Tensile and Buckling of Prosthetic Pylon Made from Hybrid Composite Materials

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ABSTRACT

Compared to traditional prosthetic pylon materials (Aluminum, Titanium, or Stainless steel.), composite prosthetic pylon materials are used instead of metals. Vacuum bagging technique was adopted for the preparation of specimens made of Poly methyl methacrylate (PMMA) as matrix with constant Perlon layers and different number of Hybrid (Carbon + Glass) fibers layers as reinforcement materials at (±45º&0º/90º) orientation relative to applied load. Also the finite element method (ANSYS-15) were used by create a model of prosthetic pylon and applied compressive load at heel strike step from gait cycle to known the critical buckling stress. The experimental and numerical results shown that the tensile strength, modulus of elasticity, and critical buckling stress increases with increasing number of Hybrid fibers layers, that equal to (145 MPa, 6.25 GPa, and 670 MPa) respectively, and the percentage of increase in tensile strength, modulus of elasticity, and critical buckling stress for specimen with three Hybrid (Carbon + Glass) layers and Perlon layers in PMMA resin compared with pure PMMA specimen was (302.7% , 300% & 257.22%) respectively, at (0º/90º) fibers orientation relative to tensile force.

Keyword: Prosthetic pylon; Hybrid fibers; tensile test; Buckling analysis and Vacuum bag technique.

List of symbols

Symbol	Description
E	Modulus of elasticity
R	Radius of cylindrical shell
t	Thickness of cylindrical shell
σ_{cr}	Critical buckling stress
	Passion's Ratio
K_e	elastic stiffness matrix
$\emptyset i$	Eigen vector
λi	Eigen value for buckling mode
$K_{\sigma L}$	the initial stress matrix

INTRODUCTION

A prosthetic pylon with light weight, high strength, and also the most important factor is with low cost, the composite technology, is the best selection.

Composite lamination polymers involve bonding the reinforcement layers together to create a lamination. This lamination process is performed under mechanical vacuum to give the prosthetic pylon good properties as compared with metal prosthetic pylon [1]. Composite materials have the important factor of low cost in addition to have good mechanical properties and ease of fabrication. Therefore, it is used in biomedical applications, prosthetic limb for socket and foot [2]. The researchers are studied in this field, Thurston, replaced the conventional rigid below knee prosthesis by using the glass fibers and resin composite material to form a

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semi-rigid shank but sufficiently flexible to allow its energy storing properties to be used in amputee gait [3]. Coleman explored the effect of prosthetic pylon flexibility on ground reaction force (GRFs) to two types of pylons. The first was nylon (more flexible) pylon and the other an aluminum (rigid) pylon. The results indicated, to distinguish between two pylons, that the nylon pylon component was more comfortable, more flexible, and would enable the person to walk more quickly than the rigid pylon [4]. Shasmin, studied the developed low priced pylon by replacing the conventional materials used in pylon by Ti, St. St., or Al to bamboo. The mechanical properties for this pylon such as (flexural, tensile, and compression) shown the bamboo had the strength and modulus that are adequate, the former being stronger than aluminum pylon [5]. *Muhsin*, studied analytically, numerically, and experimentally for prosthetic pylon made from composite materials, acrylic as a matrix and (carbon fibers with different number of perlon layers) as reinforcement materials. The results for (tensile, impact, and fatigue) tests show the mechanical properties increase with increased number of perlon layers and all types of prosthetic pylons are light weight and cheap [6]. *Albert,* presented 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 contained two parts, the upper, made from aluminum, and the lower part, made from beach wood. The results of upper and lower parts of adjustable shank showed 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]. *Priyadarsini et al* investigated the buckling of fiber reinforced composite. This study details a numerical (FEM) and an experimental study on buckling carbon fiber reinforced plastics (CFRP) layered composite cylinders. The effects of different types of loadings, geometric properties, lamina lay –up and amplitudes of imperfection on the strength of the cylinders under compression are studied [8]. *Jadhav et al* studied the buckling load for different glass fiber orientation laminate to find optimum laminate which can sustain maximum critical buckling load and compare experimental and ANSYS result. The study was conducted to in different fiber direction and load direction for all lamina is decreased then critical buckling load also increases [9].

