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Effect of Temperature on Buckling of Polymer Matrix Composite Materials Columns

A Thesis
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Dedication

TO
Messenger of Allah

(محمد صلى الله عليه وعلى آله الطيبين الطاهرين)

TO
My dear Parents,
TO
My dear brothers and my dear sister

جمهورية العراق
وزارة التعليم العالي والبحث العلمي
الجامعة المستنصرية
قسم هندسة المواد

تأثير درجة الحراره عل أنبعاج أعمده المواد المتراكبة ذات ألاساس البوليمري

رسالة مقدمة إلى
كلية الهندسة في الجامعة المستنصرية كجزء من متطلبات نيل درجة الماجستير في علوم هندسة المواد

من قبل

نور كاظم فهيد
بكالوريوس 2013

بإشراف

الأستاذ المساعد د.كاظم كامل رسن

الأستاذ المساعد محمد هادي علي

MAY 2016
شعبان **1437**

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Abstract

The increased use of Fiber Reinforced Polymer (FRP) composites brings many challenges to materials scientists and structural engineers. One is the understanding and prediction of the behavior of FRP composites under service temperatures.

This work presents results from an experimental investigation pertaining to the buckling behavior of slender fiber-reinforced polymeric columns subjected to axial loading at varying temperatures (room temperature to 50 °C). Two groups of composite materials were used for manufacturing of test specimens, one consist of Perlon fiber as reinforcement with 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 define the column as Euler buckling column.

In this study, a special experimental rig was designed, manufactured and calibrated to study the effect of thermal and buckling load subjected to test columns.

The results show that the temperature has considerable effect on properties of fiber reinforced Polymer composites where the value of critical load and Young's Modulus decreases with increase temperature for both groups. In (Perlon & Carbon reinforcement) composites Carbon fibers tend to exhibit high stiffness and low coefficient of thermal expansion, so the column can have an exceptional buckling resistance under the combined effect of temperature and service loading. The different in critical buckling load between room temperature to (50 °C) was (63.8 %, 62.1%) for group (A, B) respectively.

A derived formula for buckling behavior for net critical load as a function of temperature variation was obtained by fitting curve.

Numerical analyses pertaining the buckling behavior for both groups were conducted. Eigenvalue buckling analysis has shown a good agreement with the predicted Euler buckling load.

Chapter One

Introduction

1-1General

The use of composite structures increase gradually in aerospace, automotive and energy industries since composite materials have many advantages like light weight, high specific strength and stiffness, ease in fabrication and other significant features.

Composites are engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure and having bulk behavior which is considerably different from those of any of the constituents.

The primary phase of composite material having a continuous feature is called matrix phase. Matrix is usually less hard and more ductile. The secondary phase is a discontinuous feature imbedded in the matrix. The dissipated phase is generally harder as compared to the continuous phase and is called reinforcement. It serves to strengthen the composites and improves the overall mechanical behavior of the matrix [1].

As a result of this increased use, the design criteria which have been specified to attain the structural safety of composite structures must be ensured by the manufacturers. One of these design criteria is buckling test for the composite structures. During operation the composite materials are commonly subjected to compression loads that may cause buckling if overloaded [2].

1-2 The buckling phenomenon

The structural members are prone to be subjected to different types of loading [3]:

1. Simple stress [normal (tension & compression), shear and bearing].
2. Torsion.
3. Bending.
4. Combined stress.

In many engineering structures such as columns, beams, or plates, their failure is developed not only from excessive stresses but also from buckling [4].

Columns are one of the most widely used structural elements. The elastic stability of columns with different properties, shape and material and their behaviors was the subject of many studies.

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 [5].

Buckling refers to the loss of stability of a component and Instead of failing by direct compression, the member bends and deflects laterally as shown in plate (1.1) [3].

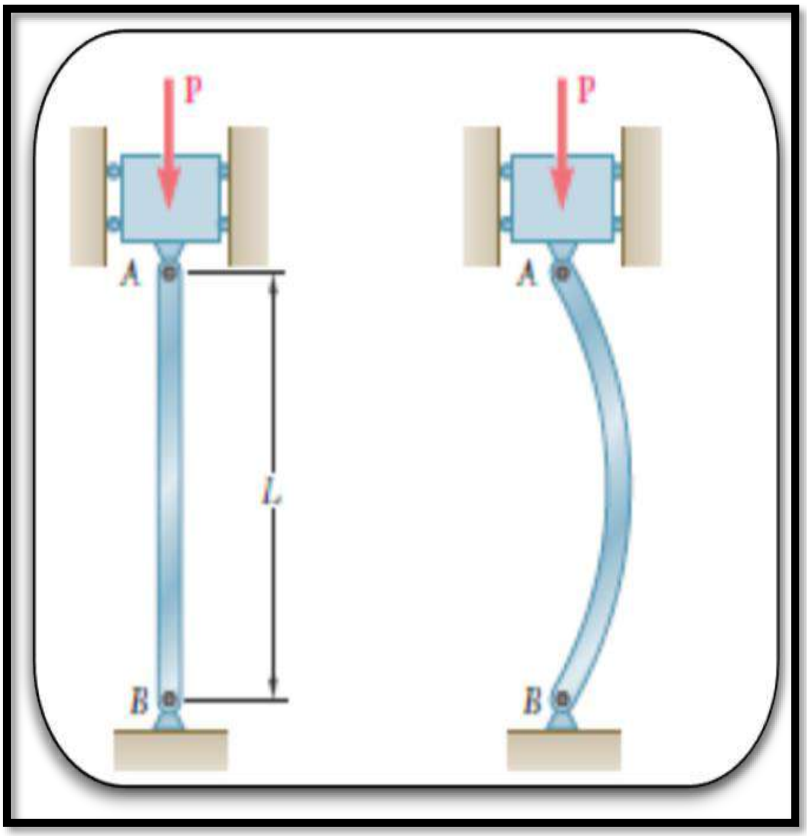


Plate (1. 1) Buckling of a slender column due to an axial compressive load [3]

The value of the critical load (i.e. the load causing buckling) of a member is affected by several factors including [6]:

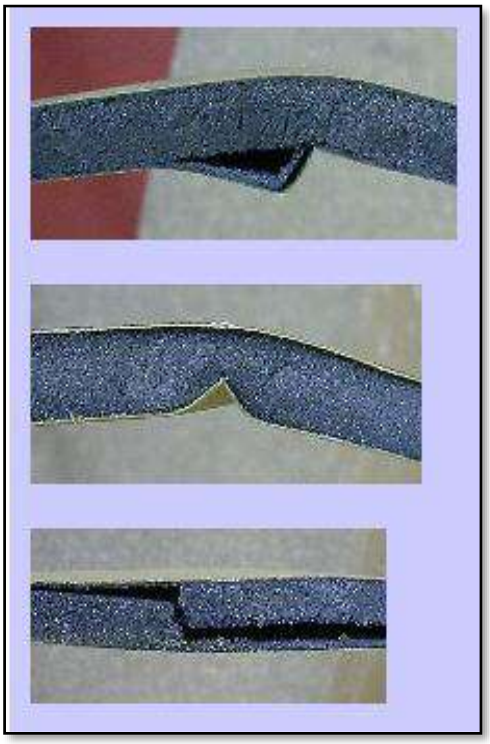
1. Stiffness characteristic of the member.
2. Material properties of the member.
3. The cross-section of the member.
4. The un-supported length of the member.
5. The support conditions.
6. The position of the applied loads.

