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MANUFACTURING AND NUMERICAL ANALYSIS OF ELBOW ORTHOSIS MADE OF POLYPROPYLENE – CARBON FIBER – POLYPROPYLENE

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Abstract: In this work, elbow orthosis which represents one of the upper extremity orthosis is manufactured from two layers of polypropylene reinforced by a sheet of carbon fiber between them to construct a new composite material called "PCP" material. More flexibility is gained by minimization of the modulus of elasticity of polypropylene-carbon fiber- polypropylene to about 3.5 against old material. Average pressure is measured between the patient's arm and bicep part of elbow using a portable pressure device (has mat of sensors) which reach to about 217 kPa. ANSYS PACKAGE version 11 is used for numerical analysis the bicep part of elbow by using the estimated internal pressure to investigate deformation and to determine the Von – Misses stress. The investigated numerical results showed that the new material maximizes the deformation to about 280 % (still in elastic region) and make the design more safe by increasing the factor of safety more than 4 % against polypropylene material. Mechanical properties are measured also in present work by carrying out the tensile test for the two materials under study to conclude finally that, the sheet of carbon fiber which is added has increased the mechanical properties to about 8.25 % and 248 % for yield and ultimate stresses respectively.

Keywords: *elbow orthosis, carbon fiber, polypropylene, stresses.*

الخلاصة: في هذا البحث، تم تصنيع مسند كوع والذي يمثل احد انواع المساند العلوية من طبقتين من مادة البولي بروبلين مع شريحة كاربون محشوة بينهما لغرض تشكيل مادة مركبة جديدة تدعى (PCP). نحصل على مرونة اكثر بتقليل معامل المرونة للمادة المركبة بولي بروبلين – شريحة كاربون – بولي بروبلين لغاية معامل ٣,٥ من المادة القديمة. تم قياس معدل الضغط المتولد بين الذراع العلوي للمريض ومسند الكوع باستخدام جهاز ضغط محمول (يمتلك حصيرة من المتحسسات) ليصل الى ٢١٧ كيلوباسكال. استخدم برنامج ANSYS للنسخة ١١ للتحليل العددي للجزء العلوي للمسند من خلال تطبيق الضغط المقاس سلفا وذلك لايجاد اجهاد فون مايسز. اظهرت النتائج المستحصلة عدديا زيادة للتشوة للمادة الجديدة بمقدار ٢٨٠ % عن المادة القديمة (ولا تزال ضمن منطقة المرونة) وكذلك جعل التصميم اكثر امانا من خلال زيادة معامل الامان بحدود ٤ %. في البحث الحالي تم قياس الخصائص الميكانيكية عن طريق اجراء اختبار الشد لكلا المادتين موضوع البحث واستنتج ان اضافة شريحة الكاربون عملت على زيادة اجهاد الخضوع والاجهاد الاقصى بمقدار ٨,٢٥ % و ٢٤٨ % على التوالي.

1.Introduction

To improve the function of the movable parts of the body in the lower and the upper extremities due to accidents or diseases, orthoses orthopedic appliances were used

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to support, align, prevent or correct deformities of a patient. Elbow orthoses are commonly prescribed as upper limb orthoses including wrist orthoses [1]. The elbow device was constructed and designed to improve the benefits of counterforce dampening elements for the treatment of lateral tendinosis [2].

In upper-extremity weight-bearing athletes, rib fractures were the most common type of stress fracture in rowing athletes, whereas olecranon fractures were most common among base ball players [3].

The upper arm was held in 65^o to 70^o of shoulder abduction and external rotation with the forearm fully supinated. The greater medial stability was restored to the elbow at lower pressures (49 % at 5 kPa) than at higher pressures (35 % at 15 kPa). At 10 kpa of pressure, the brace restore 38 % support to medial stability [4].

Orthotic devices based its mathematical formulation on the principle of static progressive stretching and effective in treating elbow contraction. This results in realignment of fibers and elongation of the material [5].

The polypropylene elbow orthosis can be fabricated easily in 2 to 4 hours. It is cosmetic, light in weight, durable, and easy to keep clean. The elbow joint is located, and copper rivets and burrs are used to join two parts of elbow (forearm and bicep) [6].

The JAS elbow device (Joint Active Systems) incorporates the principles of stress relaxation and static progressive stretch. The device consists of 2 padded sleeves for the forearm and upper arm that are connected by a metal connector bar that applies a spring – loaded force. It is designed to flex the elbow joint up to 135^o [7].

Under static loading case with a vertical load of 500 N, the greatest stress occurred at the middle of the coronoid process when the elbow flexion angles were 0^o and 15^o. When the flexion angles were 30^o and 45^o, the greatest stress occurred at the base of the coronoid process [8].

The elbow muscle strength was reduced after repeated bench – press cycles. The myodynamic decline rate in the forearm pronation condition was 46 %. Reduced elbow muscle strength affects the stability of the upper extremity [9].