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

Experimental part

Hybrid fibers contain two or more types of different fibers materials. Which give the composite materials a great performance in mechanical such as impact, tensile, and rigidity or other properties such as electrical or thermal conductivity required for application [10]. In this research the Hybrid fibers are combinations of 50% Carbon fibers and 50% Glass fibers. Carbon fibers have properties higher than Glass fibers, but have higher cost from Glass fibers. So the combination between two fibers in woven gave good results by balancing between the cost and mechanical properties in prosthetic pylon. 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. (1) and Table (1) illustrate the mechanical properties of these materials.

(A): Hybrid fibers **(B): Perlon fibers** **(C): PMMA resin**

Figure (1): Materials that used in this research.

Table (1): The mechanical properties of materials [12&13]

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
Hybrid fibers (Carbon + Glass)	151	3625	2.8	0.235
Perlon fibers	2.6-3	78	1-30	0.39
Stainless steel	193	515	30	0.3
Titanium alloy	114	1172	10	0.34
Aluminum alloy	69	124	40	0.33

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 pressure reach to (5MPa) as show in Fig. (2), the arrangement of fibers layers in specimens as shown in Table (2).

Figure (2): Vacuum bagging technique.

Table (2): Type of lamentation

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

Tensile Testing

The tensile test was used to construct a stress-strain curve for each prosthetic pylon specimen. This curve is used to get 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) [14], and then the test was carried out at room temperature by tensile testing machine with capacity load (5 KN) and strain rate about (5mm/min.), the tensile specimens are shown in Fig.(3).

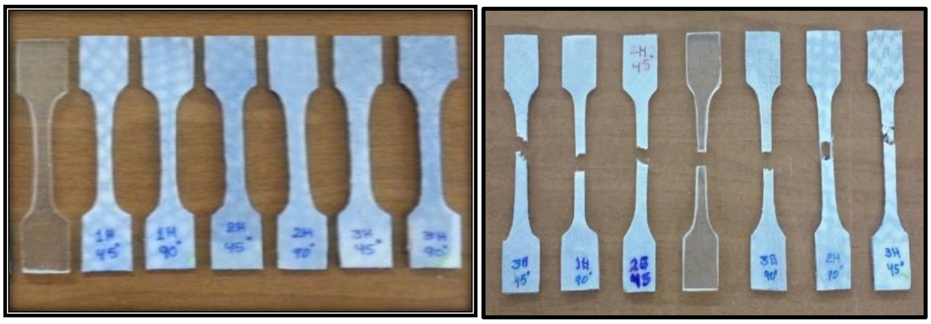


Figure (3): Samples of prosthetic pylon specimens before and after tensile test.

Theoretical part

Critical buckling stress

The prosthetic pylon was considered a hollow cylindrical shell with a small thickness. When hollow cylindrical shell structures are subjected to compressive load, their strength is limited by buckling can be defined "as the failure of structures under compression load ". The load for which a structure ceases to be stable and starts to buckle is known as the "Critical Buckling Stress" (σ_{cr}), eq. (1) using to determine critical buckling stress [15]:

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

Where, **R** is the radius of the cylindrical shell (mm), **t** is the thickness of the cylindrical shell (mm), ***E*** is the Young's modulus (Gpa), and **ν** is the Poisson's ratio.

Numerical analysis

Eigenvalue buckling analysis to predict the theoretical buckling stress of an ideal elastic structure represented the prosthetic pylon in this paper. This analysis is used to predict the "bifurcation point" which represents the critical buckling stress before the structure fail. The basic form of the eigenvalue buckling analysis is given by eq. (2):

$$[K_e]\{\emptyset i\}=\lambda[K_{\sigma L}]\{\emptyset i\} \qquad .....(2)$$

Where, $[K_e]$ is the elastic stiffness matrix, $\{\emptyset i\}$ is the Eigen vector, λi is the Eigen value for buckling mode, and $[K_{\sigma L}]$ is the initial stress matrix [16].