Buckling phenomenon is not restrictive only to columns; it can occur in different types of structures and can take many forms. For example when you step over an empty aluminum can, the thin walls will buckle under the influence of your weight and the can collapse.

Few years ago investigators studied abridge collapsing; they found that buckling of a thin steel plate under the compressive stresses was the cause of failure [3].

For structures buckling is one of the major reasons of failures, and therefore it should always be considered in design and development of high performance composite and it is considered critically dangerous to structural components because it occurs at a lower applied stress and generates large deformation [7].

The buckling phenomena are shown in plate (1.2) where, (A) present the phenomena of buckling in composite sandwich panels, (B) present buckling failure in (I- Beams) composite structural element while, (C) & (D) present the buckling failure in concrete buildings due to axial compression load.



(A)

(B)

(C) (D)

Plate (1.2) Buckling Phemonen.

(A) Buckling in composite sandwich panels, (B) buckling failure in (I- Beams) composite structural, (C) & (D) present the buckling failure in concrete buildings due to axial compression load.

1-3 Objectives and Research Significance

The main objective of this thesis is to derive a new experimental formula takes into account the effect of change in temperature on Euler buckling load. To accomplish this goal, the following specific procedures must be undertaken:

1. Manufacturing two groups of composite materials as a testing sample.
2. Obtaining the mechanical properties for each group by preparing the standard tensile test specimens and testing them.
3. Designing and assembling the rig for measuring the critical buckling load for the composite fixed supported testing samples under the effect of thermal and buckling loading.
4. Numerical analysis using ANSYS Software program (version 15) to obtain the critical buckling load for each of the isotropic composite group.

1-4 Thesis Layouts

This thesis contains six chapters. In Chapter one, a brief introduction and description of the buckling phenomenon were presented.

In chapter two, a review of the literatures which are pertinent to the previous works made in this field.

In Chapter three, theoretical and numerical analyses that define the composite materials behavior, their classification and characteristics and the all equations related to buckling of column.

In Chapter four, the experimental work for manufacturing the composite materials column specimens and the experimental testing rig are described in detail.

In Chapter five, the results and discussions which are obtained in the study have been presented in detail.

Finally in chapter six, the conclusions drawn from the above work are described. There is also a suggestion for future work.

Chapter Two

Literature Review

2-1General

During the past decade there have been many studies and researches that addressed to the buckling of column. Euler's researches on buckling of columns under their own weight are considered as the starting point of this line of research topics.

2-2 Literature Review of Buckling Behavior of Composite Materials due to Axial Compression Loading

The following reviews discuss the previous research works specifically focused on the buckling of axially loaded members.

Barbero& Tomblin performed buckling tests on pultruded columns with different size and length. They asserted that for the long column buckling was the governing failure mode. Buckling test was conducted on long columns with the following I-beams section: [102mm x l02mm x 6.4mm, l52mm x 102mm x 9.5mm (depth, width, and thickness)] with pinned-pinned support condition. It was apparent from the results that the theoretically predicable (Euler) load was extremely precise when testing these different materials. All percentage differences between the theoretical and experimental were below (6.2%) since the theoretical prediction assumes perfect manufacturing and lay-up conditions, and so the Euler buckling load could be considered an accurate prediction of the load-carrying capacity of pultruded composite columns [8].

Bank .et al. (1994) conducted an experimental investigation on the mechanism of failure of E-glass/polyester and E-glass/vinlyester wide flange beams. The pultrusion process was ideally suited for the manufacturing of these beams. The dimensions of beams section were (203 mm × 203 mm× 90.5 mm) (height ×width ×thickness). The test results seem to indicate that the ultimate failure mechanism for vinylester beams was markedly different from that of the polyester beams, the vinylester beams failed due to local failure at the junction between the web and the flange in the buckled region, while the polyester beams on the other hand failed due axial compression of the compression flange [9].

Seangtith (2000) reported experimental results of a buckling test conducted on (Glass Fiber Reinforced Polymer) box section configuration having cross section dimension of (130 mm x130 mm), a wall thickness of (9.5 mm) subjected to axial compression load. The test specimens were made of E- glass fiber reinforced with vinylester resin. In this study, the columns had pinned-pined and pinned- fixed support conditions and the effective slenderness ratio was calculated for the purpose of establishing a criterion for clearly distinguishing between the long columns from the intermediate columns. It was found that the long GFRP column would experience flexural buckling while for the intermediate GFRP column were failed with flexural buckling and crushing, the buckling load increases with decreasing the effective slenderness ratio [10].

Hashem & Yuan (2001) clarified the difference in behavior between short and long fiber reinforced polymer composite column, experimental as well as analytical investigation were executed on pultruded columns with 'Universal' and 'Box' cross sectional shape. In this study the column were manufactured with E-glass and vinylester and polyester resins for the 'Universal' and 'Box' columns, respectively. Experimental work was conducted using eight different slenderness ratios and all columns were tested under compressive axial loading with pinned- pinned end conditions. Based on experimental evaluations and analytical results, a slenderness ratio (L / r = 50) was established for distinguishing between short and long composite column behaviors. As such, the columns with (L /r) less than (50) will fail in localized buckling marking short columns behavior, while columns with (L /r) more than (50) will fail in Euler buckling mode **[11]**.

Akhbari et al. (2008) executed an experimental and numerical investigation pertaining to the buckling resistance of the hybrid composite materials. By using glass fibers and polyester fibers, a hybrid woven fabric was manufactured then with polyester resin, laminated composite plates were manufactured. The results obtained by experiment shows that the hybrid materials would have higher strength than the composite materials and consequently better buckling resistance since the hybrid composite polyester fibers help the damaged glass fibers so as to increase the load carrying capacity of these composite materials. The average results obtained from the experiments shows a good agreement between the experimental and numerical analyses where the critical bucking load of unidirectional composite plates was about (1291.1) N and magnitude calculated from the software is (1249.2) N **[12]**.

Kumar (2009) studied experimentally the influence of cut-out shape, length/thickness ratio, ply orientation and aspect ratio on the buckling behavior of woven glass epoxy laminated composite plate. The specimen was clamped at two sides and kept free at other two sides for all cases. Experiments have been carried out on laminated composites with circular, square and rectangular cut-outs. It was concluded that the presence of cutout lowers the buckling load and it varies with the cutout shape, the buckling load for plate without cutout were about (25%) and (30%) higher than that with circular and square cutout, and the plate with circular cutout yielded the greatest critical buckling load while the plate with rectangular cutout gives the minimum buckling load. As length/thickness ratio, aspect ratio and the fiber angle increases, buckling load decrease but the rate of change of buckling load is almost uniform **[13]**.

