theoretical Part (Critical Buckling Stress)

The prosthetic pylon was considered a hollow cylindrical shell with lower thickness. When hollow cylindrical shell structures are subjected to compressive load, their strength is limited by buckling, so that buckling can be defined "is the failure of structures under compression load". The finite element method (FEM) has been used widely in biomechanics to obtain in this work the buckling analysis that are involved found critical buckling stress in complicated systems in composite prosthetic pylon [17]. Critical buckling stress in this research are found at heel strike step from gait cycle for prosthetic pylon from this eq.(6) [18]:

$$\sigma_{cr} = \frac{E\ t}{R\sqrt{3(1-v^2)}} \qquad\qquad ….(6)$$

Where:
R = Radius of the cylindrical shell (mm).
t = Thickness of the cylindrical shell (mm).
E = Young's modulus (Gpa).
v= Poisson's ratio.

Numerical Part

The Numerical part by using Finite element method (ANSYS APDL-15) in this research is divided into the following steps when analyzing and solving a problem.

Three- dimensional shell elements (SHELL181) [20] is the element type that chosen for this study, the geometry of element as shown in Fig. (5) and the mechanical properties of the composite prosthetic pylon specimens as shown in Table (3) for thickness (2.5mm), then create geometry of the prosthetic pylon (hollow cylindrical shell) and meshing are automatically meshing generated by using meshing tool in (ANSYS-15), as shown in Fig.(6).
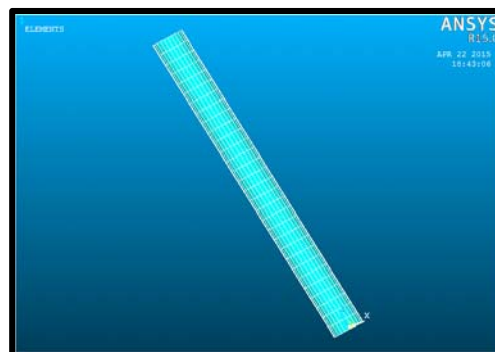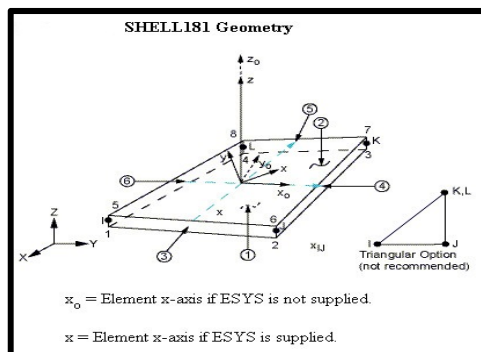

Figure (5): Details of SHELL181 element.   Figure (6): Meshing the element.

Table (3): The mechanical properties of prosthetic pylon contours.

Property	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	v_{12}	v_{23}	v_{13}	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)
Pure(PMMA)	1.5	1.5	1.5	0.35	0.35	0.35	0.829	0.829	0.829
Laminate 1	1.9	1.9	1.5	0.362	0.35	0.35	1	0.829	0.829
Laminate 2	3	3	1.5	0.364	0.35	0.35	1.075	0.829	0.829
Laminate 3	3.75	3.75	1.5	0.366	0.35	0.35	1.162	0.829	0.829
Laminate 4	1.68	1.68	1.5	0.362	0.35	0.35	1	0.829	0.829
Laminate 5	2.25	2.25	1.5	0.364	0.35	0.35	1.075	0.829	0.829
Laminate 6	2.7	2.7	1.5	0.366	0.35	0.35	1.162	0.829	0.829

This analysis is used to predict the critical buckling stress before the structure fail. The boundary condition (fixed-pin) for two end of composite prosthetic pylon as shown in Fig. (7). Then the solution of buckling analysis are doing to known the critical buckling stress for each cases.
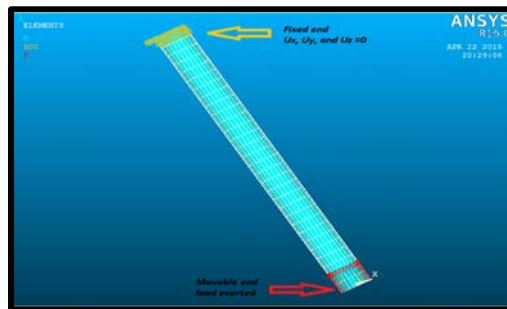

Figure (7): The boundary condition of prosthetic pylon.