The eigenvalue buckling represents the ratio between the buckling load and the applied load, as follows from eq.(3):

$$\lambda i=\frac{\text{Buckling Load}}{\text{Applied Load}} \qquad .....(3)$$

Three- dimensional shell elements (SHELL181) [17] is the element type that chosen for this paper, the geometry of element as shown in Fig.(4) and the mechanical properties of the composite prosthetic pylon specimens as shown in table (3) for cylindrical shell with diameter of 30mm, height of 300mm and thickness of 2.5 mm, then create geometry of the prosthetic pylon (hollow cylindrical shell) and meshing are automatically meshing generated by using meshing tool in (ANSYS-APDL 15), as shown in Fig.(5).

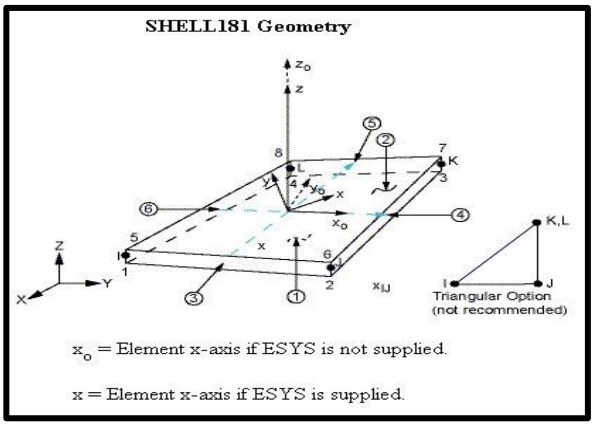


Figure (4): Details of SHELL181 element.

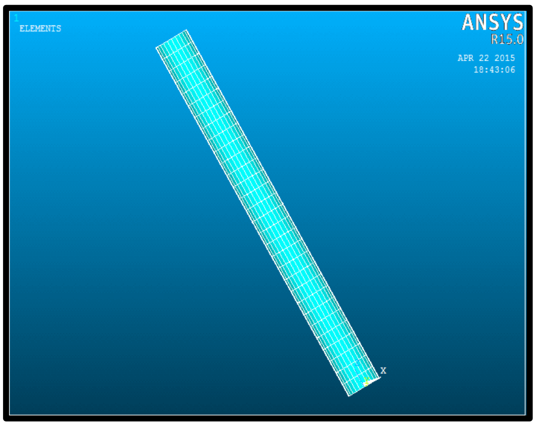


Figure (5): Meshing the element.

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

Property	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{23}	ν_{13}	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)
Pure(PMAA)	1.5	1.5	1.5	0.35	0.35	0.35	0.829	0.829	0.829
Laminate 1	4.5	4.5	1.5	0.347	0.35	0.35	0.944	0.829	0.829
Laminate 2	5.55	5.55	1.5	0.34	0.35	0.35	1	0.829	0.829
Laminate 3	6.25	6.25	1.5	0.333	0.35	0.35	1.098	0.829	0.829
Laminate 4	3	3	1.5	0.347	0.35	0.35	0.944	0.829	0.829
Laminate 5	3.7	3.7	1.5	0.34	0.35	0.35	1	0.829	0.829
Laminate 6	4.2	4.2	1.5	0.333	0.35	0.35	1.098	0.829	0.829

The boundary conditions (fixed-pin) for two end of composite prosthetic pylon are shown in Fig. (6). Then the solution of buckling analysis are doing to known the critical buckling stress for each cases.