Alwan et al. (2011) illustrated the effect of increasing the volume fraction (3 %, 4 %, 5 %, and 6%) of natural jute fibers on the tensile strength and buckling behavior of unsaturated polyester matrix composite column experimentally and numerically. Hand Lay- molding method was ideally suited for the preparation of composite materials. The test sample for tensile test was cut according to ASTM-D638 and for the buckling test was long column with dimensions (length =160 mm, width =22 mm, thickness =6 mm) and to ensure Euler buckling equation for long column both slenderness ratio and the effective slenderness ratio were calculated. The results show that for tensile test the maximum stress was (127 MPa) at (V_f = 6%) and the minimum was (112 MPa) at (V_f

= 3%) and the critical load was increased with increasing the fiber volume fraction (P_{cr} = 610N) at (V_f = 3%) and (P_{cr} = 830N) at (V_f = 6 %) for the experimental results ,While (P_{cr}= 619N) at (V_f = 3%) and (P_{cr} = 877N) at (V_f = 6 %) for the finite element results [14].

Guades et al. (2011) investigated experimentally and numerically the behavior of hollow fiber reinforced composite pile under axial compression. Two basic lamina materials were used in the experiment and in finite element analysis namely; (0.5 mm) thick lamina reinforced by fiberglass with vinyl ester and (2.0 mm)thick lamina reinforced by Soric XF with vinyl ester. Based from the result, it was found that fiber glass-reinforced lamina bears (96%) of the applied load while (4%) was carried by Soric XF-reinforced lamina, therefore it can be concluding that the total behavior of the fiber reinforced composite pile under axial compression with this kind of laminate lay-up depends solely on the response of glass-reinforced lamina and the effect of Soric XF-reinforced lamina is very minimal [15].

Bouazza et al. (2012) studied buckling analysis for simply supported rectangular thin functionally graded plates under uniaxial and biaxial compression and also investigated the effects of volume fraction distributions and system geometric parameters. Functionally graded materials plate were made of a mixture of ceramic and metal with material properties vary continuously across the thickness. Based on the numerical results, it was concluded that the buckling load of the plate under uniaxial compression is greater than the one under biaxial compression and it increases with increasing the aspect ratio and decreasing volume fraction [16].

Priyadarsini et al. (2012) investigated buckling behavior of carbon fiber reinforced polymer (CFRP) composite cylinders numerically and experimentally, in addition to the effects of different types of loadings, geometric properties, lamina lay-up and amplitudes of imperfection on the strength of the cylinders under compression. A carbon composite cylindrical shell specimen with (300 mm) inner diameter, (400 mm) length, (1mm) thickness and a lay-up sequence of [0°/45°/-45°/0°] has been chosen for the experimental study. It was shown that the ultimate strength is affected by the method of loading, the lay-up sequence, radius to thickness ratio and geometric imperfections [17].

Julias et al. (2013) illustrated experimentally and numerically the effect of delamination length and position on the critical buckling loads of hybrid composite laminate and its mode of failure. Hybrid composite plate was fabricated with hand lay –up technique with carbon and glass fibers as a reinforcements and epoxy resin as a matrix. With length (200 mm), width (40 mm) and thickness (3.6 mm) test specimens were fabricated .Delamination of different of length (0.2, 0.3, 0.4 and 0.5) and position were created artificially. Non- linear buckling analyses were conducted to predict the buckling load. The results shows that the critical buckling loads decreases with increasing the delamination length and buckling load with mid – plane delamination is higher than near – surface delamination [18].

Jacob et al .(2013) identified the influence of the length-to-thickness ratio, the aspect ratio, the fiber orientation and the cut-out shapes on the buckling load for the glass epoxy laminated composite plate in clamped-free-clamped-free configuration by finite element analysis. In order to study the effect of the cut-out shapes on buckling behavior of composite plate, three different cut-out shapes, namely, circular, square, and rectangular were analyzed. The result shows that the buckling load decreases with increase in length -to- thickness ratio and aspect ratio, but the rate of decrease is not uniform and the fiber orientation where the maximum buckling loads occurred for (0°) fiber orientation. It was observed that buckling load generally decreases with the presence of cut-out, the plate with rectangular cut-out gives the least buckling load of (7.23 KN) and for the one with the circular cut-out; the highest buckling load was observed with (7.89 KN)**[19]** **.**

Atlihan (2013) investigated buckling behavior of delaminated composite beams having general boundary conditions (clamped-free, clamped –clamped, and clamped –hinged), different stacking sequence and orientation angles analytically and numerically. The dimension of the beam were (length = 400 mm, width = 20 mm, height = 3.3 mm). As the analytical results are compared with numerical results, it has been seen that their results are very close. The results show a reduction in the buckling loads with increasing the ratio of delamination length to beam width, fiber orientation angle and delamination number. Since delamination is one of the main forms of damage in the laminated composite and it can cause substantial loss of the structure's load carry capacity **[20]**.

Oleiwi et al. (2014) reported preliminary results of a buckling test conducted on composite columns made from glass fiber reinforced unsaturated polyester. The composite specimens were prepared by using hand lay-up technique with different fibers volume fraction (V_f) of (0, 3, 5 & 8 %) for coarse fibers and (0, 4, 7 & 11%) for fine fibers, angle of fiber ($0^o/90^o$) and ($45^o/-45^o$) and aspect ratio (Length/Thickness). It can be seen from the results that the critical load increased as the fiber volume fraction increased because the glass fiber has high stiffness and this led to increase the stiffness of composite specimens and improved the overall buckling resistance, also when the column length is increased, the buckling resistance is decreased and the fiber orientation ($0^o/90^o$) have higher critical load than fiber orientation ($45^o/-45^o$) for two type of fiber **[21]**.

Narayana et al. (2014) described the effects of size of square/rectangular cutout, cutout orientation angle, plate aspect ratio, plate length/thickness ratio and boundary conditions on the buckling behavior of graphite/epoxy composite plates subjected in-plane compressive loading with finite element method. The results show that for a rectangular composite plate with rectangular cutout, the magnitudes of buckling loads were decreased by increasing of cutout orientation angle from (0° to 90°) while for a rectangular composite plate with square cutout, the magnitudes of buckling loads are decreased by increasing of cutout orientation angle from (0° to 45°) and were increased by increasing of cutout orientation angle from (45° to 90°). The buckling load of the rectangular composite plate with (clamped-clamped) boundary condition is twice that of the buckling load of the composite plate with (clamped-simply supported) and it decreases by increasing aspect ratio and length/thickness ratios [22].

