INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 9, Issue 3, 2018 pp.283-294

Journal homepage: www.IJEE.IEEFoundation.org

Effect of the carbon nanotube (CNT) in the materials used for prosthetics and orthotics applications

Jumaa S. Chiad, Wajdi Sadik, Abbas Hameed Jeryo

Department of Mechanical Engineering, College of Engineering, Al-Nahrain University, Baghdad, Iraq.

Received 20 Oct. 2017; Received in revised form 20 Nov. 2017; Accepted 29 Nov. 2017; Available online 1 May 2018

Abstract

In this work, the optimal mechanical properties of the lamination materials that used in manufacturing prosthesis and orthoses parts are studied. The optimization is selected according to high yield, ultimate stresses, bending stress and fatigue properties. The method of selection the optimal materials is a response surface methodology (RSM) which depend on two parameters, reinforcement material Perlon fiber and percentage of multi-wall carbon nanotube MWCNTs which is mixed with matrix lamination resin. Thirteen samples are suggested according to RSM method by controlling two variables which are the layers number for Perlon and MWCNTs percentage. This method leads to select the optimum materials which give a maximum yield, ultimate and bending stresses. According to ASTM D638 and D790, the three imported tests are performed which are tensile, three-point bending and fatigue tests for all laminations materials as selected by RSM method and manufactured by vacuum method. Also, fatigue test is performed for optimal lamination material and compared with laminations manufactured in the previous study, 10 layers Perlon lamination and 424 laminations (4Perlon, 2carbon fiber and 4Perlon). The results obtained by Design Expert program version 10.0.2 showed that the lamination (10 layers Perlon and 0.75%of MWCNTs) is the optimum lamination according to the maximum yield, ultimate and bending stresses, and, endurance stress.

Keywords: Mechanical and fatigue properties; Response surface methodology (RSM); Perlon layers; Multiwall carbon nanotube (MWCNTs).

1. Introduction

Recently, researchers have shown an increased interest in prosthesis and orthoses because of many patients suffering from loss their limbs as a result of amputation or a birth defect. The prosthesis is an artificial replacement for any missing part of the body, while orthoses is an outer device using in the body part to provide one or more deferent capacity include, decreasing a pain, correct deformity, improvement in a function, assist motion or augment weak muscles, control spastic muscles and others functions [1]. After World War II, advanced in prostheses were remarkable. New fitting techniques, new materials and new concepts of design all aided the amputee. There was no similar technologic progress in orthotics, however. Recently the early 1970s seemed appropriate to appear the field of orthoses as the most Prominent, parochial and provincial portion of orthopedic surgery and rehabilitation [2]. The lower limbs orthoses or prostheses explores to fatigue and outer load for this reasons, studying and enhancement of mechanical

properties of materials that used in manufacturing are important demanded. The new ideas are to improve and enhance the properties by suggesting new materials or new designs for orthoses and prostheses. This means that the enhancement can be done in some applications by adding nanomaterials which lead to high mechanical properties. Multi-wall carbon nanotube MWCNTs are a subject that have attracted considerable interested from scientific researchers, community and industries due to its remarkable properties such as, good young modulus, excellent flexibility and high electrical and thermal conductivity [3]. CNTs also have extraordinary mechanical properties, they are 100 times stronger than steel as shown in the Table 1 [4].
This work aims to enhance and improve the mechanical and physical properties of the lamination materials and to get the best mechanical specifications such as high mechanical properties lighter, weigh, low cost and ease manufacturing. Moreover, for these reasons using MWCNTS instead of carbon fiber is suggested.

Table 1. Mechanical properties of some carbon nanotubes types.

	Young modulus (Gpa)	Tensile strength (Gpa)	Density (g/cm^3)
SWCNTs	1054	75	1.3
MWCNTs	1200	150	2.6
Graphite in-plane	350	2.5	2.6
Steel	208	0.4	7.8

2. Response surface methodology
The RSM is a combination of mathematician and statistic techniques which are used for experimental model building and analysis of problems, in which a response of interest is affected by multi-variables, and the goal is to improve this response. It is also efficient in the improvement of existing studies and products. By careful Design of experiments, the mean objective is to select optimum a response (output variable) which is affected by several independent variables (input variables). The benefits of the design of experiment are as follows [5]: (1) Numbers of trails are reduced as possible as. (2) the Optimum magnitude of parameters can be obtained. (3) Guess of experimental error is estimated. (4) a Qualitative estimate of the input and output parameters can be made. (5) Inference regarding the effect of parameters on the characteristics of the process is obtained.
In this analysis, the design of experiment used was the response surface methodology that using a central composite design for 2^2 factors, with five central points and $\alpha=\pm 2$. Thirteen runs are performed according to the experimental design matrix (five center point). Each parameter was used at different code levels of -2,-1, 0,1and 2 whereby each level used conformed to an actual value equivalent to the coded value. Thus, the input parameters studied are multi-wall carbon nanotube (MWCNTs) and numbers of Perlon layers. The experimental design matrix used for input parameters in term of actual factors is given in Table 2. The software DESIGN-EXPERT 10.0.2 was used to develop the model.

Table 2. Levels of input parameters used with respective coding.

Factor	Unit	Low level (-1)	High level (+1)	- alpha (-2)	+ alpha (+2)
MWCNTs	%	0.25	0.75	0	1
perlon	No. layers	6	10	4	12

3. Selecting optimal lamination materials parameters using optimization tool design
The range of multi-wall carbon nanotube percentage which mixed with lamination resin 80:20 are varied between 0% and 1 %, whereas the number of Perlon layers is varied from 4 to 12 layers as shown in Table 3.