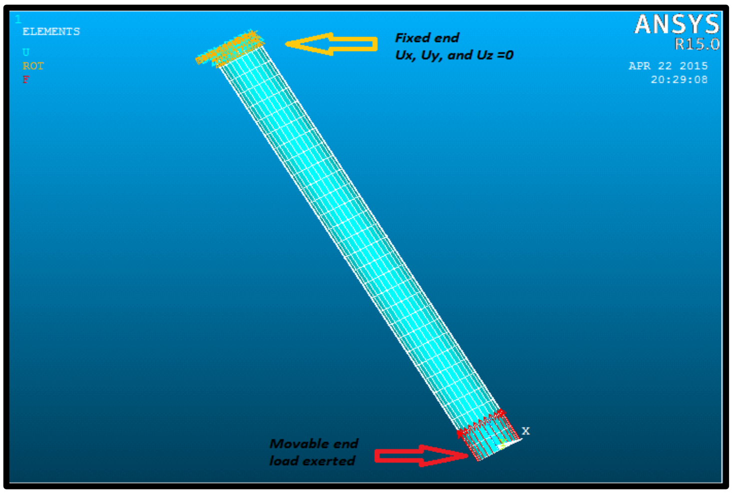


Figure (6): The boundary condition of prosthetic pylon.

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. (7).

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 [18].

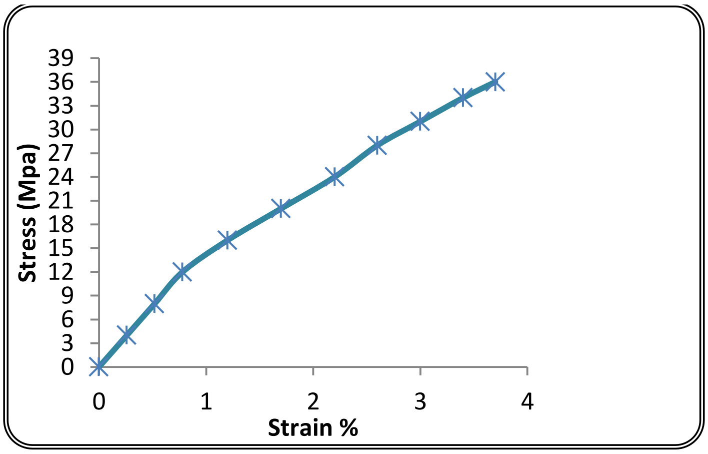


Figure (7): Stress-Strain curve for pure PMMA specimen.

When adding reinforcing fibers layers to PMMA resin, the stress-strain curves become as shown in Figs. (8&9) for specimens with Hybrid (Carbon + Glass) fibers, using Perlon layers in PMMA matrix, at different fibers directions.

The curves show linear and ultimately develop into nonlinear behavior [19]. The linear region occurs due to the deformation of Hybrid fibers reinforcement. The nonlinear region is basically due to the deformation of PMMA matrix.

It is clear from figures that, the tensile strength increase with the increment number of reinforcing layers of Hybrid reinforcing layers 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.

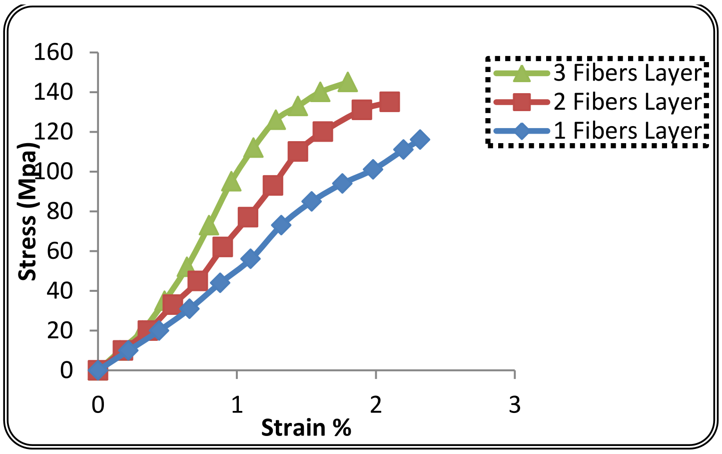


Figure (8): Stress-Strain curves for laminated composite specimens having woven Hybrid (Carbon + Glass) fibers at ϴ=(0º/90º).