2-3 Literature Review of Buckling Behavior of Composite Materials due to Thermal Loading

Buckling failure can occur not only due to compressive load but it took place when a column subjected to heat. The following reviews addressed this phenomenon:

Dutta.et al. (1991) examined experimentally the effect of low temperature on the buckling behavior of unidirectional graphite fiber-epoxy composite. The rectangular plates were simply supported at the two loaded opposite edges and free in the remaining two unloaded edges. The experiment was conducted with basic ranges of temperature (21℃, -10℃, -14℃, and -19°C). It was found that graphite/epoxy plates of (127 mm x 254 mm) would developed out-of- plane bending under cooling even without any mechanical load due to their negative thermal expansion coefficient, thus upon bending and by the application of mechanical load, the deflection would be increased and the in-plane load carrying capacity of the plate would be significantly reduced and the bending of the plate due to thermal load was treated as an initial geometric imperfection having the same shape as the buckling mode [23].

Liu L. & Kardomateas (2006) discussed the case of thermal buckling of a fire-damaged composite column, which is exposed to heat flux from one side. Two end fixity cases were considered: an axially restrained column (immovable ends case) and a column free to move axially (unconstrained case). The results show that when fire is applied on one side of a column, two things happen: first, a char (damaged) layer appears and, second, a non-uniform temperature develops through the thickness of the undamaged layer. These two effects result in a non-uniform distribution of stiffness through the thickness. In addition, a thermal moment is developed, which causes bending of the column when only the slightest change of temperature occurs. Thus, the column bends and cannot buckle in the classical Euler buckle behavior [24].

2-4 Concluding Remark

From the previous literature reviews, it can be concluded that many studies and researches have studied the buckling behavior of composite materials Awith different factors that may affect the buckling strength of those materials but till now a limited studied regarding the effect of different types of loading on the buckling resistances of columns. While the present work investigated experimentally the failure mechanism of Euler long composite column under the combined effect of thermal and axial compression loading and a new experimental formula takes into account the effect of change in temperature on Euler buckling load was obtained.

Chapter Three

Theoretical Considerations and Numerical Analysis

3-1Composite Material

For many years, metals have been largely used as structural materials mostly because of their strength and ductility, but with the growing demand for stronger and lighter materials, composites have become very important for structural applications. By definition, a Composite is a combination of two materials in which one of the materials called the reinforcing phase is in the form of fibers, sheets, or particles, and is embedded in the other materials called the matrix phase. The reinforcing material and the matrix material can be metal, ceramic, or polymer. Composites typically have a fiber or particle phase that is stiffer and stronger than the continuous matrix phase and serve as the principal load carrying members [25]. Reinforcements which compose the strength and stiffness characteristics of composite structure are bonded together by using matrix material keeping them in the proper orientation and position, and load is transferred between fibers. The matrixes which are more ductile than the fibers act as a source of composite toughness. Furthermore the environmental moisture, chemical corrosion and oxidation are prevented by matrix material [2].

Depending on type of matrix materials used, composite materials can be classified into four categories such as metal matrix composite, polymer matrix composite, ceramic matrix composite and carbon-carbon matrix composites. The most common and popular advanced composites are polymer matrix composites; the reason for this is: Firstly, their strength and stiffness are less as compared to ceramics and metal, but these difficulties are overcome by reinforcing other materials with polymers. Secondly the processing of polymer matrix composites doesn't involve high pressure and doesn't require high temperature. Also the equipment required for manufacturing polymer matrix composites are simpler. For these reasons polymer matrix composites are developing rapidly and soon becoming popular for structural applications [1]. PMCs consist of a polymer (e.g. epoxy, polyester, etc.) reinforced by thin-diameter fibers (e.g. glass, carbon, aramid). The PMC is designed so that the mechanical loads to which the structure is subjected in service are supported by the reinforcement [26].

They play a major role in the repairing of existing structures, in order to upgrade their service or to increase their life time [27].

Plate (3-1) represents a commonly accepted classification scheme for composite materials.

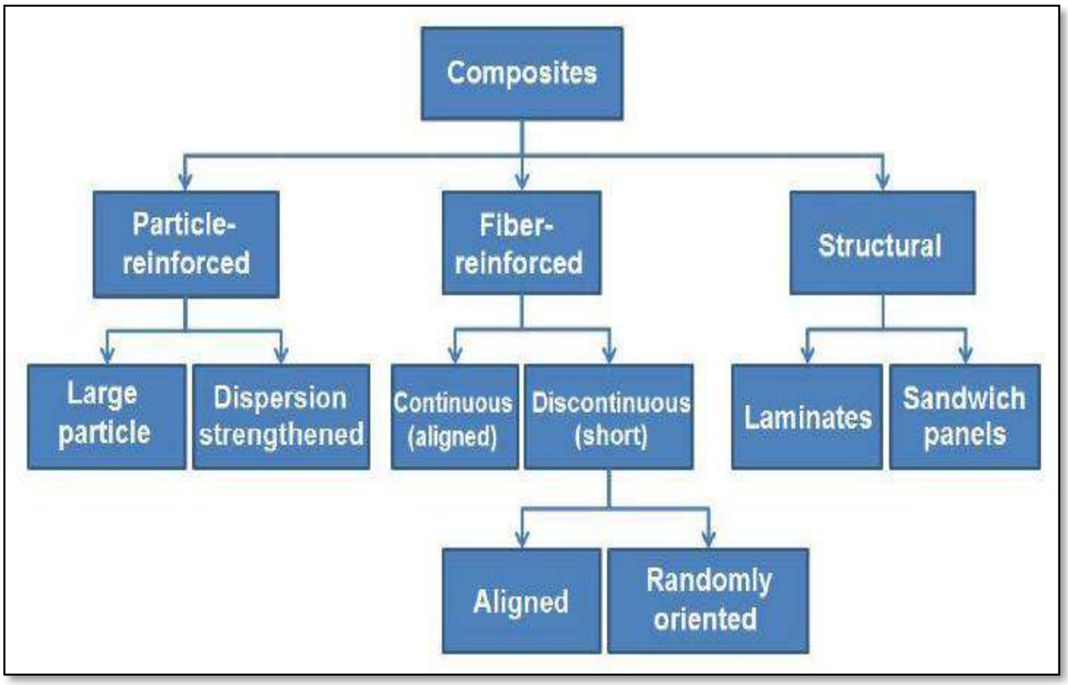


Plate (3.1) A Classification Scheme for the various Composite type [28].

3-2 Influence of Fiber Volume Fraction

Fiber volume fraction is one of the major factors which vary the composite strength. A greater volume fraction of fibers increases the strength and stiffness of the composite, as we would expect from the rule of mixtures. The maximum volume fraction is about 80%, beyond which fibers can no longer be completely surrounded by the matrix [29].

3-3 Effect OF Environmental Temperature on Components of Composites Materials

Confidence in the long-term reliability of composite materials must be fully developed to use their advantages; one of the problems concerning the engineering uses of fiber reinforced composites is the environmental effects on the composite materials which must be considered in the early stages of design .When composite materials are subjected to distinct and repetitive ranges of temperature, the material properties and consequently the structural behavior could be damaged. The degree of damage depends on several factors, such as the temperature level to which material is exposed and exposure duration. The heating and cooling processes can generate interlaminar stresses, causing defects in the microstructure or delamination of their lamina and in these cases can generate mechanical deformations [30]. The composites can be severely degraded 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 [31].