The small value of E indicate flexible materials and large values of E means the material has more stiffness with higher rigidity [10]. As improvement of flexion and extension for patient is represented the main goal of design elbow which due to gave physical therapy of arm's muscles during usage, and then reduce the time for healing as a result. A laminate structures may not be represented the most efficient with regard to strength and performance. The damage initiation and progression in the microstructures due to applied loading are much more complex for laminated fiber composites than they are for homogenous material [11].

The matrix (continuous phase) performs several critical functions, including maintaining the fibers in the proper orientation and spacing. In polymer matrix composites that form a strong bond between the fiber and the matrix, the matrix transmits loads from the matrix to the fibers through shear loading at the interface. In ceramic matrix composites, the objective is often to increase the toughness rather than the strength and stiffness; therefore, a low interfacial strength bond is desirable [12]. In present work, a new material has lower modulus of elasticity, therefore more flexion is gained.

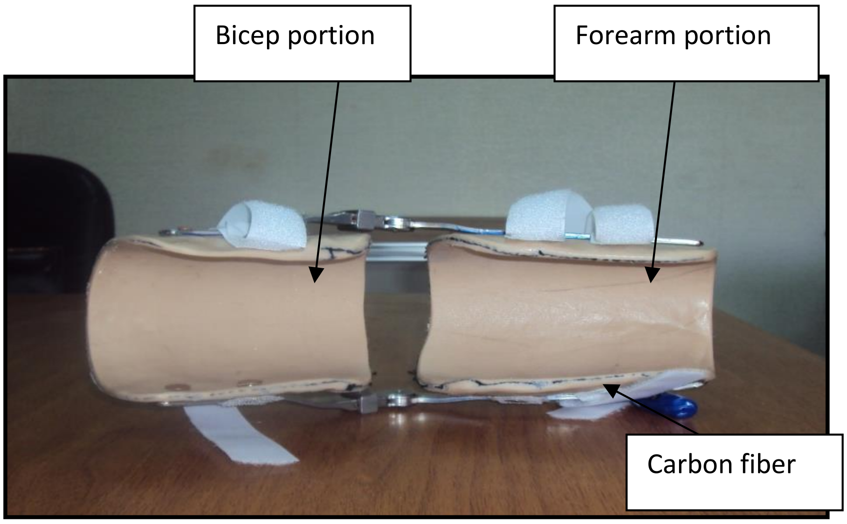
2. Manufacturing of elbow

Elbow orthosis is manufactured from two layers of polypropylene and a layer of carbon fiber is inserted between them, fastend rigidly so it can not be delaminated a parts due to the method of manufacturing which based on heating the composite material in a furnace to the recrystallization temperature lead to replacing the particles (in adjacent surfaces) its location as seen in fig. 1(a) and will be taken the shape of the gypsum model as shown in fig. 1(b) . The precise dimensions of elbow is achieved in final form as shown in fig. 1(c) .

(a)

(b)

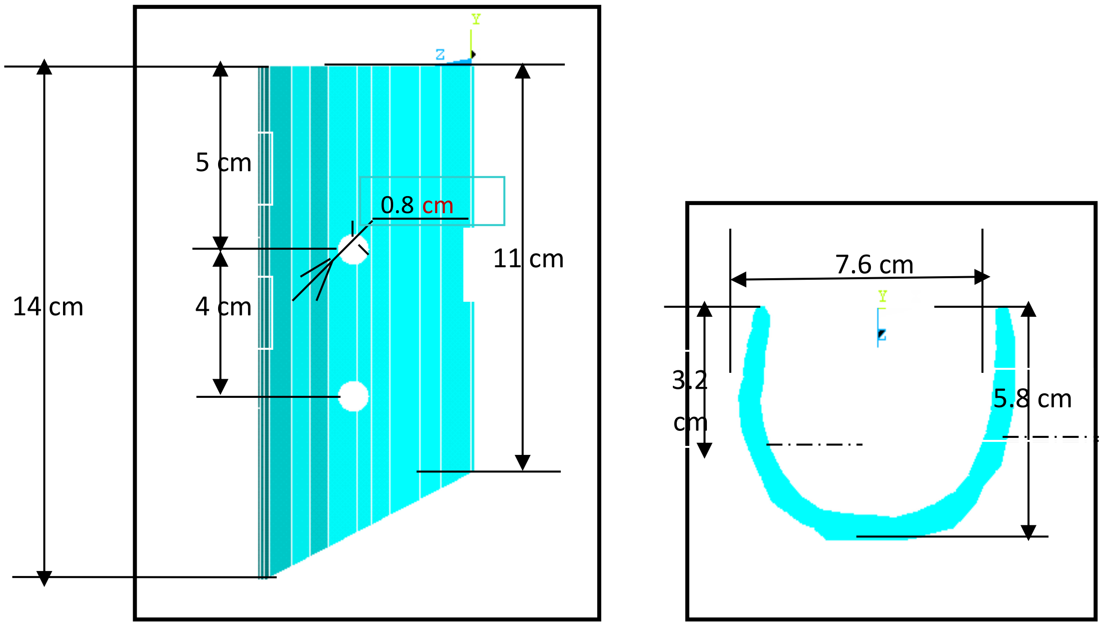
(c)



(d)

Figure 1. Manufacturing of elbow orthosis.
(a) sheet of PCP material, (b) Gypsum model, (c) molded of sheet,
and (d) final product.