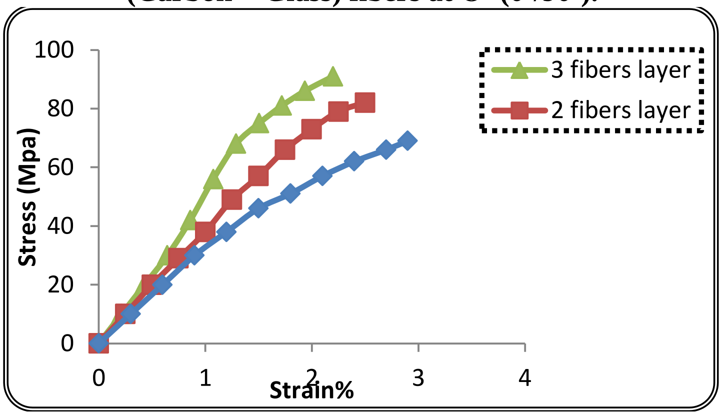


Figure (9): Stress-Strain curves for laminated composite specimens having woven Hybrid (Carbon + Glass) fibers at ϴ= (±45º).

The prosthetic pylon specimens with three layers of reinforcing fibers Hybrid have the highest failure strength and modulus of elasticity than from specimens with one or two layers; the fibers are usually stiffer and stronger than matrix because they have strength and modulus of elasticity higher than matrix. These results agree with those mentioned by [19]. So, the increase of layers of fibers to resin means increase of strength and modulus of elasticity for composite specimens, are shown in Figs. (10&11).

Higher values of tensile strength were found and young's modulus reaching to (145 MPa &6.25GPa), respectively.

In the case of (0º/90º) orientation of fibers to load axis have tensile strength and modulus of elasticity higher than in (±45º) direction for Hybrid fibers in matrix. The strong covalent bonds along the fibers length, in parallel direction gave the high properties for specimens and because it is difficult to break or extend the fibers, the covenant bonds must also be broken or extended [20].

Usually PMMA matrix is much weaker in strength than specimens with reinforcement layers, because the matrix alone is unable to resist the applied tensile force and fails with lower strength from the specimens with reinforcing layers that withstand the tensile load. The tensile strength of PMMA resin from tensile test is (36 MPa) [21].

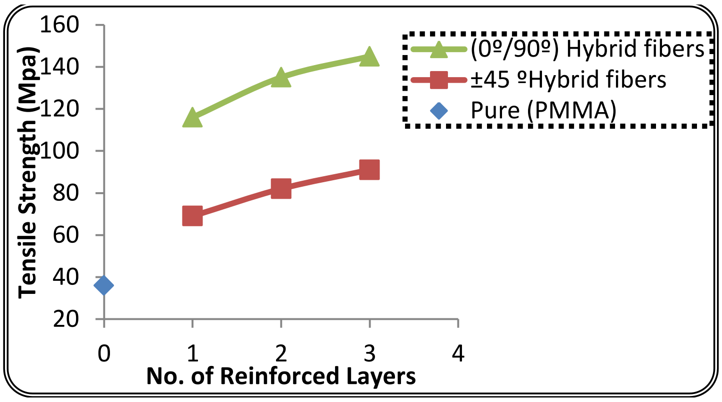


Figure (10): Relationship between the tensile strength and number of reinforcing layers.