The effect of temperature on the component of composite can be classified into three categories:

3-3-1 Temperature Effects on Reinforced Fibers

Carbon fibers offer the highest strength and stiffness of all the reinforcement fibers. They also have excellent high temperature performance. Since the carbon fibers are dispersed uniformly into the matrix, the resin protects them from many environments. The degradation of carbon fibers with polymer matrices is not usually as great as that of the matrix and interface between them [32].

3-3-2 Temperature Effects on the Fiber / Matrix Interface

Composite materials consist of reinforcement and matrix, which have different elastic and physical properties. It is the interface that provides the adhesion between them in order to give the macroscopic mechanical properties of composite.

The chemistry, morphology and properties of the fiber-matrix interface play a major role in the properties of composites. To produce high quality composite materials, the bond between the matrixes to the fibers must be strong. To retain the properties of composites under environment attack, the fiber-matrix interface must have excellent environmental resistance. Degradation of composite properties due to environmental effects may be attributed to the loss of adhesion and bond strength at the fiber-matrix interface [32].

3-3-3 Temperature Effects on Polymer Matrices

The purpose of the matrix is to bind the fibers together, keep them in the right orientation and protect them from environmental attack. Generally, it is the matrix that determines the acceptable working environments and controls the environment resistance.

At high temperatures, progressive changes occur in the properties of fiber reinforced composites, it has been reported that the material state and properties of a polymer composite remain stable below the onset of glass transition temperature (*Tg*) of its resin. However, when the temperature reaches *(Tg*), significant changes in the material state and properties occur [33]. The bonds existing in the polymers matrix can be divided into two major groups: primary and secondary.

When temperature increases, secondary bonds are broken during glass transition and the material state changes from glassy to leathery. As temperature is raised further, the polymer chains form entanglement points where molecules, because of their length and flexibility, become knotted together. This state, designated the rubbery state, even when higher temperatures are reached, the primary bonds are also broken and the material decomposes, which is known as the decomposition process. As a results, it can be seen that almost all the resin was decomposed, leaving only the fibers, but since these fibers no longer provide composite action, the load-bearing capacity is considerably reduced [34].

3-4 Fiber Materials

Reinforcing fibers are a key component of polymer-matrix composites (PMCs), ceramic-matrix composites (CMCs), metal- matrix composites (MMCs) and carbon matrix composites (CCCs). They impart high strength and stiffness to the matrix material that they modify, and in addition, may offer other valuable properties. Depending on the design requirements, it is possible to select an appropriate composite-reinforcing fiber to manufacture a commercial composite parts having high value-in-use.

3-4-1 Carbon Fiber

Carbon fibers are characterized by a combination of high strength, high stiffness and lightweight. The advantages of carbon fibers are their very high tensile strength-to-weight ratio, high tensile modulus-to-weight ratio, very low coefficient of thermal expansion and an excellent durability in aggressive environments, when coupled with the proper resins [35]. Carbon fiber reinforced composites materials are ideally suitable for improving the structural properties like buckling behavior, stiffness, load-carrying capacity and durability [27].

Table (3-1) Mechanical Properties of Carbon Fiber [36]

	Density (g/m3)	Linear Coefficient of Thermal (10^{-6} K^{-1})	Tensile modulus (GPa)	Tensile strength (MPa)
Carbon Fiber	1.77	-0.1	238	3950

3-4-2 Perlon Fiber

Perlon fibers are the commercial name of nylon (6) fiber and can be defined as a group of polymer thermoplastic fiber with a wide variety of application. Its high tendency to crystallize makes perlon fiber harder and stiffer than other types of fiber. Their low thermal stability and high sensitiveness toward exposure to sunlight are considered as their most essential disadvantages. Perlon reinforced composites materials are ideally suitable for prosthetic [37].

Table (3-2) Mechanical Properties of Perlon (Nylon 6) Fiber [37]

	Density (g. cm-3)	Coefficient of thermal expansion (K^{-1})	Tensile modulus (GPa)	Tensile strength (MPa)
Perlon	1.13	9.5 x10^{-5}	2.6-3.0	78

3-5 Matrix Materials:

As already mentioned, the main function of a matrix in a fiber composite is to keep the fibers together, transfer the load to them, and provide environmental protection. However, although the fibers are the main component responsible for carrying the load, the matrix has an important influence on the compressive strength of the composite, since it provides lateral support for the fibers. This lateral support will increase the resistance against buckling.

3-5-1 Acrylic Matrix

Acrylic resin is a Thermoplastic (resin) generated through a chemical reaction by applying a polymerization initiator and heat to a MMA monomer. Its chemical name is Poly Methyl Methacrylate, but it is called acrylic resin or Methacrylic resin in general. MMA is an abbreviation for Methyl Methacrylate which is a transparent and colorless fluid substance.

Acrylic resins are appreciated for their exceptional clarity and optical properties, surface gloss, weather resistance, high surface hardness and superior design adaptability. However, acrylic resins generally exhibit poor flexibility and low impact resistance and, therefore, pose a problem in that they are prone to fracture when given an extraneous load or impact. Acrylic resins have been widely used as materials for various parts of electronics products, household appliances, office automation appliances, etc because of their excellent transparency and stiffness [38].

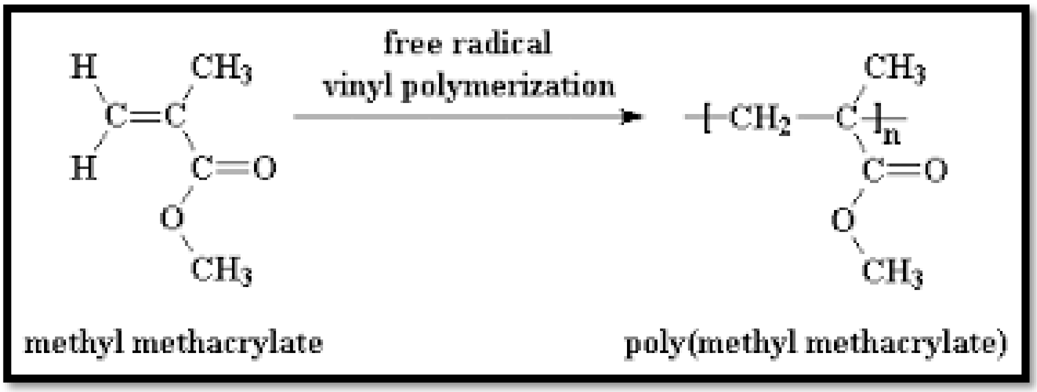


Plate (3.2) Chemical Formation of PMMA Polymer [38].

3-6 Rule of Mixture

The properties of composites may be estimated by the application of simple rule of mixture theories. These rules can be used to estimate average composite mechanical and physical properties along different directions, which may depend on volume fraction or weight fraction. The density of the composite material can be calculated from the following rule [39].

$$\rho_c = \sum v_i \rho_i = V_1\,\rho_1 + V_2\,\rho_2 + \dots\dots + V_n\rho_n \qquad \left(\frac{kg}{m^3}\right) \qquad \dots(3-1)$$

Where:

$\rho_c,\ \rho_f,\ \rho_m$:The density of composite, fiber and matrix respectively.

