Effect of Temperature on Buckling of Composite Materials Column

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Abstract

A theoretical and experimental investigation pertaining to the buckling behavior of slender fiber reinforced polymer columns subjected to axial loading under varying temperatures (from room temperature to 50℃). Two groups of composite materials were used for manufacturing of test specimens, the first consist of perlon fiber as a reinforcement and acrylic resin as a bonding matrix, while the second consists of a combination of perlon and carbon fibers as reinforcement. The composite specimens were fabricated by vacuum molding technique and cut according to ASTM D-638 for conducting tensile test. The data from tensile test were used to calculate the effective slenderness ratio and defining the column as Euler buckling column. An experimental rig was designed, manufactured and calibrated to study the effect of thermal and buckling load subjected to columns.

Numerical analyses pertaining the buckling behavior for both groups were conducted. The results show that the temperature has a considerable effect on properties of fiber reinforced polymer composites where the value of critical load and Young's Modules decrease with the increase of temperature for both groups. Perlon & Carbon reinforcement composites gave best mechanical properties, which make them the best candidate to improve the buckling resistance characteristics of composite materials.

KeyWords: Buckling, Temperature, Composite Materials, Carbon and Perlon fibers

1. Introduction:

The increased use of Fiber Reinforced Polymer (FRP) composites in major load-bearing structures brings many challenges to material scientists and structural engineers. One of these challenges is the prediction of its behavior under sustained service loads [1].Thin-walled composite column, if subjected to compressive normal stresses over all or part of the cross-section most frequently fail by loss of stability which makes buckling a major consideration in design [2].

The composites can be severely degradated under thermal loading caused by high service temperature .This temperature-dependent behavior reduces mechanical load carrying capacity and thus can lead to structural failure under operational loads [3].

Preliminary results of a buckling test conducted on composite columns made from glass fiber reinforced unsaturated polyester were reported by oleiwi et al [4]. Where the specimens were prepared by using hand lay-up technique with different fibers volume fraction Vf. While Julias A. et al [5]. Illustrated experimentally and arithmetically the influence of delamination defect length and on the critical buckling failure load of hybrid laminate and its form of mechanical failure. The results indicate that the critical buckling loads reduce with raising the delamination defect length.

Hashem and Yuan [6] developed a criterion for clearly distinguishing between short and long FRP composite column behaviors, experimental and analytical investigations were conducted on column sections manufactured using E-glass fibers and polyester and vinylester as binding matrices.

The aim of the present study is to obtain basic understanding of the effect of various temperatures on the buckling behavior of composite materials. The effect of the proposed temperatures may be obtained by investigating the changes of the critical buckling load.

2. Theoretical Analyses:

The slenderness ratio is a primary indicator of the mode of failure one might expect for a column under load. According to the slenderness ratio the columns are categorized as long, intermediate and short [7]:

$$Sr = L / r \quad \dots (1)$$

$$r = (I / A)^{1/2} \quad \dots (2)$$

Where:

Sr = slenderness ratio.
r = radius of gyration.
L= the effective height.
I = Least moment of inertia.
A= Area of cross section.

The determination of whether the column is long, intermediate or short can be found by calculating the critical slenderness ratio [7], which is:

$$Sr\ critical = \sqrt{\frac{2\,\pi^2\,E\,C}{\sigma\ yield}} \quad \dots (3)$$

Where:

E =Modules of elasticity.

C = The end condition number, when both end are fixed to use (C=4).

If the actual slenderness ratio is greater than (Sr critical), then the column is long, and Euler formula should be used to analyze the column. If the slenderness ratio is less than (Sr critical), then the column is intermediate.