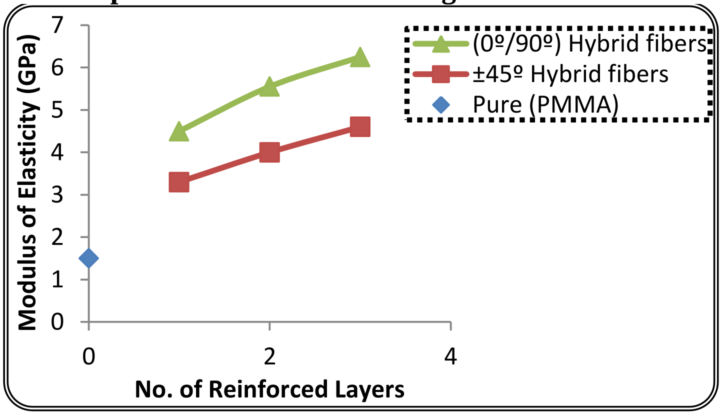


Figure (11): Relationship between the modulus of elasticity and number of reinforcing layers.

PMMA matrix have the highest elongation percentage equal to (3.7%), While the lower value found with specimens have three Hybrid reinforcing layers about (1.85%), as shown in Fig.(12). Increase the number of Hybrid 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 [22].

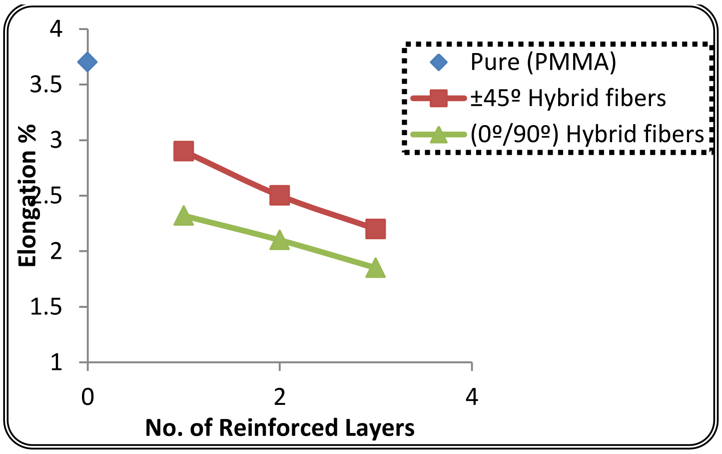


Figure (12): Relationship between the elongation percentage and number of reinforcing layers.

Numerical results are shown in Figs. (13,14,&15), 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 paper [20]. Higher critical buckling stress are found with three Hybrid fibers layers in PMMA resin at (0°/90°) orientation relative to compression load.