V_1, V_2, V_n : Volume fraction of each element.

To calculate the volume fraction of each of fiber and matrix basis as follow:

- In term of volume fraction:-

$$V_f = \frac{v_f}{v_c} \times 100\% \qquad \dots(3-2)$$

$$V_m = \frac{v_m}{v_c} \times 100\% \qquad \dots(3-3)$$

Where:-

V_f, V_m : Volume fraction of each of the fiber and matrix.

v_f , v_m, v_c : The volume of each of the composite materials, matrix and fiber.

- In term of weight fraction:

$$W_f = \frac{\mathrm{w_f}}{\mathrm{w_c}} \qquad \dots(3-4)$$

$$W_m = \frac{\mathrm{w_m}}{\mathrm{w_c}} \qquad \dots(3-5)$$

$$V_f = \frac{\rho_c}{\rho_f} W_f \qquad \dots(3-6)$$

$$V_m = \frac{\rho_c}{\rho_m} W_m \qquad \dots(3-7)$$

$$V_f + V_m = 1 \qquad \dots(3-8)$$

Where:

W_f = Fiber weight fraction

W_m = Matrix weight fraction

w_f = Fiber weight

w_m = Matrix weight

w_c = Composite material weight

Here it should be noted that:

$$W_f + W_m = 1 \qquad \dots(3-9)$$

3-7 The Basic Concept of Column Buckling

Buckling is a broad term that describes a range of mechanical behaviors; it generally refers to a catastrophic mode of failure characterized by a sudden failure of a structural member subjected to high compressive stresses, where the actual compressive stress at the point of failure is less than the yield stresses.

Leonhard Euler derived a formula that shows a critical load for buckling of a Column. The critical load is the maximum load that a structure can support prior to Structural instability or collapse [40].

Columns are divided into three categories [41]:-

1. Long column
2. Intermediate column
3. Short column

There are three different cases of failure of the column which depend on the geometry (slenderness ratio) of the member and the properties of the materials [42]:

1. The failure of a long compression member:

For long column, buckling occurs before the normal stress reaches the strength of the column materials as shown in plate (3.3).

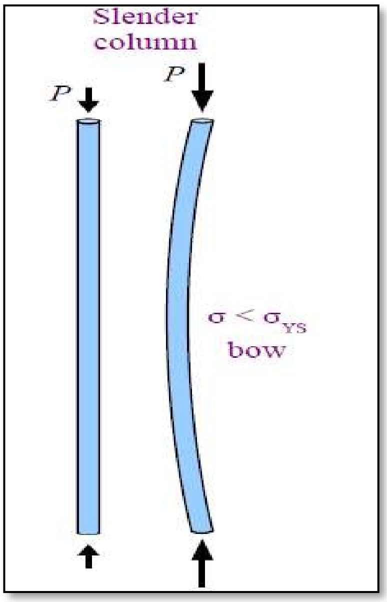


Plate (3.3) Buckling failure in long columns [42].

2. The failure of an intermediate compression member:

The failure of an intermediate length compression member, kneeling occurs when some area yields before buckling, as shown in plate (3.4).

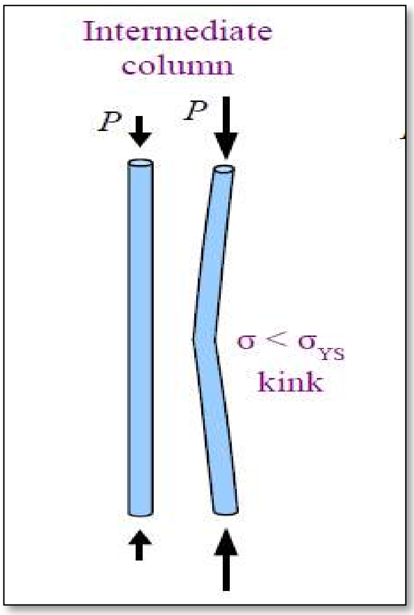


Plate (3.4) Failure in intermediate columns [42]

3. The failure of a short compression member:

The failure of a short compression member, resulting from the compression axial force as shown in plate (3.5).

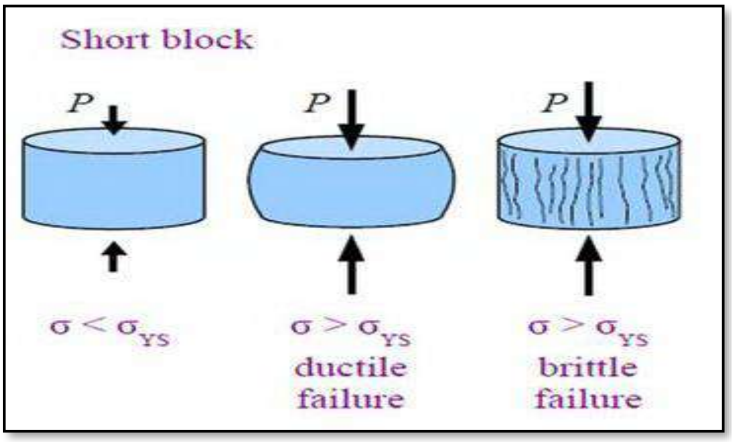


Plate (3.5) Failure in short columns [42]

3-8 Governing Differential Equation

To begin with, the elastic behavior of an idealized, fixed-ended, uniform strut was considered as shown in figure (3.5). The classical Euler analysis of this problem makes the following assumptions:

1. The material of which the strut is made is homogeneous and linearly elastic (i.e. it obeys Hooke's Law).
2. The strut is perfectly straight and there are no imperfections.
3. The loading is applied at the centric of the cross section at the ends.

Consider the strut of Figure (3.1) with the origin at the centre.

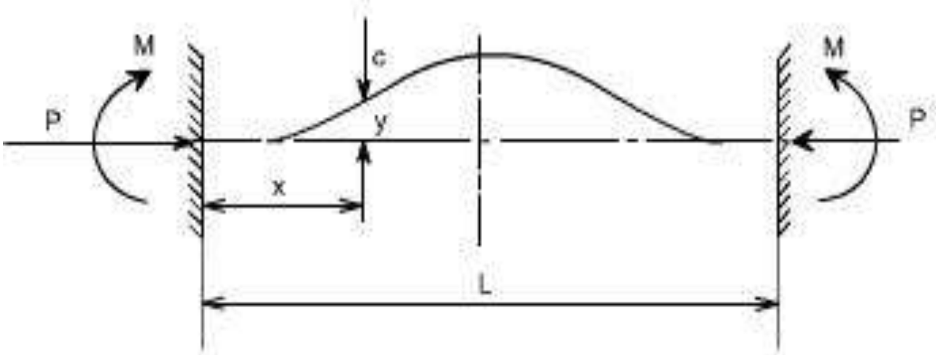


Figure (3.1): Strut with fixed ends [43].