For a long two ends fixed-supported column under an external compression load (P). The theoretical critical buckling load (elastic stability limit) is given by Euler's formula [8]:

$$Pcr = \frac{4\pi^2 EI}{L^2} \quad \dots (4)$$

3. Experimental Work:

The steps of this paper will be summarized as:

3.1 Material

The materials needed in the manufacturing of test specimens are as shown in figure (1):

a) Perlon fibers
b) Carbon fiber
c)Lamination resin: Polymethyl methacrylate (PMMA)
d)Hardening powder

Figure (1): The Materials used in the manufacturing of test specimens.

3.2 Specimens for mechanical properties:

The tensile specimens are cut using CNC machine according to a standard of tensile test of ASTM (D-638) type. The specimens were tested using universal tensile test device (Tinnitus Olsen type machine) with (100 KN capacity) at room temperature with linear speed of (5 mm/min).

3.3 Manufacturing the groups of composite materials:-

The mass of the reinforcement material for a composite testing sample and a composite testing sample are measured using digital sensitive weighting device according to the required volume fractions. Composite specimens were fabricated by vacuum modeling technique according to lamination arrangement given in table (1). For manufacturing the specimens ,the mold of gypsum are prepared with dimensionality (28,18.5,12.5) cm, the PVA bag is stretch on the mold, reinforcement layers (5 layers of perlon fiber) are applied then two layers of carbon fiber then another five layers of perlon fiber with layer of PVA bag is put on , the matrix materials which consist of a mixture of acrylic resin and hardening powder mixed according to the standard ratio for each 100 part of acrylic resin mixed (2-3) part of hardening and injected to the layers and distributed homogenously by small tube and applied for 10 minute a cubic composite material is obtained which will be cut according to the required dimensions of specimens with 20cm height and 5cm as width as in figure (2).The same procedure was applied for all groups. This lamination arrangment has been chosen due to it use in the prosthesis.

Table (1): Lamination arrangement

Groups	No .of Layers	Lamination arrangement	Description of Layers	Thickness (mm)
A	10	10	perlon fiber as (reinforcement)	4.7
B	12	5-2-5	(5perlon& 2carbon fibers &5 perlon fiber) reinforcement)	4.9

Figure (2): Specimens for buckling test.

3.4 Design and Calibration of New Buckling Device:

In this study, a special experimental rig was designed and manufactured for a particular purpose to study the effect of thermal and buckling load subjected to column members.

The rig was assembled from the following parts to have a new and special device prepared and ready to study the effect of heat on a column under a compressive load as shown in figure (3). This figure shows the main items of the experimental rig which are:

1- Hydraulic press (10 tons) capacity.

2- Load cell (SS 300 model with (2 tons force capacity) as shown in figure (4).

3-Digital load indicator (model: SI 4010 R) as shown in figure (5).

4- The dial gauge.

5-Set of Jaws: it is made of tool steel. It was manufactured according to special design to fix the sample without any movement as shown in figure (6).

6-The thermal chamber: to study the thermal effect on composite materials, thermal chamber is designed and manufactured. The thermal chamber consists of the following parts:

a) Chamber: An equally split cubic metallic box made of aluminum was designed and constructed with dimensions of the chamber are (40 cm × 36 cm ×30 cm). The box is closed tightly to keep a constant temperature and lowering the heating loss as shown in figure (7).

b) Heater (400 watt) as shown in figure (7).

c) Fan as shown in figure (7).

d) Ducting: a system inside the chamber is used to distribute the heat homogenously.

e) Digital temperature controller (model (AI K3)): it used to [- 50 ℃ to 200 ℃] with allowance of (± 1℃)as shown in figure (5).

The load cell was experimentally calibrated in the laboratory using standards weights; it was found that the reading was exactly the same as the standards weights.

3.5 Thermal Property Tests (Thermal Expansion Coefficient Measurement):

The thermal property of composite material required in this study is the thermal expansion coefficient. The linear thermal expansion coefficient is evaluated using the following equation:

$$\alpha = \frac{\Delta L}{L \,.\, \Delta T} \qquad \dots (5)$$

Where:

α = Thermal Expansion coefficient (m/m.℃)

L = Original length of the sample (m)

ΔL = Change in length of the sample (m)

ΔT = Temperature change (℃).