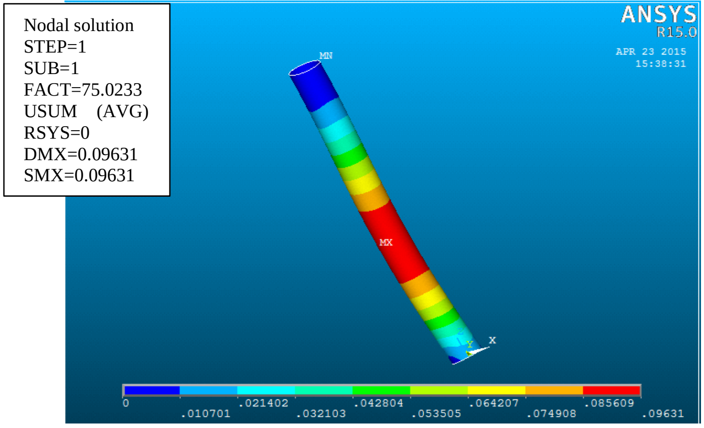
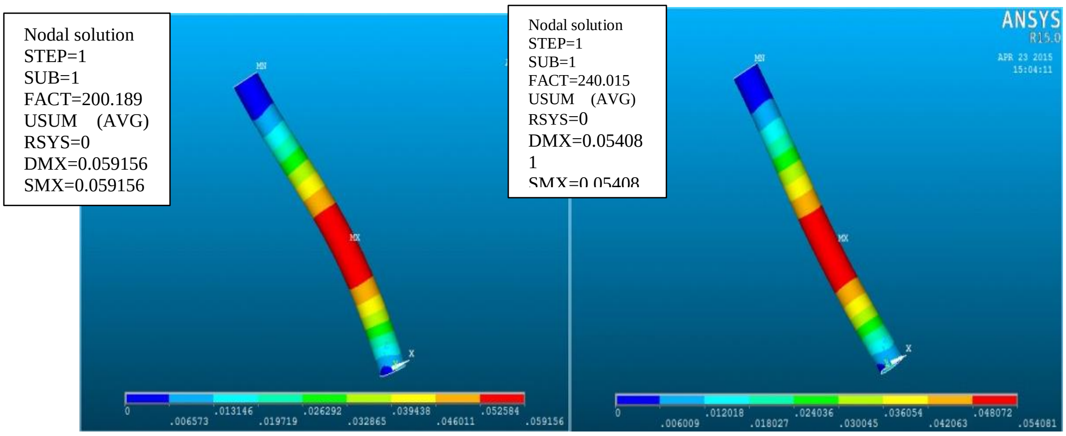
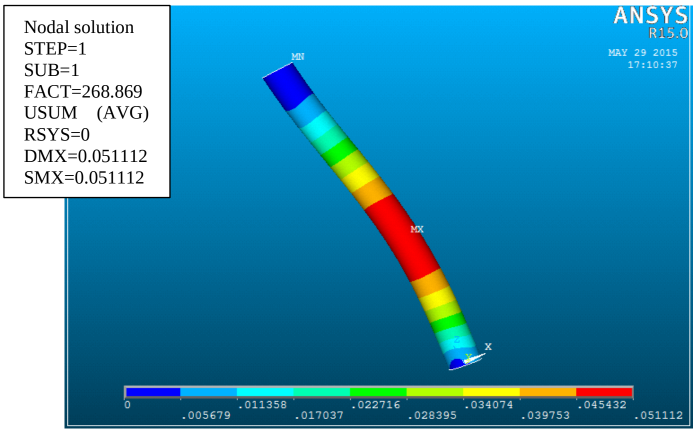


Figure (13): Buckling mode shape for pure (PMMA) prosthetic pylon.

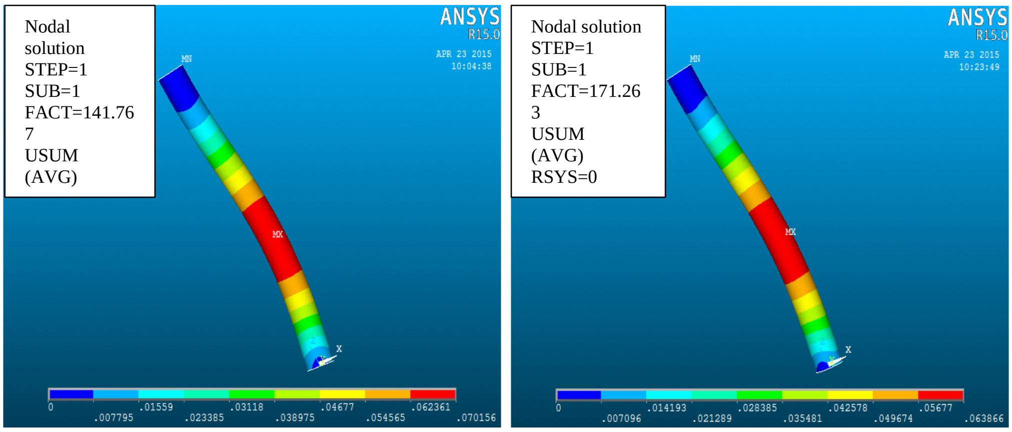


(A): One Hybrid Reinforced layer. (B):Two Hybrid Reinforced layers.