The final design of elbow is illustrated in fig.1(d) which consists of two portions (upper and forearm portions) connected together by two steel bars. The upper portion of elbow or as called " bicep portion " is taken as case study for numerical evaluations for PCP material and PP material as a comparison and its dimensions are seen in fig.2 with about 0.5 cm average thickness.



(a) (b)

Figure 2. Dimensions of bicep portion of elbow.
(a) Font view, (b) Top view.

3. Mathematical model

The main assumptions used in this work are depends on wall thickness and internal pressure, and as follows:

1) The classification of cylinders are depends on its internal diameter to thickness ratio, which namely less than 10, between 10 and 20, and more than 20 are defined as thin shell, thin cylinder, and thick cylinder respectively. In this work d/t = 15.2, so its modeled as thin cylinder.
2) Internal pressure is assumed applied uniformly and constant on internal surface of elbow.

The two portions of elbow orthosis (bicep and forearm) are considered as thin cylinders with cutouts. Hoop and longitudinal stresses are induced in these cylinders due to applying internal pressure are listed as follows [10] :

$$\sigma_H = \frac{pd}{2t} \qquad (1)$$

$$\sigma_L = \frac{pd}{4t} \qquad (2)$$

The hoop stress acts at every point of the bicep part, being tangential to the circumference to the axis of the cylinder, while the longitudinal stress acts at every point parallel to the length of the elbow.

The circumferential is proportional to the diameter, so that the diametric strain is equal to the circumferential strain, where these strains are represented as follows [10]:

$$\varepsilon_H = \frac{\sigma_H}{E} - \upsilon \frac{\sigma_L}{E} \qquad (3)$$

$$\varepsilon_d = \frac{\partial d}{d} \qquad (4)$$

From which the increase in diameter can be calculated by equating (3) and (4), while the increase in length is estimated by equating the (5) and (6) which are illustrated as follows:

$$\varepsilon_L = \frac{\sigma_L}{E} - \upsilon \frac{\sigma_H}{E} \qquad (5)$$

$$\varepsilon_L = \frac{\partial L}{L} \qquad (6)$$

The volume of the bicep part is calculated, represents the upper arm of elbow, as a complete thin cylinder subtracted the cutout portion from it, as follows:

$$V = \frac{\pi}{4} d^2 L - V_{cutout} \quad (7)$$

$$V_{cutout} = \frac{1}{2} dtL\,\theta_{cutout} \quad (8)$$

By taking differentials of (7), gives:

$$\frac{\partial V}{V} = \frac{\partial d}{d} - \frac{\partial t}{t} \quad (9)$$

Then, from (9) the increase in volume is calculated.

4. Experimental Tests

4.1 Tensile Test

Tensile tests are carried out for both PCP and PP materials to investigate the mechanical properties of each of them using jaws with a constant speed no more than 10 mm/min which all tests are carried out in Al – Mustansryia University – college of Engineering. The force – extension chart for PCP material is illustrated in fig.3 . The rectangular specimen dimensions considered in current test are 2 x 0.7 x 33 cm for width, thickness, and length respectively, which approximately near in dimensions for standard specimen. Finally, the mechanical properties investigated in this test for both materials under study are listed in Table 1 . Table 2 illustrates the modulii of elasticity of several selected materials in addition to current materials for the purposes of comparison.