Results and Discussion

Tensile analysis for laminated composite specimens is show from stress-strain curves. Pure (PMMA) specimen stress- strain curve is show in Fig.(8).

The results about pure specimen illustrate elastic and plastic deformation in nonlinear curve by depending on the rate at which the force machine is applied in test [62].
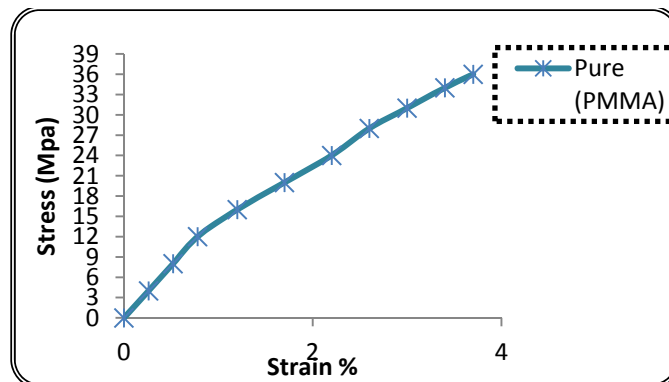

Figure (8): Stress-Strain curve for pure PMMA specimen.

When adding reinforcing fibers layers to PMMA resin, the stress-strain curves become as shown in Figs.(9 & 10) for specimens with Jute fibers and Perlon layers in PMMA matrix at different fibers directions.

It is clear from figures that, the tensile strength increase with the increment number of reinforcing layers of Jute fibers as well as the rate of increment in tensile strength depend on the direction of these layers respective to nature of the fibers in the layer.
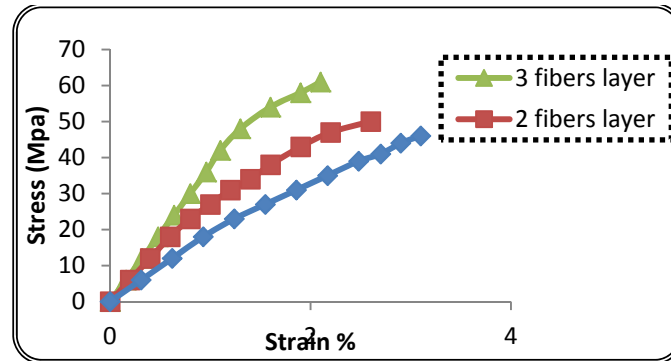

Figure (9): Stress-Strain curves for laminated composite specimens having woven Jute fibers at Ɵ=(0º/90º).
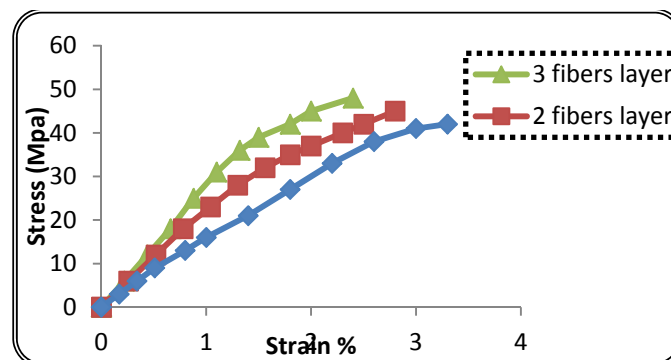
Figure (10): Stress-Strain curves for laminated composite specimens having woven Jute fibers at Ɵ=(±45º).

Tensile analysis for laminated composite specimens is involved (tensile strength, young's modulus, and elongation percentage). Tensile strength and young's modulus for specimens are increases with increasing the number of Jute layers for both angles (±45°&0°/90°) as shown in Fig.(11&12) respectively. Usually PMMA matrix is much weaker in strength rather than from specimens with reinforcement layers, because the matrix alone is unable to resist the applied tensile force and fails with lower strength from the specimens have reinforcing layers that withstand the tensile load [21]. The tensile strength of PMMA resin was (36 MPa), while the higher tensile strength was (61MPa) for three Jute layers in matrix. The percentage of increase in tensile strength for specimen with three Jute fibers layers and Perlon layers in PMMA was (69.4%) from pure PMMA specimens, at (0º/90º) fibers orientation relative to tensile force.