In this case the Bending Moment at ***C*** *point* is given by,

$$EI\,\frac{d^2y}{dx^2} = M - Py \qquad \ldots(3-10)$$

$$\frac{d^2y}{dx^2} + \frac{\mathrm{P}}{\mathrm{EI}}\cdot y = \frac{M}{EI} \qquad \ldots(3-11)$$

$$(D^2 + n^2)\,y = M/EI \qquad \ldots(3-12)$$

Here the particular solution is

$$y=\frac{M}{n^2 EI}=\frac{M}{P} \qquad \ldots(3-13)$$

$y = A \cos nx + B \sin nx + M/P$

Now when $x = 0$, $dy/dx = 0$ $B = 0$

And when $x = \frac{1}{2}L$, $y = 0$:. $A = -\frac{M}{P}\sec\frac{nL}{2}$

$$y = -\frac{M}{P}\sec\frac{nL}{2} - \cos nx + \frac{M}{P} \qquad \ldots(3-14)$$

But when $x = \frac{1}{2}L$, dy/dx is zero,

$$0 = \frac{n\,M}{P}\ sec\frac{nL}{2} - \sin\frac{nL}{2}$$

$$0 = \frac{nM}{P}\tan\frac{nL}{2}$$

The fundamental buckling mode is then given when ($n \times L/2 = \pi$)

The critical buckling load, or Euler load, can be evaluated with ($n = 4$) as this is the smallest load for which instability will occur [43]:

$$P_{cr} = \frac{4\,\pi^2\,EI}{L^2} \qquad \ldots(3-15)$$

Where:

E = modulus of elasticity of the materials [MPa].
I = moment of inertia of the cross section [mm^2].
L = length of column [mm].

3-9 Effective Length Coefficients and End Support Conditions

Theoretically, end supports are either pinned or fixed. In reality they can be designed to be pinned or rigid and may actually fall somewhere in between. The support conditions will have an impact on the effective length (L_e), of the column and can be different in each plane. The effective length (L_e), of a column is the distance between successive inflection points or points of zero moment.

The effective length can be expressed as [44]:

$$L_e = K \,.\, L \qquad \ldots(3-16)$$

Where:

L: The actual length of the column.

K: Effective length coefficient factor, whose value depends on the condition of end support of the column as shown in plate (3.6).

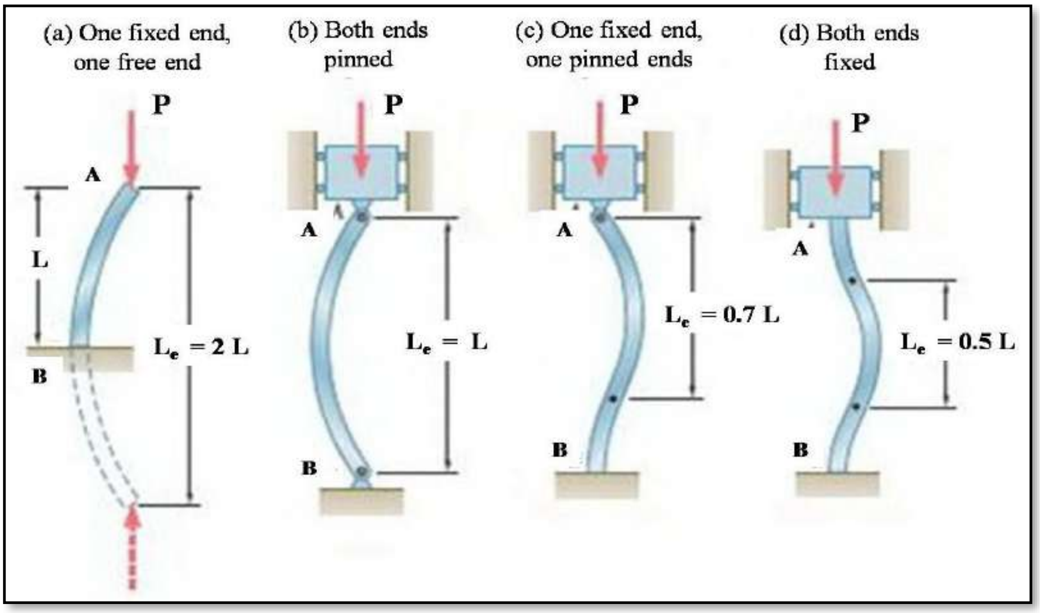


Plate (3.6) Illustration of End Conditions for Columns [45]

3-10 Radius of Gyration

The geometric property of a cross-section called the radius of gyration. It introduces the effects of cross-sectional size and shape to slenderness. It is one measure of effectiveness to resisting buckling. The radius of gyration (r) is given by the following formula [46]:

$$r = \sqrt{\frac{I}{A}} \qquad \dots(3-17)$$

Where:

I = The second moment of inertia (mm^4).
A = The total cross-sectional area (mm^2).

3-11 Slenderness Ratios:

Slenderness ratio of a column is defined as the ratio of the effective height (L) of the column to the least radius of gyration (r) of the column section. The critical buckling stress of a column depends inversely on the square of the slenderness ratio. High slenderness ratios mean lower critical stresses that will cause buckling; conversely, lower slenderness ratios result in higher critical stress.

The effect of slenderness ratio is shown in plate (3.7).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 [46]:

Slenderness ratio is given by the following formula:

$$Sr = \frac{L}{r} \qquad \dots(3-18)$$

Where:

Sr = slenderness ratio.

r = radius of gyration (mm).

L= the effective length (mm).

The determination of whether the column is long, intermediate or short can be found by calculating the critical slenderness ratio, which is [3]:

$$Sr_{critical} = \sqrt{\frac{2\,\pi^2\,E\,C}{\sigma\ \text{yield}}} \qquad \ldots (3-19)$$

Where:

$Sr_{critical}$ = Critical Slenderness Ratio

E= Young Modulus [MPa]

C= End Support Condition

$\sigma\ \text{yield} = Yield\ Stress\ [MPa]$

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 (S.R critical), then the column is intermediate.