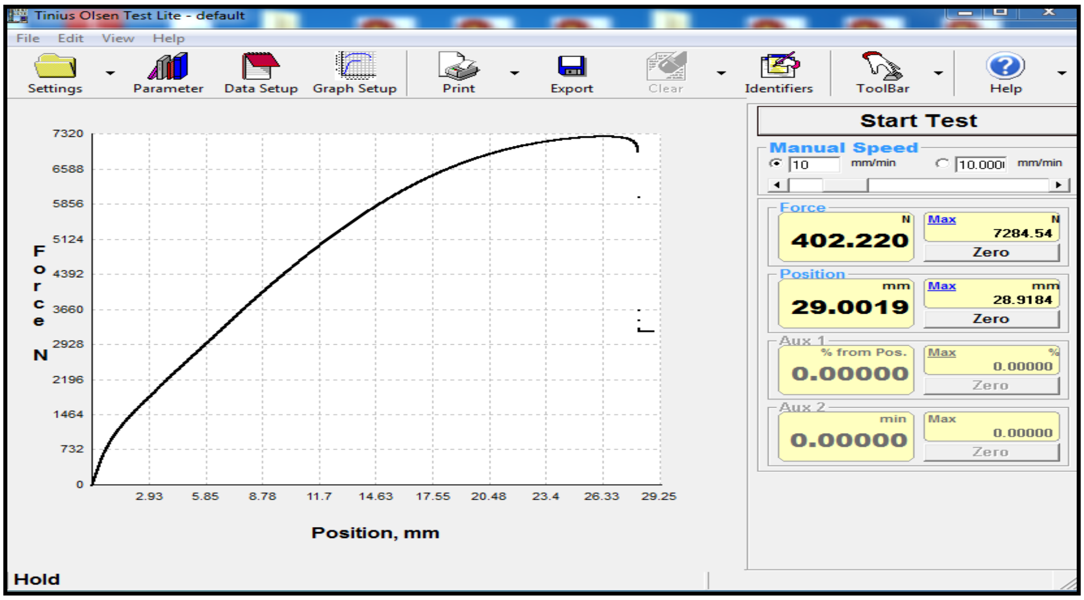


Figure 3. Load – extension chart for PCP material

Table 1. Mechanical properties for PP and PCP materials

Materials	*Young's Modulus* *MN/m^2*	*Yield stress* *MN/m^2*	Ultimate stress MN/m^2
PCP	22.1	6.54	52
PP	77.27	6	21

Table 2. Modulii of elasticity for comparison [13]

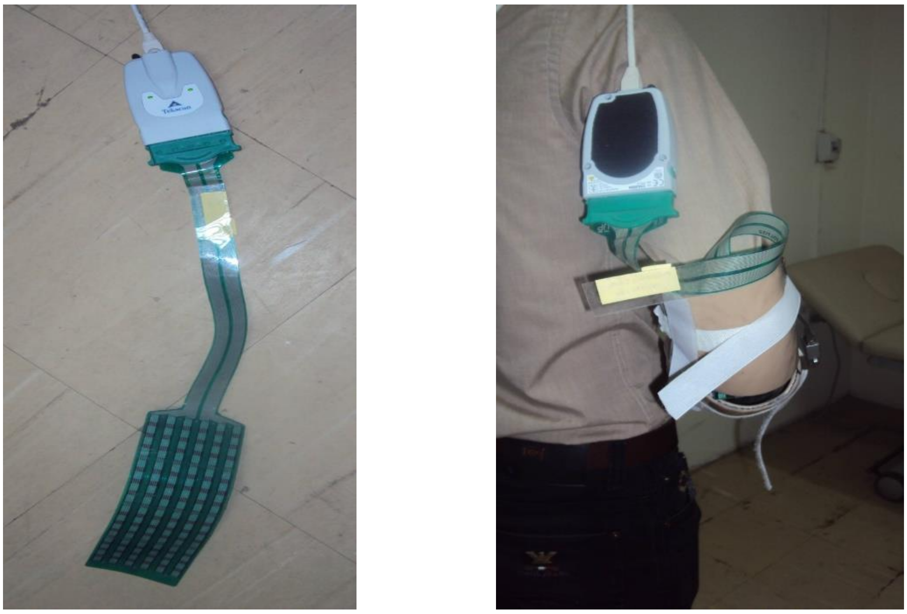
Steel *GN/m^2*	*Copper* *GN/m^2*	*aluminum* *GN/m^2*	*tin* *GN/m^2*	*PP* *GN/m^2*	PCP GN/m^2
210	120	72	42	0.07727	0.0221

4.2 Pressure Test

Determination of interface pressure between upper arm (bicep portion) and the elbow is measured in present work using a pressure cell shown in fig.4(a). The pressure cell is a merely mat of sensors is surrounded and fit between upper arm and elbow, which connected directly to a computer which has software to measure the pressure directly on a screen and that value represents the actual pressure that is required as input to ANSYS PACKAGE. The pressure device company is called "Tekscan" which concerned for medical purposes.

Fig.4(b) shows the patient wearing the elbow orthosis (14 cm length) with interface cell. The patient is 72 kg weight and 178 cm height suffers from damage in its bicep muscle due to an accident. The distribution of pressure center in elbow orthosis is shown in fig.5 , which clearly denoted that center of pressure is located and concentrated in middle period between flexion and extension.

The fluctuations of pressure during flexion and extension over seven cycles is shown in fig.6 . As the center of pressure is present in mid angular distance between flexion and extension of forearm, therefore the average is taken between 0 to 434 kPa for extension to flexion respectively; namely of 217 kPa. This value of pressure is not high when compared, for example, with the interface pressure induce between screw and nut teeth which reaches to about 703Psi (about 5 MPa).