Tensile strength and modulus of elasticity for laminated composite specimens in cases of (0º/90º) Jute fibers direction relative to tensile load have higher value from specimens with (±45º) direction, that due to (50%) from the fibers in (0º/90º) cases are longitudinal with length of specimens and carried the tensile load during test, and for the transvers fibers direction that also prevent the deformation in matrix. While for (±45º) orientation fibers that also carried the tensile load during test but have lower fibers bath in cross sectional area of specimens [22]. Young's modulus for pure PMMA was (1.5GPa), while for specimens have three layers of Jute fibers in PMMA resin were (3.75GPa). The improving percentage of modulus of elasticity for

specimen with three Jute fibers layers and Perlon layers in PMMA compared with pure PMMA specimens was (150%).
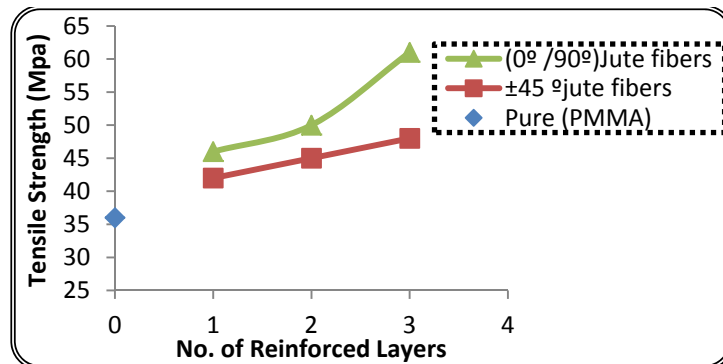

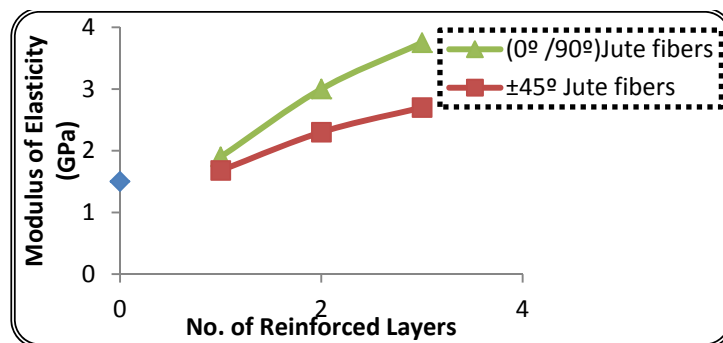**Figure (11): Relationship between the tensile strength and number of reinforcing layers.**

Figure (12): Relationship between the modulus of elasticity and number of reinforcing layers.

PMMA matrix have the highest elongation percentage equal to (3.7%), While the lower value found with specimens have three Jute reinforcing layers about (2.1%), as shown in Fig.(13). Increase the number of Jute reinforcing layers led to decrease the elongation percentage for specimens, because the fibers are stiffer than matrix and thus imposes a mechanical curb on the specimens. Also the interphase between the fibers and PMMA resin was play important factor for elongation percentage, strong structure (higher interphase) that led to decrease the elongation for specimens, that compatible with [23].
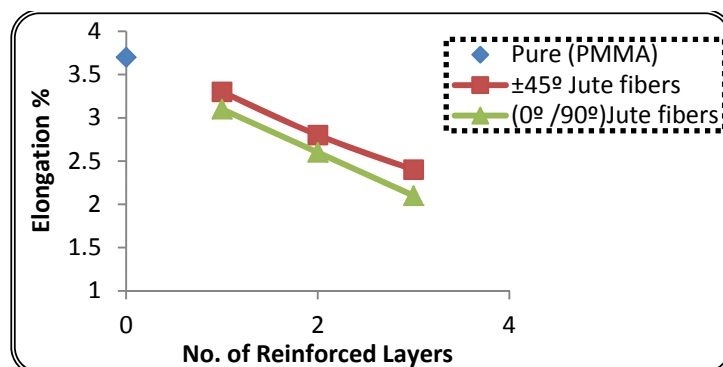

Figure (13): Relationship between the elongation percentage and number of reinforcing layers.