4. Experimental works
4.1 Materials used in research
The materials used to manufacture laminations by vacuum methodare:
- Perlon stockinet white (Ottobock health care 623T3).
- Multi-wall carbon nanotube which used to mixing with resin by ultrasonic device, MWCNTs have size (10-30) nm and length 10-30µm.
- Laminations resin80:20 (polyurethane).

- Hardening powder.
- Polyvinylacohol PVA bag.
- Materials of Gypsum mold.

Table 3. Suggested experiment by RSM.

Runs No.	Exp. No.	MWCNTs (%)	Perlon (layers)
1	1	0.5	4
2	2	0.5	8
3	3	0.25	6
4	4	0.5	8
5	5	0.75	6
6	6	1	8
7	7	0.5	8
8	8	0	8
9	9	0.75	10
10	10	0.5	8
11	11	0.5	8
12	12	0.25	10
13	13	0.5	12

4.2 Equipments used in research

- Gypsum mold: mold is made from gypsum material in parallelogram shape with dimension (9×13×24) cm^3.
- Vacuum device: the device is consists from vacuum pump, pipes, and suction hood. The main benefits of the devices are, to shape the mold perfectly and to ensure no bubbles in the first space between first PVA and mold. Also, to prevent bubbles in the cast by second space between two bags (PVA).
- The Ultrasonic mixing device of type Hielscher, ultrasonic processor UP200Ht is used to ensure mixing between MWCNTs and polyurethane resin with different weight percentage (0, 0.25, 0.5, 0.75, 1) %.
- Sensitive scale device: the digital weighing device.

Also others mechanical tools used such as forming and cutting.

4.3 Tensile test

The test is conducted by using the universal testing instrument (Testometric) as shown in Figure 1 which available in Al-Nahrain university/applied Labs of the mechanical engineering department and Kufa university/ labs of mechanical engineering. The shapes and dimensionsof all specimens are arranged according to ASTMD638 [6] by computer numeric control (CNC) machine and according to thickness of the materials to type of specimens used type (I and IV) as shown in Figure 2 all specimens for all runs are tested at strain rate equal to 2 mm/min.

Figure 1. Tensile test devices (Testometric).

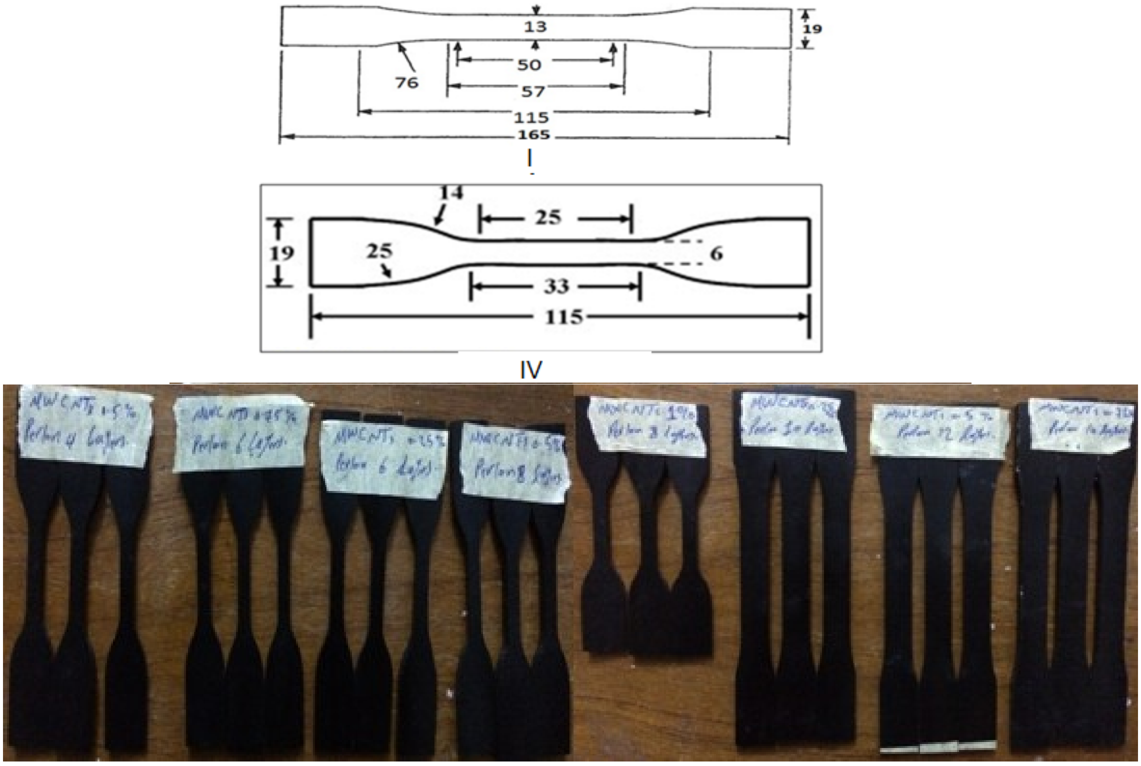

Figure 2. Specimens of tensile test types (I and IV).

4.4 Bending test

For three-pointflexure bending test samples for each lamination(Runs),by using the universal testing instrument (Testomertic) as shown in Figure 3. Samples were machined by laser CNC according to ASTM (D790-03 [7] as shown in Figure 4, three samples were tested with crosshead speed of 2 mm/min and capacity 25 KN to detect bending properties for each lamination and selection the optimal material.The calculations of bending stress, flexural bending strain, and bending modulus have been done using the following equations [7]:

$$\sigma_f = (3PL/2bd^2)[1 + 6(D/L)^2 - 4(d/L)(D/L)] \quad (1)$$

$$\varepsilon_f = 6Dd/L^2 \quad (2)$$

$$E_f = (\sigma_{f2} - \sigma_{f1})/(\varepsilon_{f2} - \varepsilon_{f1}) \quad (3)$$

Figure 3. Bending test device (Testometric).