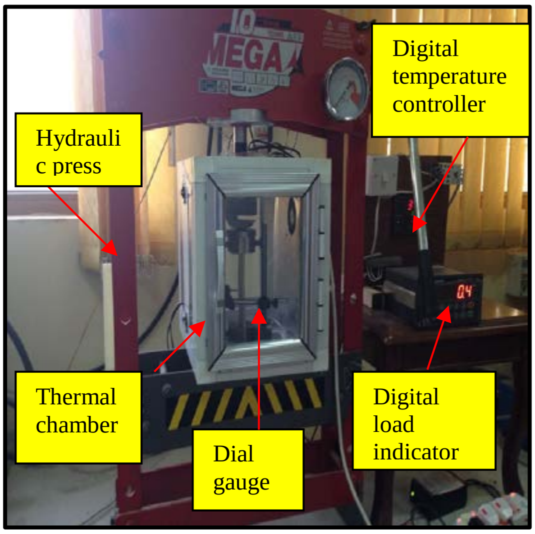

Figure (3): Buckling test device

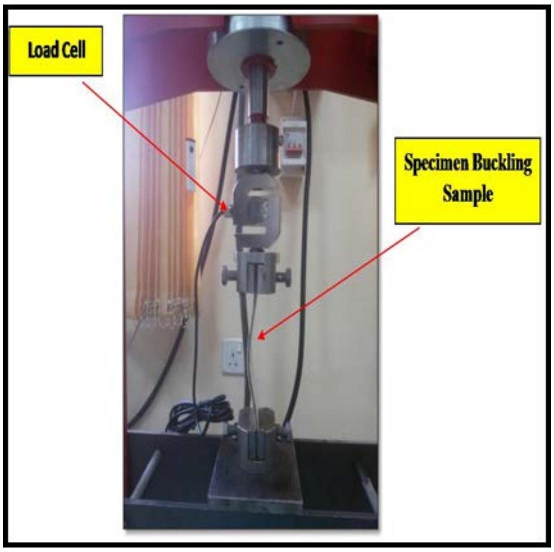

Figure (4): Load cell

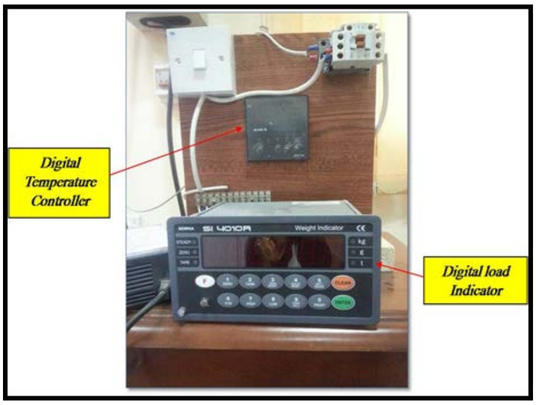

Figure (5): Digital load indicator and digital temperature controller

Figure (6): Set of jaws.

Figure (7): Thermal chamber containing (A) Heater (B) Fan.

An experimental evaluation of the thermal expansion coefficient was carried out using the same testing buckling specimen with dimension of (170 mm × 50 mm). The linear expansion test was performed for one of the each group types of buckling specimens over arrange of temperatures to (60 °C), with gradual change in temperature of (ΔT= 5 °C).