Numerical results are shown in Figs.(14,15, &16), these figures shown the critical buckling stress for prosthetic pylon contours at heel strike step from gait cycle. The critical buckling stress that represent the critical point to start failure of prosthetic pylon is found with lower value with prosthetic pylon prepared from pure PMMA, due to the weak properties of PMMA

relative to another prosthetic pylon that have reinforcing layers in this work. Higher critical buckling stress are found with three Jute fibers layers in PMMA resin at (0°/90°) orientation relative to compression load.
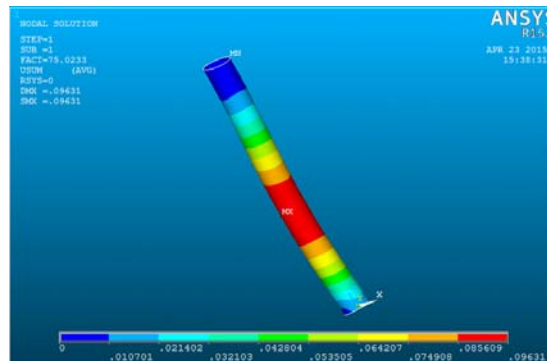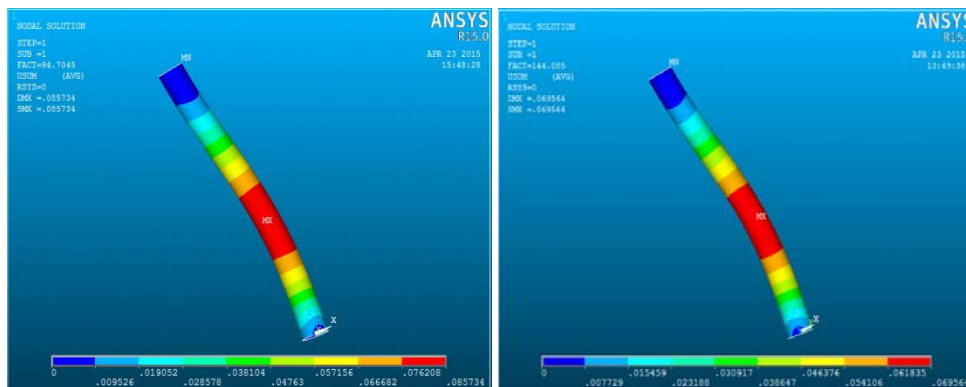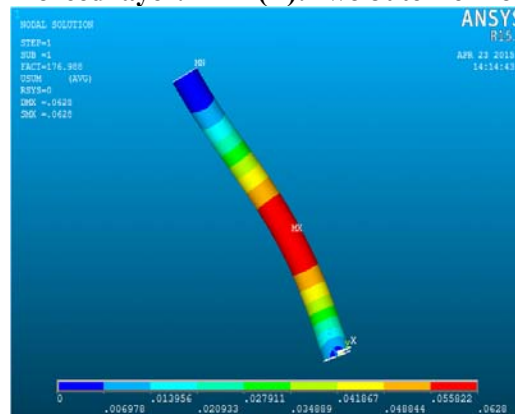

Figure (14): Buckling mode shape for pure (PMMA) prosthetic pylon.

(A): One Jute Reinforced layer.   (B):Two Jute Reinforced layers.

(C):Three Jute Reinforced layers.

Figure (15): Buckling mode shape for (A), (B), and (C) prosthetic pylon contours at (0º/90º) fibers orientation.