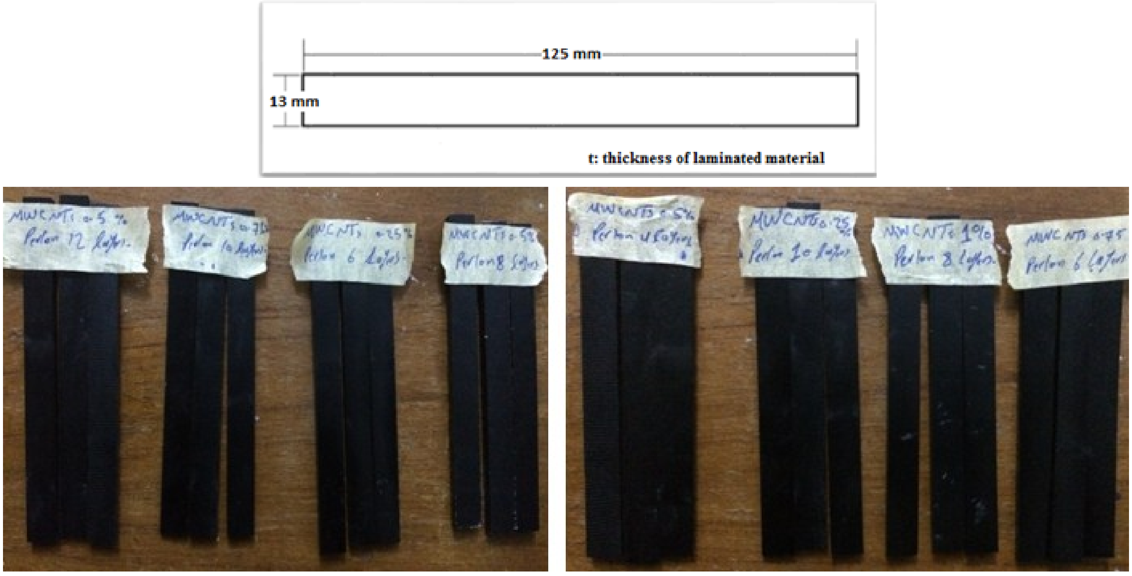

Figure 4. Bending specimen's dimensions.

4.5 Fatigue test

The fatigue test was done by using alternating-bending fatigue testing machine (HSM20), which available in Al-Nahrain University/Mechanical Engineering Department.This machine used the alternating bending stress at a rotational speed of 24 revolutions per second. The dimension and shape of thespecimen manufactured according to the manual of the machine [8] as shown in Figure 5. Also, all calculationswere calculated according to the Nomogram in manual of the machine. Seven specimens were tested for optimum lamination material and select fatigue properties and (S-N) curve and compare with available lamination material.

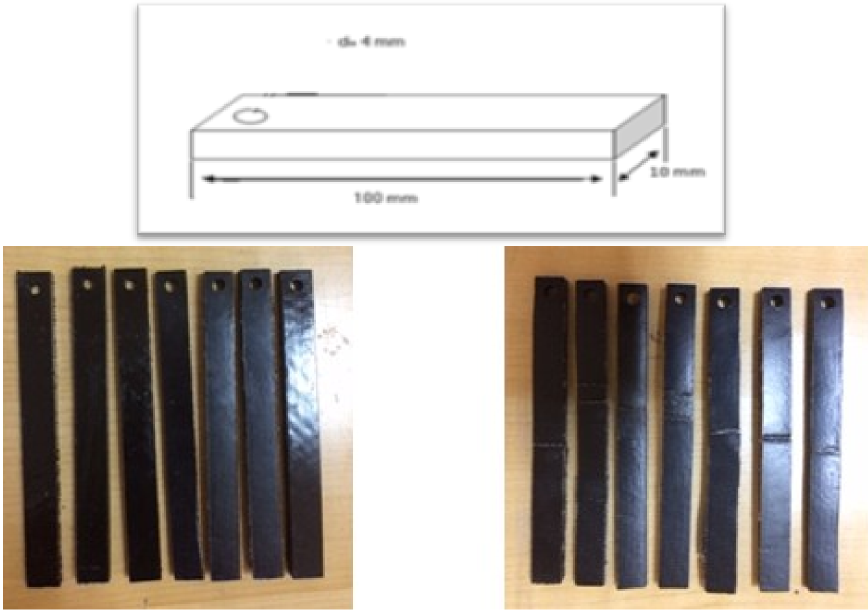

Figure 5. Fatigue test specimens.

5. Results

5.1 Physical properties

Thicknesses, density, weight per unit area and volume fraction for all lamination (runs) were calculated. The results show that average thickness and weight are affected by number of Perlon while MWCNTs have no effect on physical properties, as shown in Figure 6 which explains influence of number of Perlon layers and MWCNTs on weight, As obvious that the relation between the Perlon layers and weight is linear as well as there is no effect of MWCNTs on the weight which give indication that MWCNTS can be neglected if compared to total weight. The value of volume fraction depends on thickness and weight so that its value depends only on No. of Perlon layers.