(a) (b)

Figure 4. Pressure test

(a) pressure cell, (b) patient wear pressure cell

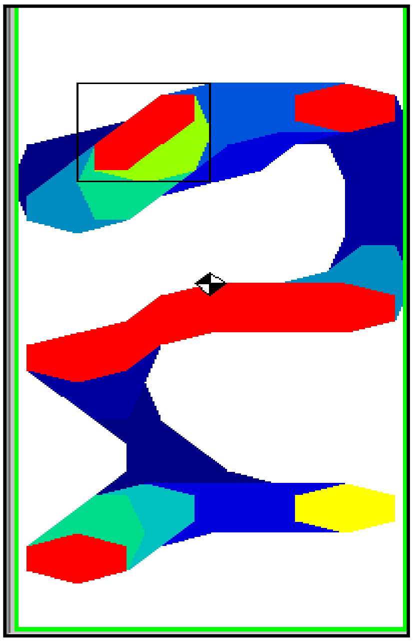


Figure 5. Distribution of pressure center in elbow

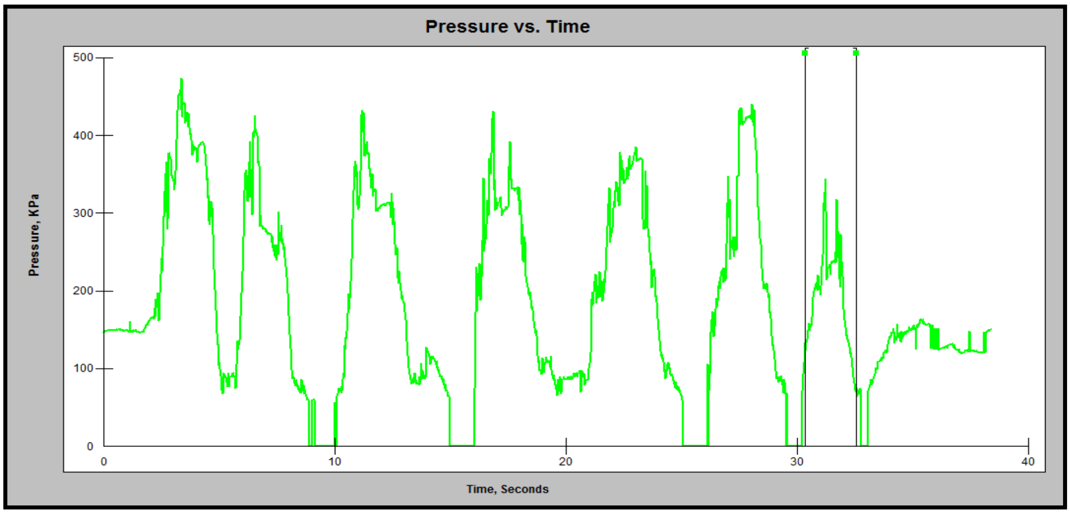


Figure 6. Fluctuating of pressure with time during extension and flexion of elbow (kPa)

5. Numerical results

The numerical investigation for the current work is done using ANSYS PACKAGE version 11 for both materials under study. The fixation of elbow are applying on four holes (zero deformation), while the number of elements are used in model is 2334 elements of (Brike 8 node 45) which quadratic element has 4 nodes in corners and the rest nodes are spreads in mid length of element side. Static pressure is applied on inner surface of elbow of 217 kPa as mean internal pressure, which is obtained from the previous test .

The deformation can be seen in figs. 7 and 8 for PCP and PP materials respectively. The Von – Misses stress was developed in elbow are illustrated in figs. 9 and 10 ; while the distribution of the stress located between the two fixed holes are shown in figs. 11 and 12 respectively for two materials under study along specified selected path (xx) as located and seen in fig.9 .

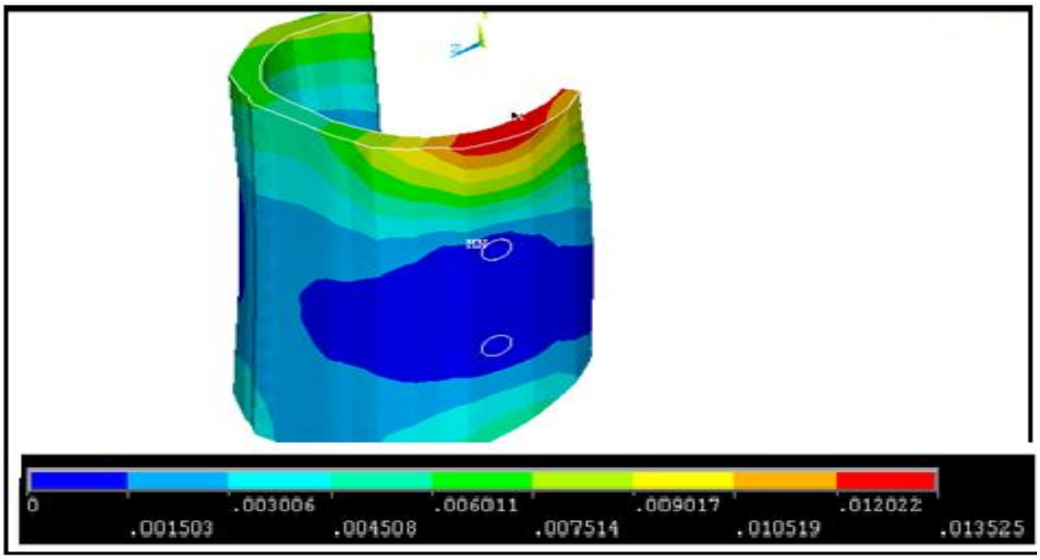


Figure 7. Deformation in elbow made from PCP material (m)