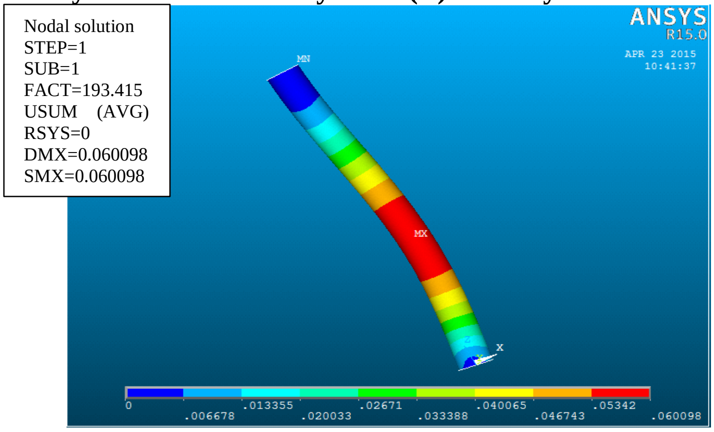


(C): Three Hybrid Reinforced layers.

Figure (14): Buckling mode shape for (A), (B), and (C) prosthetic pylon contours at (0°/90°) fibers orientation.



(A): One Hybrid Reinforced layer. **(B):Two Hybrid Reinforced layers.**



(C): Three Hybrid Reinforced layers.

Figure (15): Buckling mode shape for (A), (B), and (C) prosthetic pylon Contours at (±45°) fibers orientation.

Fig. (16) Shown the critical buckling stress for all type of prosthetic pylon in this research. The values of critical buckling stress about (187.558MPa& 670 MPa) for pure PMMA and three Hybrid fibers layers, respectively.

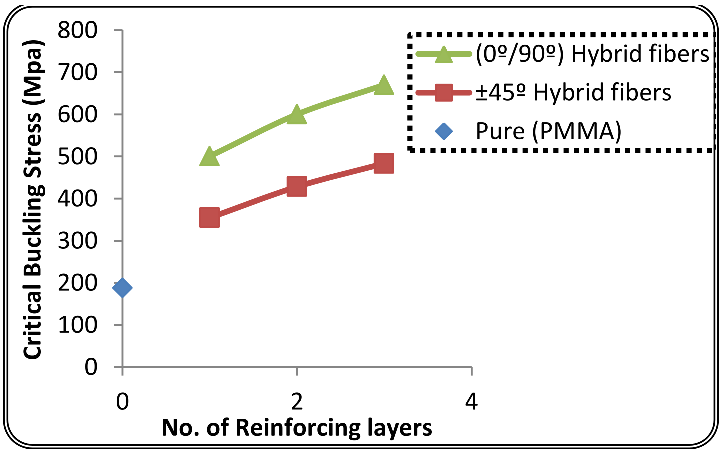


Figure (16): Relationship between the critical buckling stress and number of reinforcing layers.

CONCLUSION:

1- Tensile strength and modulus of elasticity are the mechanical properties that increase with increasing the number of Hybrid reinforcing layers at direction (0°/90°) of fibers relative to tensile load. The higher values of these properties are found with specimens have three Hybrid fibers layers at (0°/90°), that equal to (145MPa and 6.25GPa) respectively.

2- Elongation percentage is the mechanical properties that decrease with increasing the Hybrid fibers layers and with fibers at (0°/90°) orientation relative to applied load. Where equal to (1.85%).

3- Numerical results are shown the better prosthetic pylon that have the highest critical buckling stress to start the failure, the higher critical buckling stress was (670 MPa) at heel strike step from gait cycle. The comparison between the critical buckling stresses for pure PMMA prosthetic pylon relative to additional three Hybrid of reinforcing layers to PMMA is found the improving percentage about (257.22%).

4- The percentage of increase in tensile strength, modulus of elasticity, and critical buckling stress for specimen with three Hybrid (Carbon + Glass) layers and Perlon layers in PMMA resin, at (0°/90°) fibers orientation relative to tensile force compared with pure PMMA specimen was (302.7% , 300% & 257.22%) respectively.

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