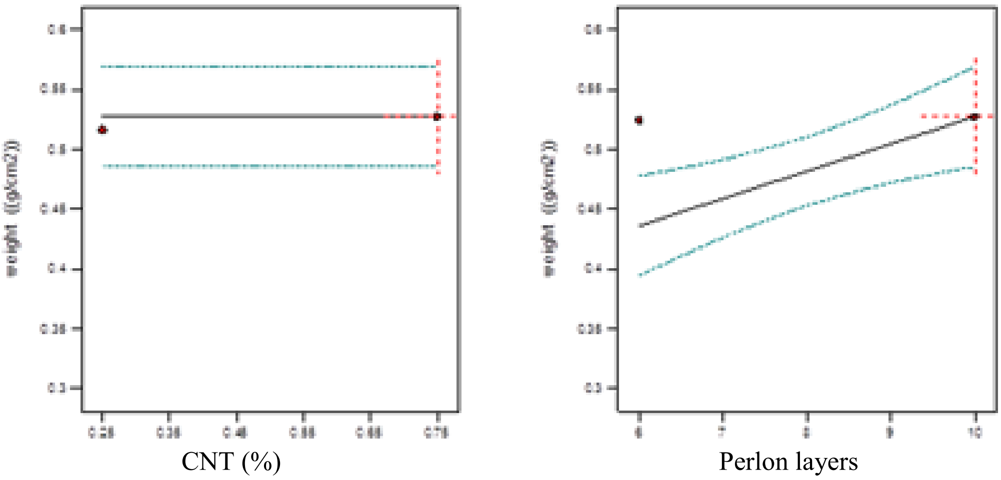

Figure 6. Influence of the number of Perlon layers and MWCNTs on the weight of the lamination.

5.2 Tensile test results

Three samples are tested at room temperature, the specimens tested for each lamination run and the average value is taken. Tensile strength, yield stress, and young modulus are calculated from strain-stress curve by tensile test calculation, these values are important in the fatigue test. Also, noted that yield stress and others properties increased by increasing percentage of multi-wall carbon nanotube and Perlon layers in different percentage according to the percentage of MWCNTs, which mixed with matrix material leads to change properties of lamination resin as result high properties of MWCNTs, and layers of reinforcement material (Perlon fiber). Figure 7 reviews the counter graph of multi-wall carbon nanotube and Perlon layers and yield stress as a response. It can be seen that the increase in both MWCNTs and Perlon leads to an increase in the yield stress. The joint exhibits poor yield stress at a low percentage of MWCNTs as well as when a lower number of Perlon layers. While reaching to a maximum at high magnitudes of MWCNTs and Perlon layers.But, But, the magnitude of yield stress results was decreased with a high weight percentage of MWCNTs due to a strong attractive force between MWCNTs leading to excessive agglomeration and MWCNTs remain in small straps or agglomerates [9].

Figure 8 shows 3D graph of yield stress as a function of MWCNTs and Perlon. It can be noted that the increase of MWCNTs resulted in a slight increase in the yield stress value, while the increase of Perlon caused a higher increase in the value of the yield stress.

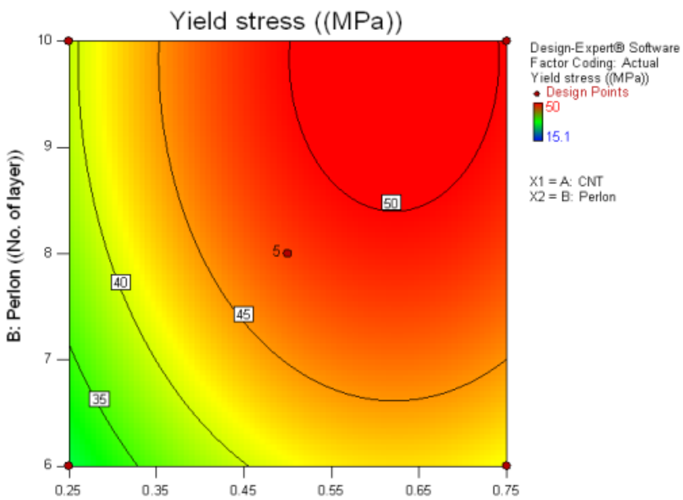

Figure 7. Contour graph of yield stress as a function of MWCNTs and Perlon.

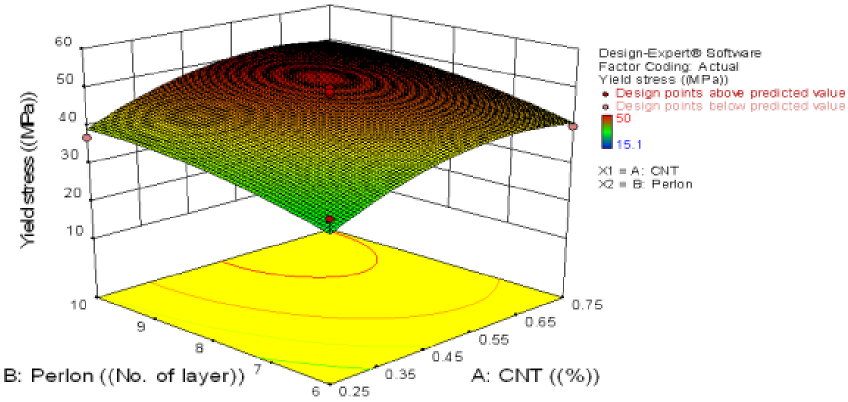

Figure 8. 3D graph of yield stress as a function of MWCNTs and Perlon layers.

5.3 Bending test results

The Testometric device was used in three-points Flexural test. Three specimens are used for each lamination material (runs) with different multi-wall carbon nanotube and Perlon layers as designed in Design Expert10.0.2 program by response surface methodology and the average valueis calculated. Figure 9 shows the contour graph of the interaction of multiwall carbon nanotube and Perlon layers. It can be noted that the increase of both MWCNTs and Perlon layers led to increase the maximum bending stress value as in values of the yield and ultimate stresses. Figure 10 depicts the predicted versus actual bending stress data for comparison reason. Whereas, Figure 11 shows the effect of MWCNTS and Perlon on maximum bending stress each individually. From figures, it can be noticed that the effect of Perlon layers lowest at a minimum value without a percentage of MWCNTs and value of bending stress reach nearly (70 Mpa). In contract affected of MWCNTs at a minimum value without affect Perlon layers is higher.