3.6 Buckling by thermal loading test:

The third type of specimens was used to study the behavior of columns under the thermal and buckling load:

Test procedure was carried out in sequence as follow:-

1. Fixing the specimens at its ends between the upper and lower jaws.
2. Mounting the dial gauge with its magnetic base on the lower jaw base.
3. Wrapping the specimen and the dial gauge with the splitting thermal chamber.
4. Euler predicated load was calculated and applied on the composite column at room temperature to obtain the critical deflection (0.1% of the specimen length).
5. Applying heat inside thermal chamber to raise the temperature to reach 30℃. The temperature change was kept for a period of time (15 minute) to ensure well heat diffused into the specimen then recording the resulting deflection and the corresponding load.
6. Compressive axial load are applied on the column till reaching the critical deflection for the specimen then recording the corresponding load.
7. The above steps were repeated for anther specimen with temperature (40 °C and 50 °C).
8. placing a new testing sample and increasing the temperature gradually from room temperature, it was noticed that the testing sample would reach the critical deflection even without applying any compressive load which makes this temperature to be considered as the critical buckling temperature and the recorded load as the critical buckling load.

4. Numerical Analyses:

Numerical analysis with ANSYS (workbench 15) Software was used to obtain the critical load that induced buckling. Eigenvalue buckling analysis in ANSYS has six steps:

1. Build the Model: with entering both material properties and geometry.
2. Generate the mesh: The next step is to create a finite element mesh for the part.
3. Defining loads and boundary conditions: The column is assumed to be fixed at both ends with a purely compressive load applied at the ends.
4. Obtain the static and the Eigenvalue buckling solution.
5. Expand the solution: This step is used to review the buckling mode shape
6. Review the results:

Buckling analysis was conducted for both groups and the mechanical properties obtained from tensile test were used as input data in ANSYS program to calculate critical buckling load.

5. The Mechanical and Thermal Test Results:

The testing results for the two groups of fiber composite materials are shown in details in forms of curves and tables.

5.1 Tensile test results:

The tensile test for the two groups specimens were carried out. The results of tensile test for these groups are shown in table (2).

The results show that group (B) gives the best mechanical properties. The difference in the mechanical properties of these materials is related to types of used materials. It is clear that reinforcing composite materials with carbon fiber improves their strength and stiffness characteristics and this combination of properties would eventually enhanced the overall performance of composite materials. Also it is noted that reinforcing with perlon fibers give the lowest tensile properties, meaning that perlon improves the mechanical properties of matrix material to a small extent.

Table (2): Mechanical properties of test specimens.

Groups	Young Modules [MPa]	Yield stress [MPa]	Ultimate stress [MPa]
Group A	951.08	7.6	14.85
Group B	2358.49	23.77	32.42

5.2 Determining the coefficient of thermal expansion (CTE):-

Two graphs were plotted between the (ΔT) against the dimension change which are shown in figures (8) and (9) for both groups (A and B) respectively.

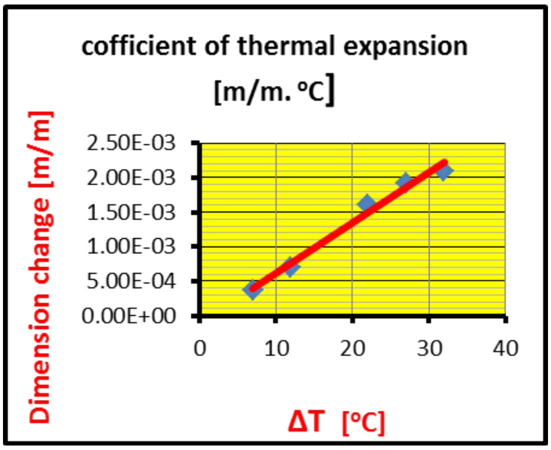

Figure (8): Coefficient of thermal expansion of group (A) materials.