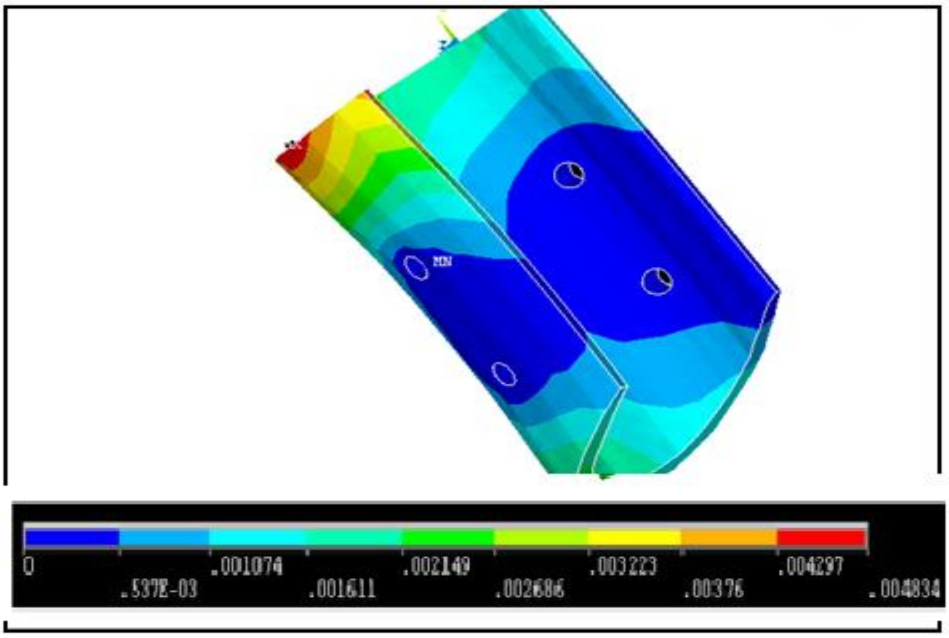


Figure 8. Deformation in elbow made from PP material (m)

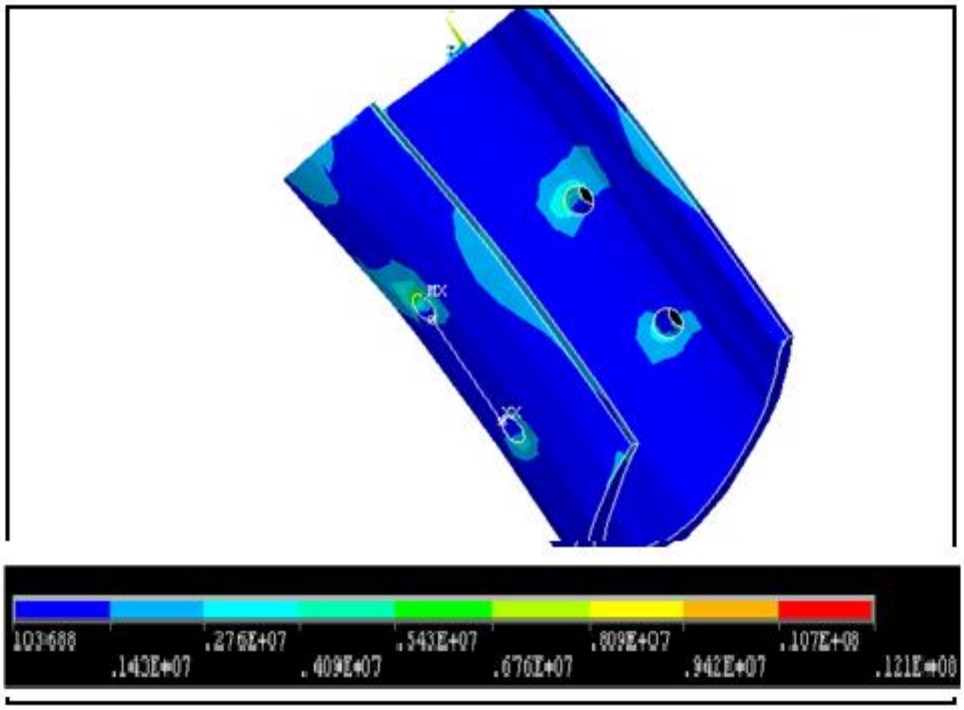


Figure 9. Von – Misses stress in elbow made from PCP material (N/m^2)