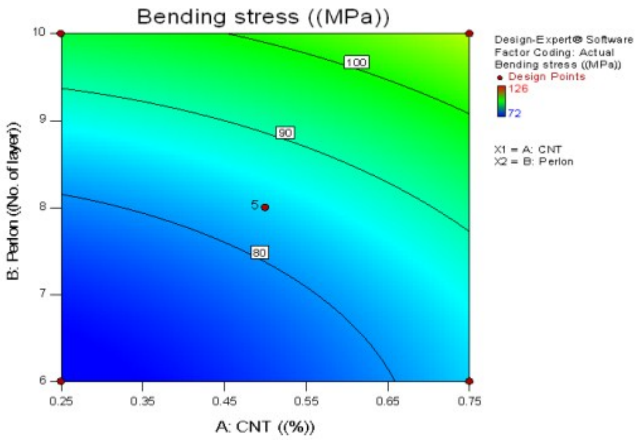

Figure 9. Contour graph of maximum bending stress as a function of MWCNTs and perlon layers.

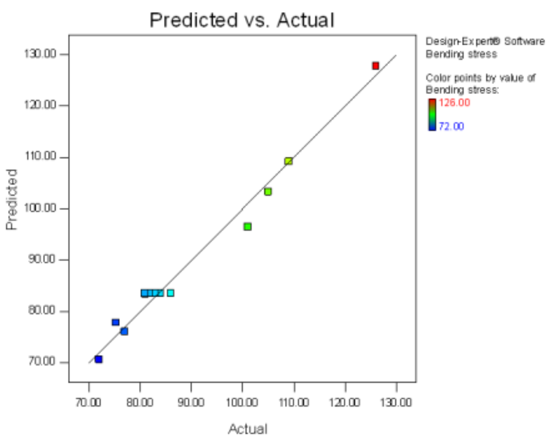

Figure 10. Predicted versus actual of maximum bending stress data for comparison.

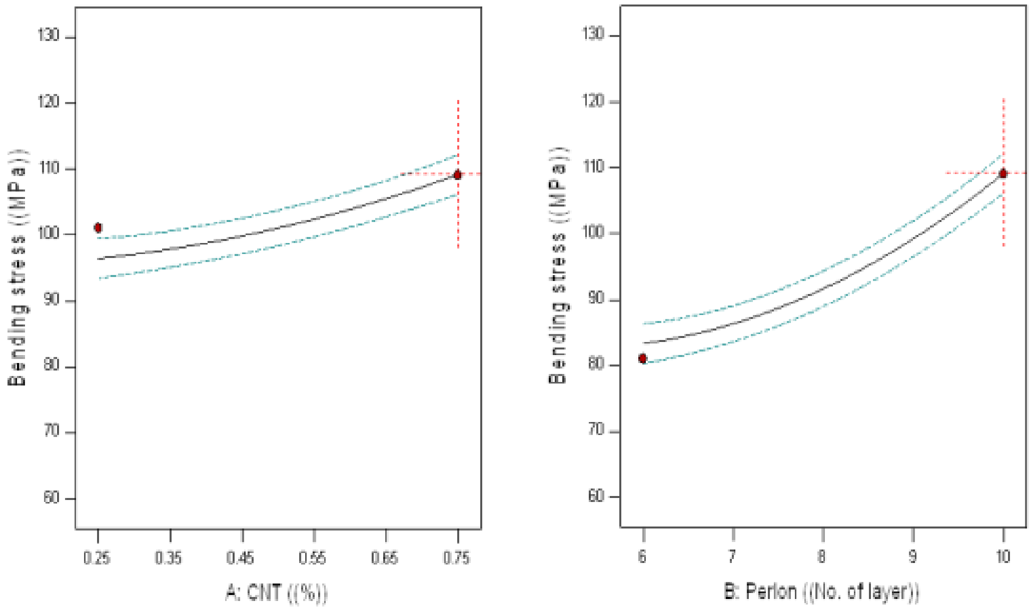

Figure 11. Maximum Bending stress as a function of MWCNTs and Perlon each individually in actual units.

5.4 Numerical optimization of yield stress, ultimate stress, maximum bending stress and weight

The numerical optimization was provided by the Design of Experiment software to find out the optimum combinations of parameters in order to fulfill the requirements as desired. Therefore, this program was used for responses, yield stress, ultimate stress, maximum bending stress and weight as a function of two factors: multiwall carbon nanotube and number of Perlon layers. From the design summary given in Table 4 for main factors and responses, it can be seen that yield stress, ultimate stress and bending stress are modeled with a quadratic model, also effect of weight entered in optimization solution.In this work, weights or importance are not change so the four responses (yield stress, ultimate stress, maximum bending stress and weight per unit area) have the same weights and are not in conflict with each other.

The ultimate aim of this optimization was to determine the maximum response that at the same time satisfied all the variable properties. Table 5 lists the constraints of each variable for numerical optimization of the yield stress, ultimate stress, maximum bending stress, and weight. According to this table, one possible run fulfilled these specified constraints to select the optimum values for the yield, ultimate, maximum bending stresses and weight, as given in Table 6. It can be seen that this run gave desirability 0.850. Figure 12 explains the bar graph for desirability. Figures 13-16 depict the optimum values of the yield stress, ultimate stress, maximum bending stress and weight, respectively. It can be concluded from these figures that the optimum value of yield stress is 49.788 Mpa, the optimum value of ultimate stress is 66.42 Mpa,the optimum value of maximum bending stress is 109.201 Mpa and the optimum value of the weight is 0.528 g/cm².

Table 4. Main factors and responses.