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(A): One Jute Reinforced layer.   (B):Two Jute Reinforced layers.
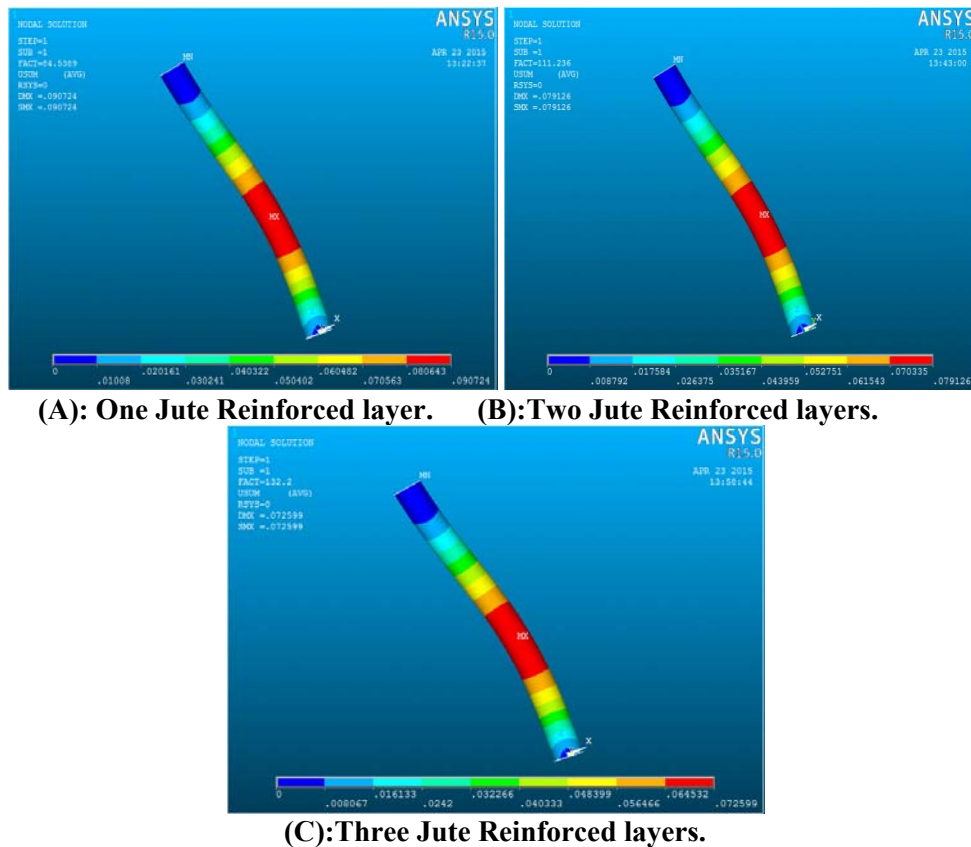

(C):Three Jute Reinforced layers.

Figure (16): Buckling mode shape for (A), (B), and (C) prosthetic pylon contours at (±45°) fibers orientation.

Figs.(17) shown the critical buckling stress for all type of prosthetic pylon in this research. The values of critical buckling stress about (187.558MPa& 442.47MPa) for (PMMA and three Jute fibers layers respectively).

The comparison between the critical buckling stresses for pure PMMA prosthetic pylon relative to additional three Jute of reinforcing layers to PMMA is found the improving percentage about (135.91%).
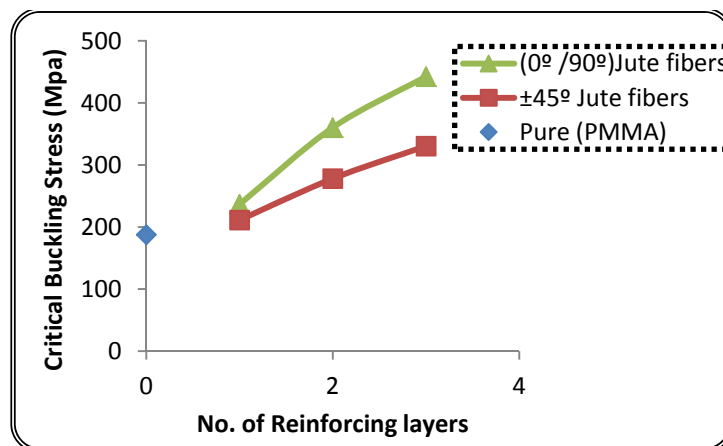

Figure (17): Relationship between the critical buckling stress and number of reinforcing layers.

CONCLUSION:

1-　　　Tensile strength and modulus of elasticity are the mechanical properties that increase with increasing the number of Jute reinforcing layers at direction (0º/90º) of fibers relative to tensile load. The higher values of these properties are found with specimens have three Jute fibers layers at (0º/90º), that equal to (61MPa and 3.75GPa) respectively.

2-　　　Elongation percentage is the mechanical properties that decrease with increasing the Jute fibers layers and with fibers at (0º/90º) orientation relative to applied load. The lower values of these properties are found with laminated composite specimens have three Jute fibers layers, these properties equal to (2.1%).

3-　　　Numerical results are shown the better prosthetic pylon that has the highest critical buckling stress to start the failure, that when specimens have three reinforcing layers of Jute fibers at (0º/90º) orientation relative to compression load in PMMA resin. The higher critical buckling stress was (442.47 MPa) at heel strike step from gait cycle.

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