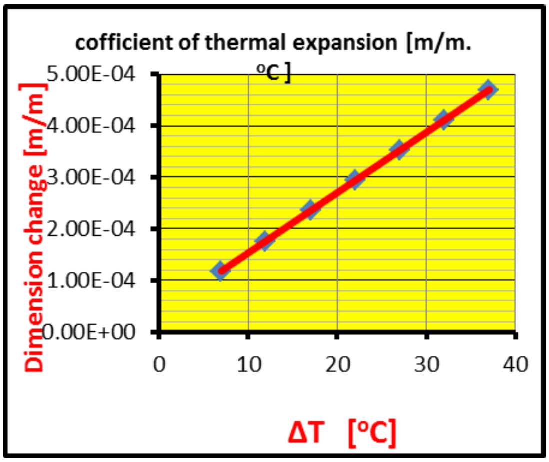

Figure (9): Coefficient of thermal expansion of group (B) materials.

The (CTE) was evaluated as the slope of those graphs which are tabulated in table (3).

Table (3): Coefficient of thermal expansion (CTE)

Groups	Coefficient of thermal expansion [m/m.°C]
Group (A)	7×10^{-5}
Group (B)	1×10^{-5}

Table (3) shows that group (A) has a higher CTE than group (B). The reason is due to the influence of fiber type used as reinforcement which is carbon fiber that may often exhibit high dimensional stability, low coefficient of thermal expansion; subsequently, it affects on temperature-dependent behavior. Obviously it is concluded that the use of (10 layers) of perlon fiber in group (A) had a much larger effect in increasing linear coefficient of thermal expansion (LCTE) values of composites.

5.3 Buckling test results:

5-3-1 Euler critical load:

For a long two ends fixed-supported column under an external compression load (P). The theoretical critical buckling load (elastic stability limit) is given by Euler's formula and tabulated in table (4).

Table (4) Euler buckling load

Groups	Theoretical buckling load [N]
Group (A)	827.56
Group (B)	2327.73

A stiff material is sensitive for high resistance to buckling. From table (4), it is clear that group (B) with high modules of elasticity of carbon fiber have an incomparable mechanical properties which are unequalled by other materials. The reduction in stiffness property resulted by using perlon fibers as a reinforcement material in group (A) decreases the buckling resistance.

5-3-2 Experimental results:

In this study, the two groups are tested under different temperatures to evaluate their behavior as they are subjected to concentric loading, the data that were recorded and tabulated in tables (5) and (6) as follows:

Table (5): Experimental results for testing group (A) of composite material (by applying heat and compression load).

Temp. [°C]	Deflection by heating [mm×10⁻²]	Deflection by force [mm×10⁻²]	Load by heating only [N]	Applied load by(compression with heat) [N]	Net critical load [N]
25	0	50	0	827.5	827.5
30	1	50	5.39	706.58	701.19
40	5	50	117.6	607.6	490
50	20	50	191.1	490	298.9

Table (6): Experimental results for testing group (B) of composite material (by applying heat and compression load).

Temp. [°C].	Deflection by heating [mm×10⁻²]	Deflection by force [mm×10⁻²]	Load by heating only [N]	Applied load by(compression with heat) [N]	Net Critical load [N]
24	0	21	0	2327.7	2327.7
30	2	21	8.82	1690.5	1681.68
40	5	21	19.6	1241.66	1222.06
50	17	21	51.94	932.96	881.02

1- Buckling analysis for group (A)

This group has (10 layers of reinforcement), the critical buckling of this group occurred only by heating the sample to a temperature of (53 °C) with a recorded load of (327.32 N) which was considered as the critical buckling load. By fitting technique, a derived formula for buckling behavior for net critical load as a function of temperature variation was obtained as follows:

$$P_{cr} = 0.150\,T^2 - 32.33\,T + 1539 \quad \dots (6)$$

Where:

P_{cr} = Net Critical Load [N]

T = Temperature [**°C**].