Factors	Name	Unit	Min.	Max.	Coded values	Mean
A	MWCNTs	(%)	0	1	-1.00=0.25 +1.00=0.75	0.5
B	Perlon	layers	4	12	-1.00=6 +1.00=10	8
Response	Name	Unit	Min.	Max.	Mean	Ratio
Y1	Yield stress	Mpa	15	50	40.692	3.333
Y2	Ultimate stress	Mpa	35	70	54.769	2
Y3	Max. bending stress	Mpa	72	126	89.430	1.75
Y4	Weight	g/cm^2	0.380	0.598	0.478	1.573

Table 5. Constraints of each variable for numerical optimization.

Type of variables	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:MWCNTs	is in range	0.25	0.75	1	1	3
B:Perlon	is in range	6	10	1	1	3
Yield stress	maximize	15.1	50	1	1	3
Ultimate stress	maximize	35	70	1	1	3
Bending stress	maximize	72	126	1	1	3
Weight	is in range	0.4	0.53	1	1	3

Table 6. The optimum values for the yield, ultimate, maximum bending stresses and weight.

Number	MWCNTs	Perlon	Yield stress	Ultimate stress	Bending stress	weight	Desirability
1	0.750	10.000	49.788	66.420	109.201	0.528	0.850 Selected

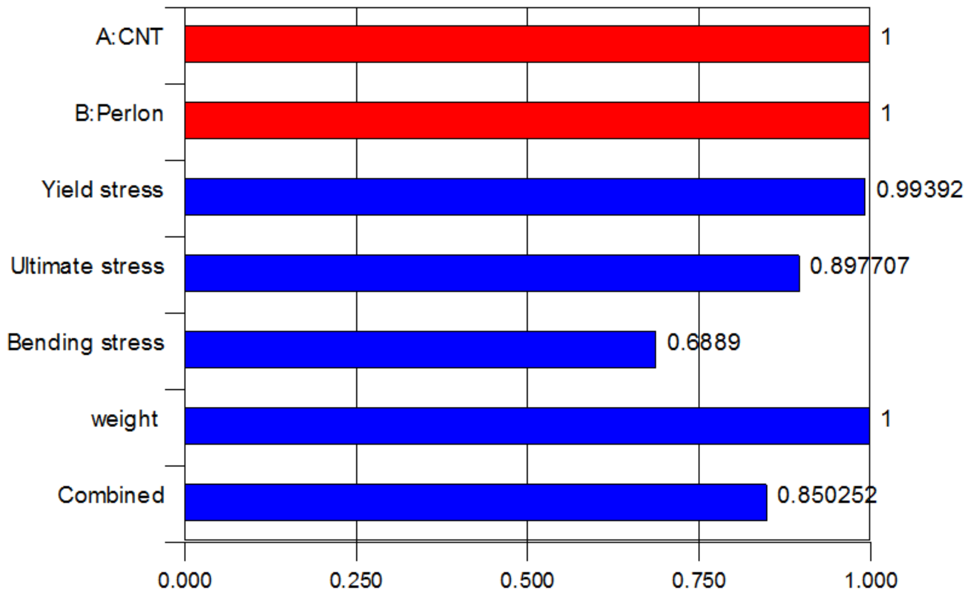

Figure 12. The bar graph for desirability.

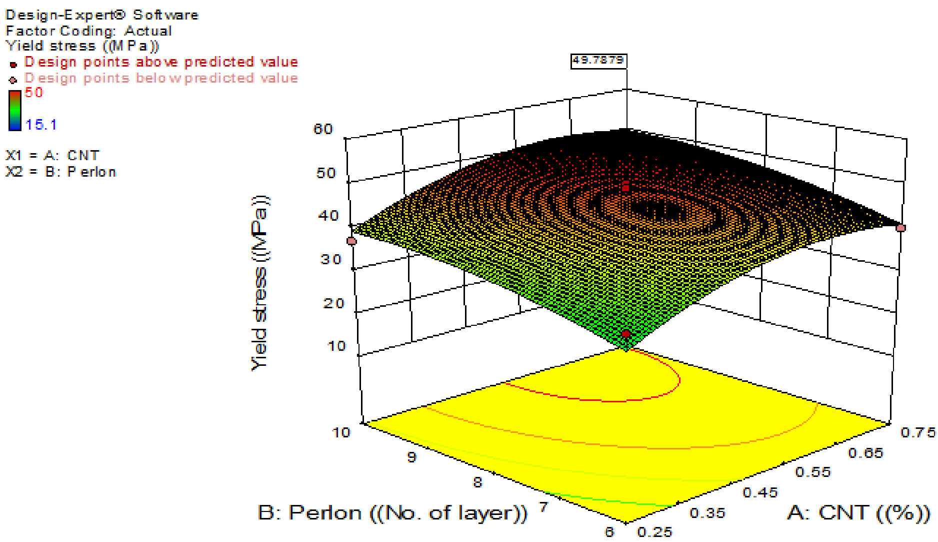

Figure 13. The otimal value of the yield stress (Mpa).

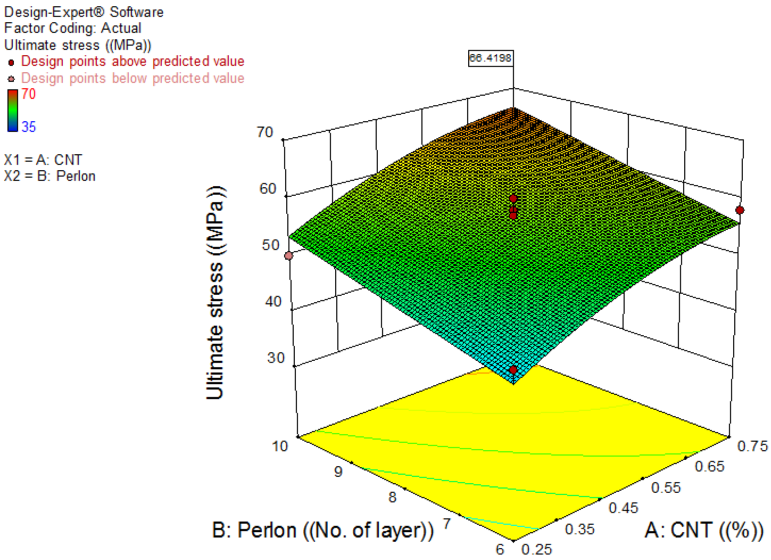

Figure 14. The optimal value of the ultimate stress (Mpa).