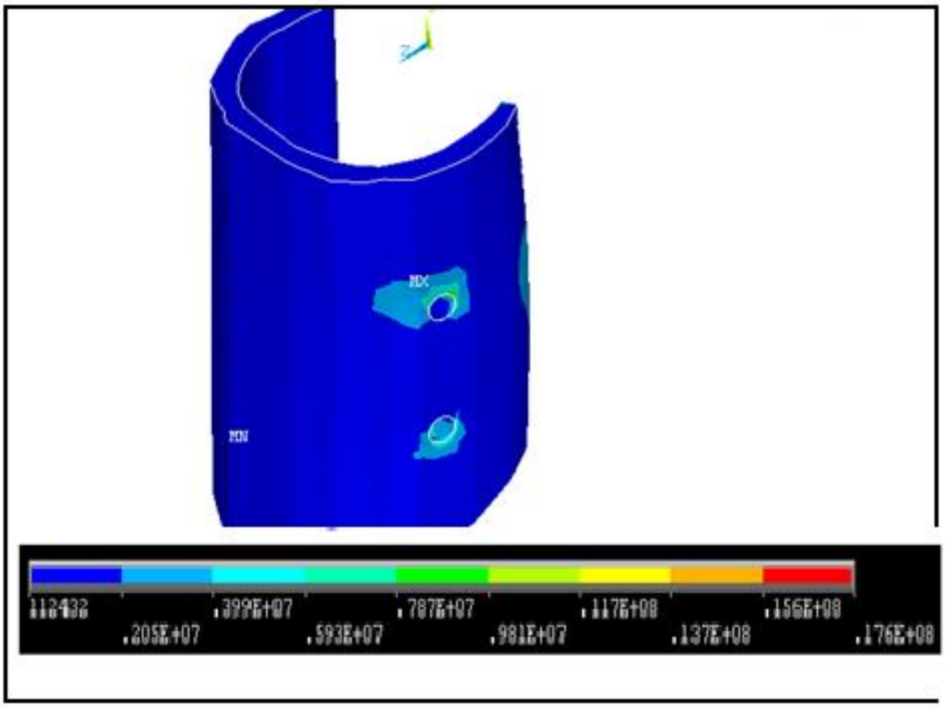


Figure 10. Von – Misses stress in elbow made from PP material (N/m^2)

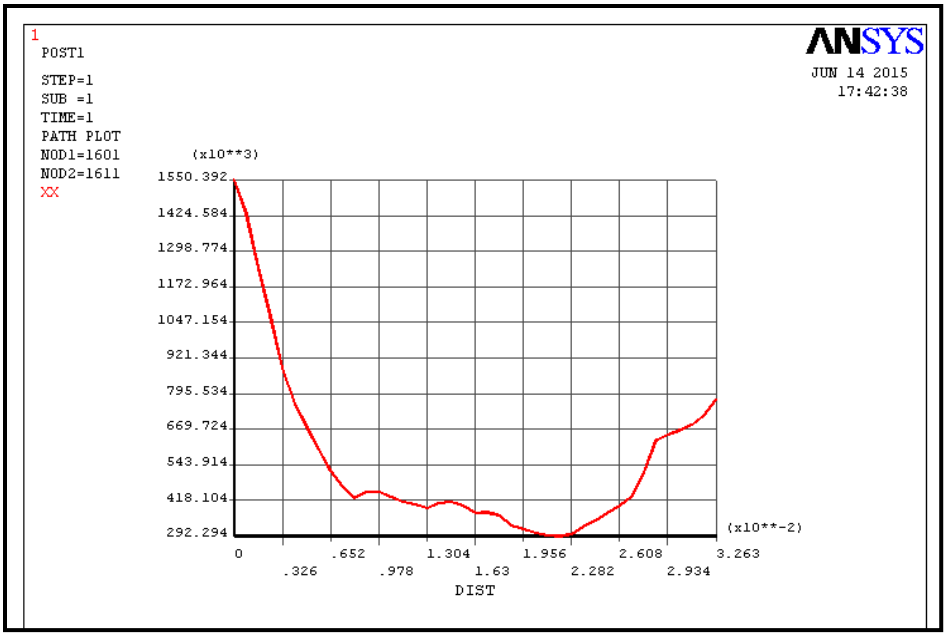


Figure 11. Distribution of Von – Misses stress between holes for PCP material(N/m^2).