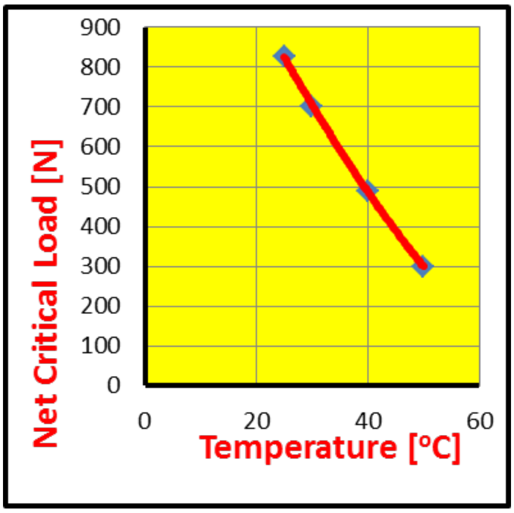

Figure (10): Critical buckling load vs. temperature.

It can be noticed from figure (10), that the net critical load for group (A) is rapidly lowered with increasing temperature because this group shows a very high coefficient of thermal expansion which can generate high mechanical deformation.

2- Buckling analysis for group (B)

This group has (12 layers of reinforcement) (5 perlon + 2 fiber carbon +5 perlon), the critical buckling occurred by heating the sample to (58 °C) with load (73.5 N) as critical buckling load. By fitting technique, a derived formula for buckling behavior for net critical load as a function of temperature variation as shown in figure (11) was obtained as follows:

Pcr = 1.706 T2 – 179.6 T + 5618 … (7)

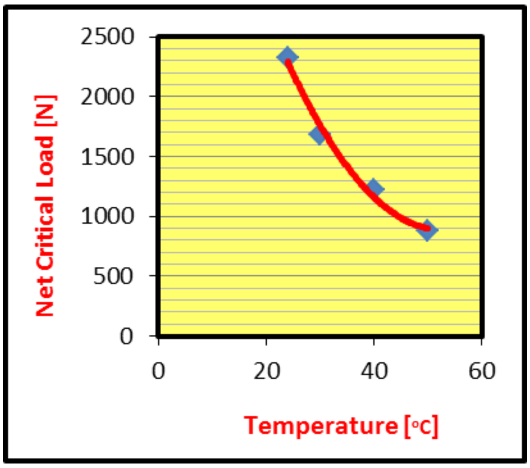

Figure (11): Critical buckling load vs. temperature.

It can be concluded that the improvement in buckling behavior exhibited by the test specimens (columns) is attributed to this combination of reinforcement materials.Poly methyl methacrylate (PMMA) acrylic resin, although being one of the most popular matrix materials, is associated with high coefficient of thermal expansion and poor mechanical properties but it can be strengthened with an addition of structural component (reinforcement) added in the acrylic matrix, to form a composite structure.

5.4 Temperature effect on elastic modulus:

The degradation of the elastic properties with temperature is reported, by using experimental data from the critical load and by adding this load to equation (8) [8].

$$E = \frac{Pcr\, L^2}{4\pi^2\, I} \qquad \dots (8)$$

Where:

E= Modules of Elasticity [MPa]

P_{cr} = Applied load by (compression with heat) [N].

L = Length of testing specimen [m]

I = Least moment of inertia [m^4].

By fitting technique, a derived formula for modulus of elasticity as a function of temperature variation was obtained as follows:

$$E = 0.413\, T^2 - 43.88\, T + 1777 \qquad \dots (9)$$

Where:

E = Modules of Elasticity [MPa].

T = Temperature [^{o}C].

By fitting technique, a derived formula for modulus of elasticity as a function of temperature variation was obtained as follows:

E = 1.791 T2 – 184.7 T + 5721 … (10)

In this study, figures (12) and (13) show that with increasing the test temperature, a significant loss in elastic modules is observed for both types of groups. While comparing the modulus of elasticity characteristics for both composite groups, carbon fiber reinforced composites in group (B) exhibit an exceptional ability to maintain their stiffness under high environmental temperatures than for the other group.

5.5 Numerical results:

The goal of this analysis is to determine the critical buckling load where the load facter times the actual applied loads provides an estimate of the critical buckling load. Buckled shapes of composite column for the two groups were obtained by using Anasys Workbench program version (15) as shown in figures (14) and (15), in addition to the numerical results of the critical buckling load was tabulated in table (7).