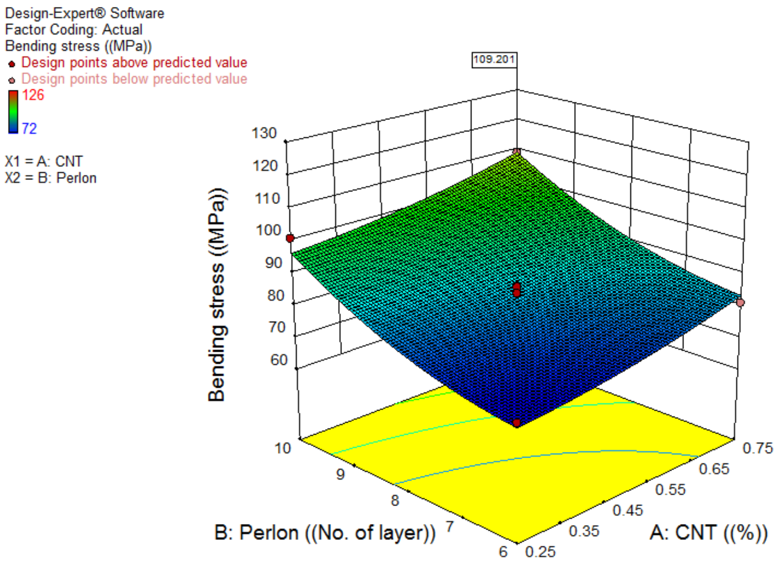

Figure 15. The optimal value of the maximum bending stress(Mpa).

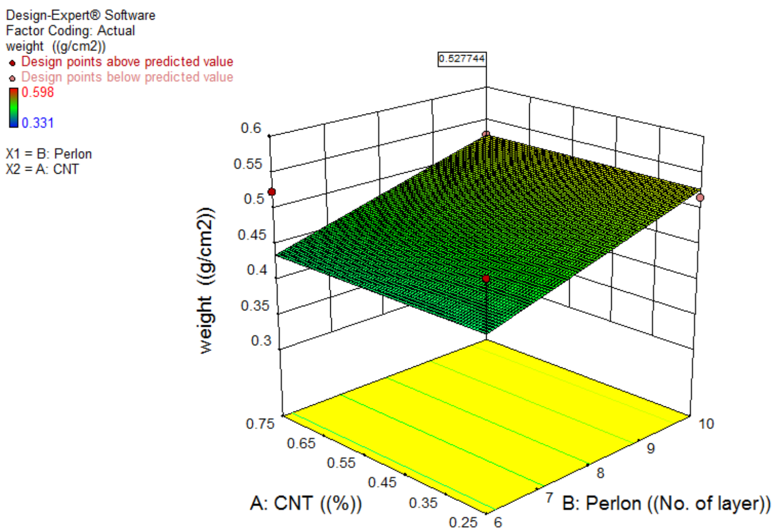

Figure 16. The optimal value of the weight (g/cm^2).

5.5 Comparison of ANOVA results with experimental ones

A comparison between the actual or experimental (with optimal tool design) and the predicted for yield stress, ultimate stress, maximum bending stress, and weight is listed in Table 7. This table also explains the percentage error between actual from experimental results and predicted results by software analysis for all responses (yield stress, ultimate stress, maximum bending stress, and weight). In addition, according to this table, it shows very good agreement between the actual results of the yield stress, ultimate stress, Maximum bending stress and weight and the predicted results obtained by the ANOVA analysis.

Table 7. Comparison between the actual and predicted responses.

	MWCNTs (%)	Perlon (No. of layers)	Yield stress (Mpa)	Ultimate stress (Mpa)	Max. bending stress (Mpa)	Weight (g/cm^2)
Actual	0.75	10	48	65	109	0.527
Predicted	0.75	10	49.788	66.42	109.201	0.528
Error (%)	-	-	3.725	2.184	0.184	0.189

5.6 Fatigue test results

After selection of the optimal lamination materials according to maximum yield stress, ultimate stress and maximum bending stress also entered affect of the weight per unit area on the select optimal materials which represent weight and cost depending on two optimum design tools (multiwall carbon nanotube and number of Perlon layers), fatigue test results obtained for optimum materials (0.75% carbon nanotube and 10 layers of Perlon) and compared with that results precedented inrefrences [10] for two cases or laminations materials (10 layers of Perlon) and (4perlon layers-2carbon fiber-4perlon layers) due to obtaining difficulty.

Table 8 gives the equation of fatigue life for each laminations materials and Figures 17-19 show the (S-N) curves for three type of composite materials From figures and the table concluded the fatigue life highly increased in lamination of (0.75% MWCNTs and 10 Perlon layers) compared with other two laminations this mean that the suggested optimum material had high fatigue properties and long time without need to replacing or maintenance also, the endurance stress of the optimum lamination was increased by limits (63.65, 40.4)% compared with 10 layers Perlon lamination and 424 laminations respectively.

Table 8. Fatigue life equations for each composite materials.