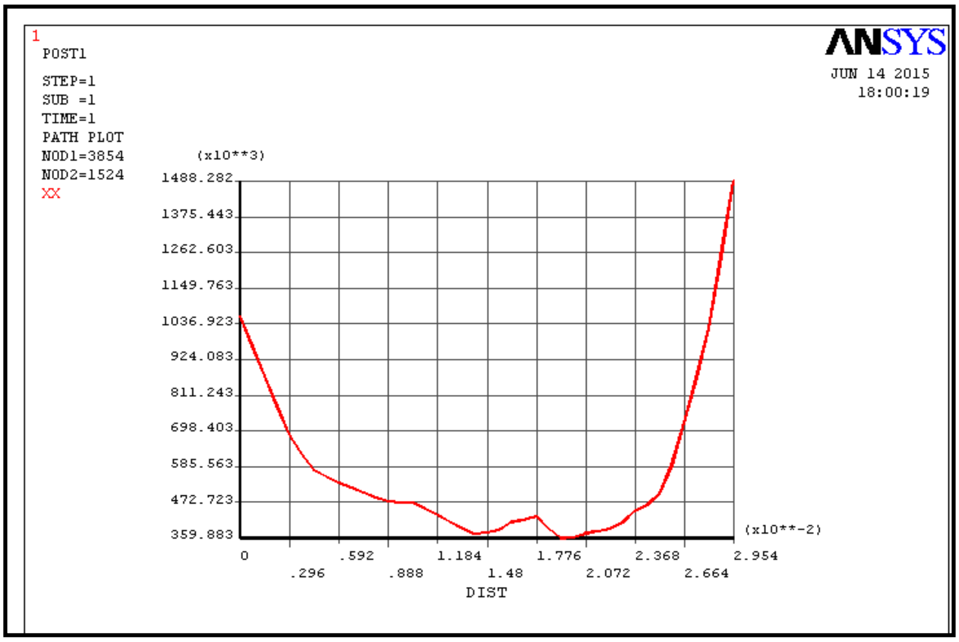


Figure 12. Distribution of Von – Misses stress between holes for PP material(N/m^2)

6. Discussion

The main goal of present work is to create a material that has more flexibility than the traditional PP material with lower modulus of elasticity (only 22.1 Mpa) for PCP material as compared with (77.27 Mpa) with reduction factor of 3.5 as illustrated in Table 1 . This means the new material is flexible and extends 3.5 time than old material and as a result the elbow orthosis is more elastic and therefore good care can be obtained especially for skin for patient who suffers from burns in their arms. Table 2 shows several modulii of elasticity of steel, copper, aluminum, polypropylene, and the new material for the sake of comparison.

The values of the mechanical properties concerning the yield stress and the ultimate tensile stress are more than the value of the old material by 8.25 % and 248 % respectively.

For numerical investigation, bicep part of orthosis are deformed due to internal pressure maximum values of 13.53 and 4.83 mm are shown in figs. (7) and (8) for PCP and PP materials respectively. The deformation results indicate that reinforcing of polypropylene increase flexibility and elasticity of orthosis under static loading of about 280 %, which means that the orthosis will be more delicate on patient's skin, and this leads to eliminate the use of padding between the arm and orthosis in order to minimize rigidity of orthosis on arm.

Figs. (9) and (10) represent Von – Misses stresses in bicep part for two materials under study with maximum values located in supported location (holes) to steel rods. Figs. (11) and (12) show the Von – Misses stress for the chosen path " xx " between two holes as shown in the previous figs. (9) and (10).

The two charts give maximum stresses in fixed holes of 1.55 and 1.48 MN/m^2 minimum values in between of 292.3 and 360 kN/m^2 for new and old materials respectively. Safety factors are determined by dividing values of yield stresses which already investigated from tensile test, namely 6.54 and 6 MN/m^2, by the maximum working stresses which finally give values of 4.22 and 4.05 for PCP and PP materials respectively.

The factor of safety for the new material of orthosis under static loading improves by 4 % when compared with the identical elbow made of polypropylene, these value of increment is really slight but the main objective has gained from this work is the elastic composite material needed to eliminated the red region must developing in old rigid material due friction between elbow and skin surfaces; in addition to hold any initiation of crack due the loading by existing carbon fiber.

7. Conclusions

The conclusions from using the new material are :

1) High reduction in modulus of elasticity by 3.5 times using the reinforced polypropylene by a sheet of carbon fiber, which means more flexibility in elbow is obtained.
2) Improvement in the mechanical properties concerning the values of yield stress (by 8.25 %) and the ultimate stress (by 248 %).
3) More elbow elasticity is obtained as the deformation gained increased by 280 % under internal pressure of 217 kPa.
4) The factor of safety of the new elbow is increased by 4 % than that of the old one.

Nomenclature

d Internal diameter

E Modulus of elasticity

L Length

P Internal pressure

PP Polypropylene

PCP Polypropylene – Carbon fiber – Polypropylene

t Thickness

V Volume

σ_H Hoop stress

σ_L Longitudinal stress

σ' Von – Misses stress

ε_H Hoop strain

ε_d Diametric strain

ε_L Longitudinal strain

τ_{xy} Shear stress in xy- plane

υ Poisson's ratio

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