From table (7), it is clear that the high elastic modules and low coefficient of thermal expansion Carbon fibers in group (B) make this material especially suitable for wide range of structural applications.

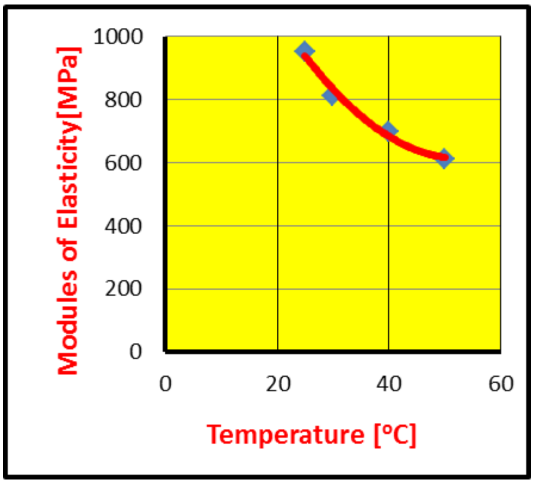

Figure (12): Variation of modulus of elasticity with temperature for group (A) of composites column.

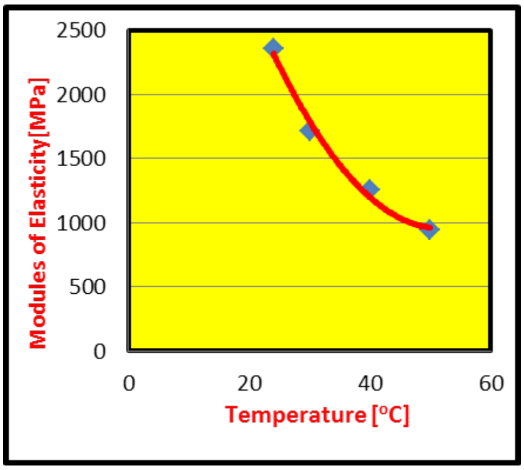

Figure (13): Variation of modulus of elasticity with temperature for group (B) of composites column.

6. Conclusions:

The effect of temperature on the buckling behavior of composite material column was investigated experimentally, theoretically and numerically and lead to the following conclusions:-

1. The mechanical properties of polymer composite materials can be expected to decrease with increasing the temperature from room temperature to the critical buckling temperature and as a result the value of critical buckling load decreases for both groups.
2. Group (B) with perlon and carbon fibers as a reinforcement material exhibits high buckling resistance under the combined effect of temperature and service loading and maintain an excellent stiffness

characteristics with increasing the temperature.

3. The modules of elasticity decrease with increasing temperature for both groups.
4. The value of coefficient of thermal expansion increases with increase temperature, where group (A) with perlon fiber as a reinforcement material shows a higher coefficient of thermal expansion than group (B).
5. The results of critical buckling load obtained by the numerical analyses shows a very good agreement with the theoretical results for both groups.

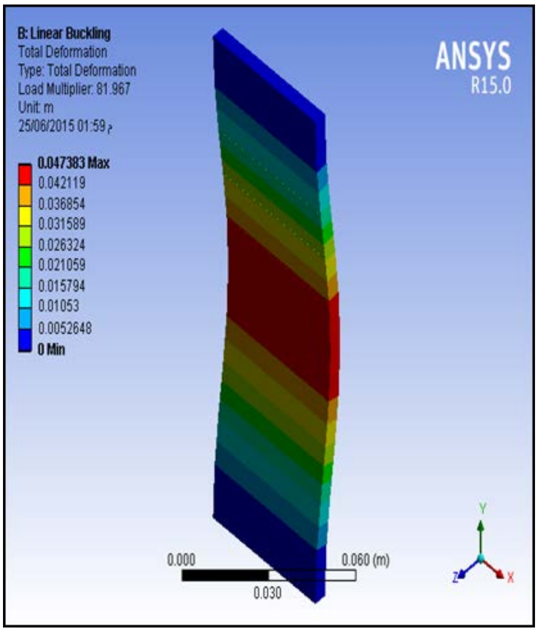

Figure (14): The buckling shape of group (A).