Material	Fatigue life equation	Endurance limits Mpa at 10^6	R^2
10 layers perlon	$\sigma=33.64\ (N_f)^{-0.059}$	15	
Perlon with carbon fiber (424)	$\sigma=60.98\ (N_f)^{-0.065}$	25	
10 perlon with 0.75% MWCNTs	$\sigma=116.33\ (N_f)^{-0.075}$	41.27	0.9949

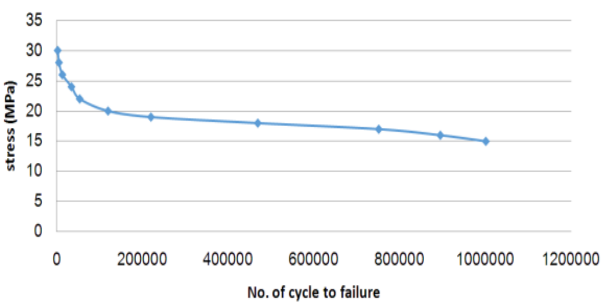

Figure 17. S-N curve for 10 layers of perlon.

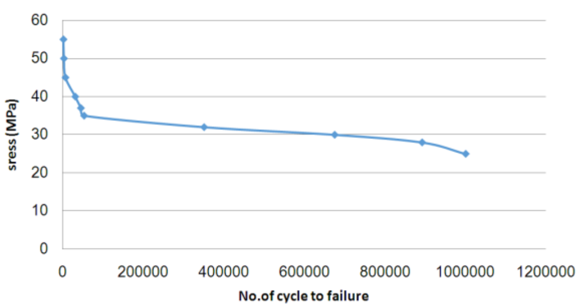

Figure 18. S-N curve for perlon& carbon fiber (424).

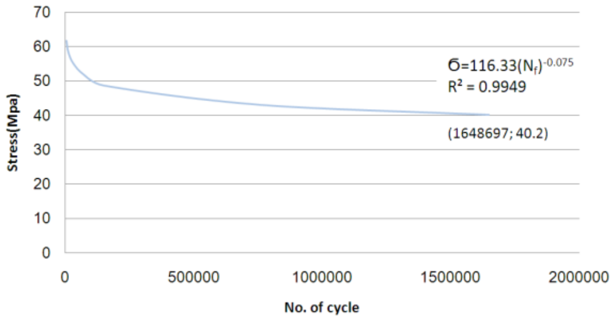

Figure 19. S-N curve for optimum material (0.75% MWCNTs & 10 perlon).

6. Conclusion

In This study,optimal mechanical properties are developedby utilizing nanomaterials. The properties achieved are significant which consideredexcellent materials that used in manufacturingof the lower limbs orthoses as well as prostheses.

1. The response surface methodology (RSM) can be used to predicting the mechanical properties accurately with maximum error of 3.725 % in comparison with the actual experimintal testing method.
2. Depending on two factors, Perlon, and multiwall carbon nanotube, the main conclusion obtained is that the mechanical properties are optimaized and improved when adding the suggested MWCNTs as clarified by the results.
3. The experimental test and RSM method show that the best lamination is obtained when the rate of MWCNTs is 0.75% and the Perlon layers number is 10. Also, the optimal mechanical properties of this lamination according to yield, ultimate, bending, and fatigue limit stresses are 48, 65,109, and 41 Mpa respectively.
4. The fatigue endurance limit for the proposed materials (0.75% MWCNTs and 10 Perlon layers) is enhanced about 40.4% when comparing to that of the taditional material used in the prosthetic and orthotic centers which consist of (4Perlon +2carbon fiber+4Perlon) layers.

Refrences

[1] H. Uustal and E. Bearga, Prosthetics and Orthotics Sara Cuccurullo, M.D. “Physical Medicine and rehabilitation board review” New York/USA Demos Medical Publishing, 2002: 409-489.

[2] St. Louis. Toronto. Princeton “Atlas of Orthotic” American Academy of Orthopaedic Surgeons, Second Edition pp. 3-7, 1985.

[3] H.J. Qia, K.B.K. Teob, K.K.S. Lauc, M.C. Boycea; W.I. Milneb, J. Robertsonb, K.K. Gleasonc “Determination of mechanical properties of carbon nanotubes and vertically aligned carbon nanotubeforests using nanoindentation” Journal of the Mechanics and Physics of Solids Elsevier Ltd 2003; 51: 2213-2237.

[4] Nasreen Raheem Jber, Alaa Adnan Rashad, Mehdi Salih Shihab, “Effects of carbon nanotubes on the physical properties of a nematic liquid crystal N-(40-methoxybenzylidene)-4-butylaniline” Journal of Molecular Structure 2013; 1043: 28-36.

[5] M. Y. Noordin, V. C. Venkatesh, S. Sharif, S. Elting, and A. Abdullah, “Application of response surface methodology in describing the performance of coated carbide tools when turning AISI 1045 steel” Journal of Materials Processing Technology, 2004; vol. 145: 46-58.

[6] American Society for Testing and Materials information, handing series "Standard Test Method for Tensile Properties ASTM (D 638-03)" 2000.

[7] American Society for Testing and Materials information, handing series "Standard Test Method for Flexural Properties ASTM (D790-03)" 2000.

[8] Alternating Bending Fatigue Machine instruction manual HSM20, 2001.

[9] M.M. Rahman, S. Zainuddin, M.V. Hosur, J.E. Malone, M.B.A. Salam, Ashok Kumar, S. Jeelani, “Improvements in mechanical and thermo-mechanical properties of e-glass/epoxy composites using amino functionalized MWCNTs”, Composite Structure, 2012; 94: 2397-2406.

[10] Muhsin J. J. Ayad M. T., Saif M. A. “Analysis, Design, and Manufacturing of Ankle Foot Orthoses” M. Sc Thesis, Mechanical Engineering Department, Al- Nahrain University, Baghdad, 2015.