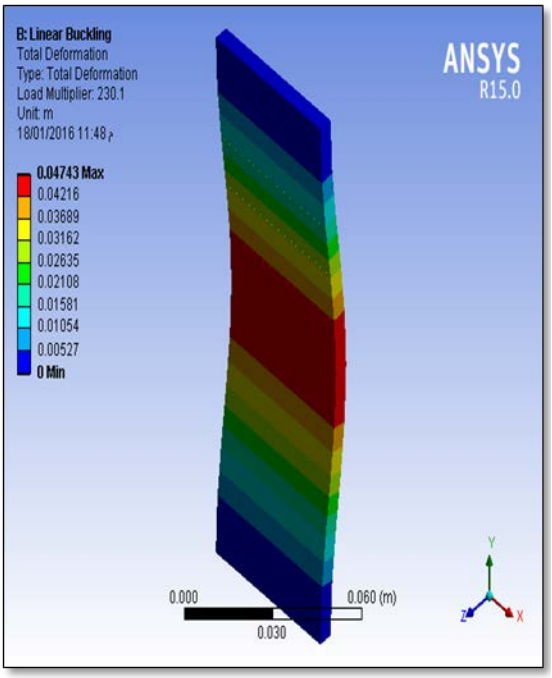

Figure (15): The buckling shape of group (B).

Table (7): The Numerical results of buckling load.

Groups	Critical buckling load [N]
A	819.57
B	2301

7. Acknowledgement

The support provided by my, family, friends, colleagues and all the staff in the Material Engineering Department, AL-Mustansiriyah University is gratefully appreciated.

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تاثير الحرارة على انبعاج عمود المواد المركبة

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الخلاصة:

يتناول البحث تحقيق نظري و تجريبي سلوك الانبعاج لأعمدة المصنوعه من الموادالبوليمريه المقوى بالألياف التي تخضع لحمل محوري في درجات حرارة متفاوتة (درجة حرارة الغرفة إلى 50 درجة مئوية). مجموعتان من المواد المركبة تم استخدامهما لإنتاج عينات الاختبار، الاولى تتكون من الياف البرلون كماده تقويه و(acrylic resin)كماده اساس رابطه بينما المجموعه الثانيه تتالف من الياف البرلون والكاربون كماده تقويه. تم تصنيع عينات الاختبار بواسطة تقنية (vacuum modeling) وقطعت وفقا ل(ASTM D-638) لإجراء اختبار الشد. البيانات من اختبار الشد تم استخدامها لحساب نسبة النحول.

في هذه الدراسة، تم تصميم جهازتجريبي خاص وتصنيعه ثم معايرته لغرض دراسة تأثير الحمل الحراري والانبعاج على الاعمده كما تم اجراءتحليل عددي يتناول سلوك الانبعاج لكلتا المجموعتين.

أظهرت النتائج أن درجة الحرارة لها تأثير كبير على الخصائص مختلفة للمواد المركبه البوليمريه المقواه بالالياف حيث ان قيمة الحمل الحرج ومعامل المرونه تتناقص مع ارتفاع درجة الحرارة لكلا النوعين من المجموعات المركبة. المواد المركبه (مع الياف البرلون والكربون كماده تقويه) أظهرت خصائص ميكانيكيه افضلَ، التي تَجْعلُهم أفضل مرشّحِ لتَحسين خصائصِ مقاومةِ الانبعاج للموادِ المركّبه.

الكلمات المفتاحية: الانبعاج , الحراره, المواد المركبه, الياف الكاربون والبرلون.