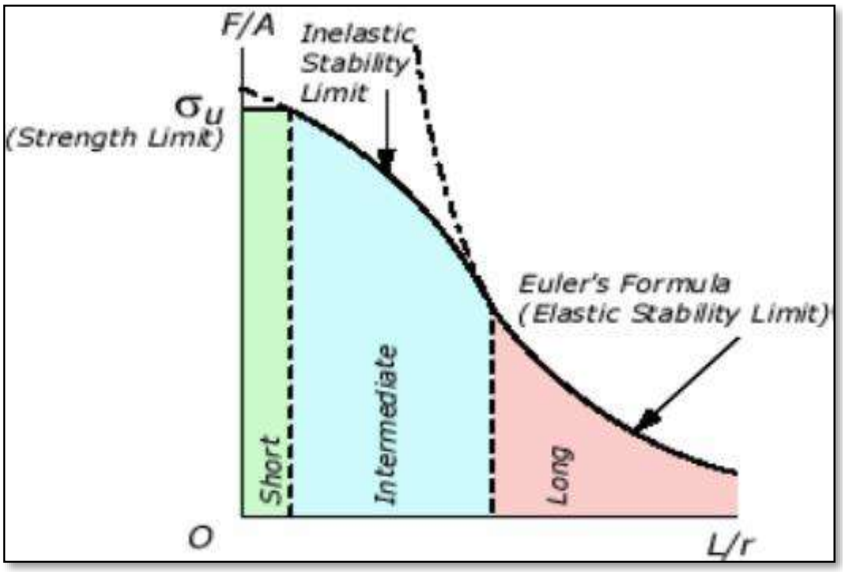


Plate (3.7) Effect of Slenderness Ratio [47]

3-12 The Numerical Analysis

The Finite Element Analysis (FEA) is a numerical method for solving problems of engineering and mathematical physics and now it is considered an important and frequently indispensable part of engineering analysis and design. Linear buckling analysis gives the load factor that would produce elastic buckling. This factor could be considered as the safety factor against buckling if the membrane compressive stresses in the cross section of critical members still remain sufficiently below yield stress. Otherwise, care must be taken to correct the load factor given by elastic buckling analyses. In this work, finite element analysis with ANSYS Workbench (15) software is used as a numerical tool to study the buckling of composite material column.

3.12.1 Steps of the Ansys Workbench (version (15)) Process:

In this part we will find the critical load for buckling of a column by Eigenvalue Buckling Analysis.

Eigenvalue Buckling Analysis predicts the theoretical buckling strength of an ideal elastic structure. This is known as classical Euler buckling analysis. However, in real-life, structural imperfections and nonlinearities prevent most structures from reaching their Eigenvalue predicted buckling strength.

Eigenvalue buckling analysis in Ansys Workbench has six steps:

1. Build up the model
2. Generate the Mesh
3. Defining Load and Boundary Conditions
4. Obtain the Static and the Eigenvalue Buckling Solutions
5. Expand the Solution
6. Review the Results

1. Build the Model:

The effectiveness of a finite element model is governed by both of, its material properties and geometry. Material properties (young modulus of composite material and yield stress) were obtained from the tensile test. This analysis was conducted for Perlon and Carbon fiber reinforced composite material. The model is (140 mm) long, (50 mm) wide, and (4.9 mm) thick column. After defining material properties, the next step is to generate the finite element model as shown in Figure (3.2).

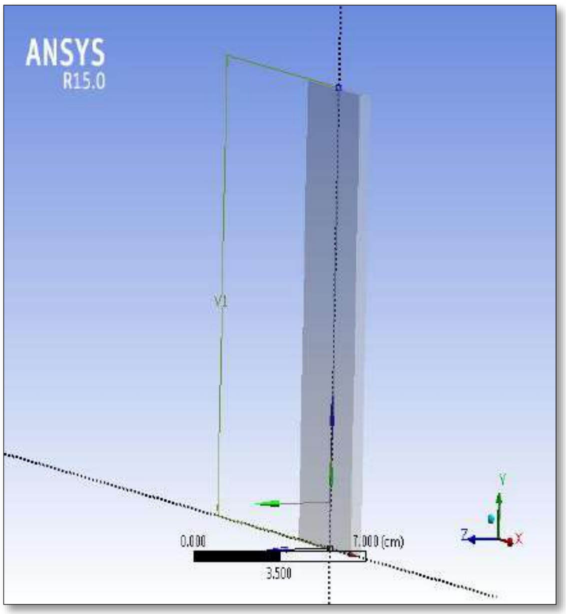


Figure (3.2) The geometry of the composite column

2. Generate the Mesh

After the model geometry has been completed, the next step is to create a finite element mesh as shown in figure (3.3). Mesh generation is one of the most critical aspects of engineering simulation, since it provides a means to balance these requirements and obtain the right mesh for each simulation in the most automated way possible.

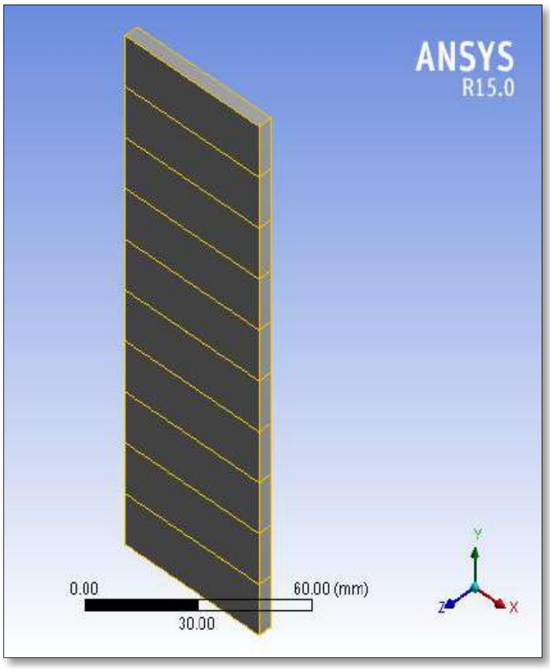


Figure (3.3) The mesh of composite column.

3. *Defining Load and Boundary Conditions*

The word loads in ANSYS terminology includes boundary conditions and externally or internally applied forcing functions [displacements, forces, pressures, temperatures (for thermal strain), and gravity]. 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 Solutions* Buckling analysis is a technique used to determine buckling critical loads at which a structure becomes unstable and obtain the buckled shape.

5. *Expand the Solution*

This step is used to review the buckled shape.

6. *Review the Results.*

Chapter Four
Experimental Work

4-1General

The composite laminations were performed under vacuum and cut according to (ASTM D -638 type IV) for tensile test to obtain modulus of elasticity, yield strength, ultimate tensile strength and percentage elongation in addition to composite specimens which have been cut according to the dimension requirements to conduct the buckling test. The process of design and construct a new buckling device with thermal chamber which was designed to take the effect of thermal parameter on buckling behavior of composite materials is described. After the sample manufacturing has finished, the testing stage begins.

4-2 Specimens Materials

Specimens preparation include a number of stages begin with the material selection, mold preparation and completed with the specimen's cutting. In this work, the materials needed in the lamination involve perlon fibers and carbon fiber sheet as a reinforcement and acrylic resin as a matrix material. The materials used in the manufacturing of composite specimens are shown in figure (4.1).

Figure (4.1) Materials used in the manufacturing of test specimens.

4-3 Preparation of Composite Specimens

4-3-1 Preparation of the Mold

Vacuum modeling technique is used to produce smooth finish column without any defect, the mold used in this study is manufactured of Jepson material, a cubic in shape with dimension (28 cm * 18.5 cm * 12.5 cm).

4-3-2 Test Specimen's Preparation

Acrylic resins, carbon fiber, perlon fiber with other materials needed for the manufacturing of composite specimens such as hardening powder, polyvinyl alcohol PVA bag and materials for Jepson mold. The composite specimens were fabricated according to lamination arrangement given in table (4-1).

Table (4-1) Lamination Arrangement.

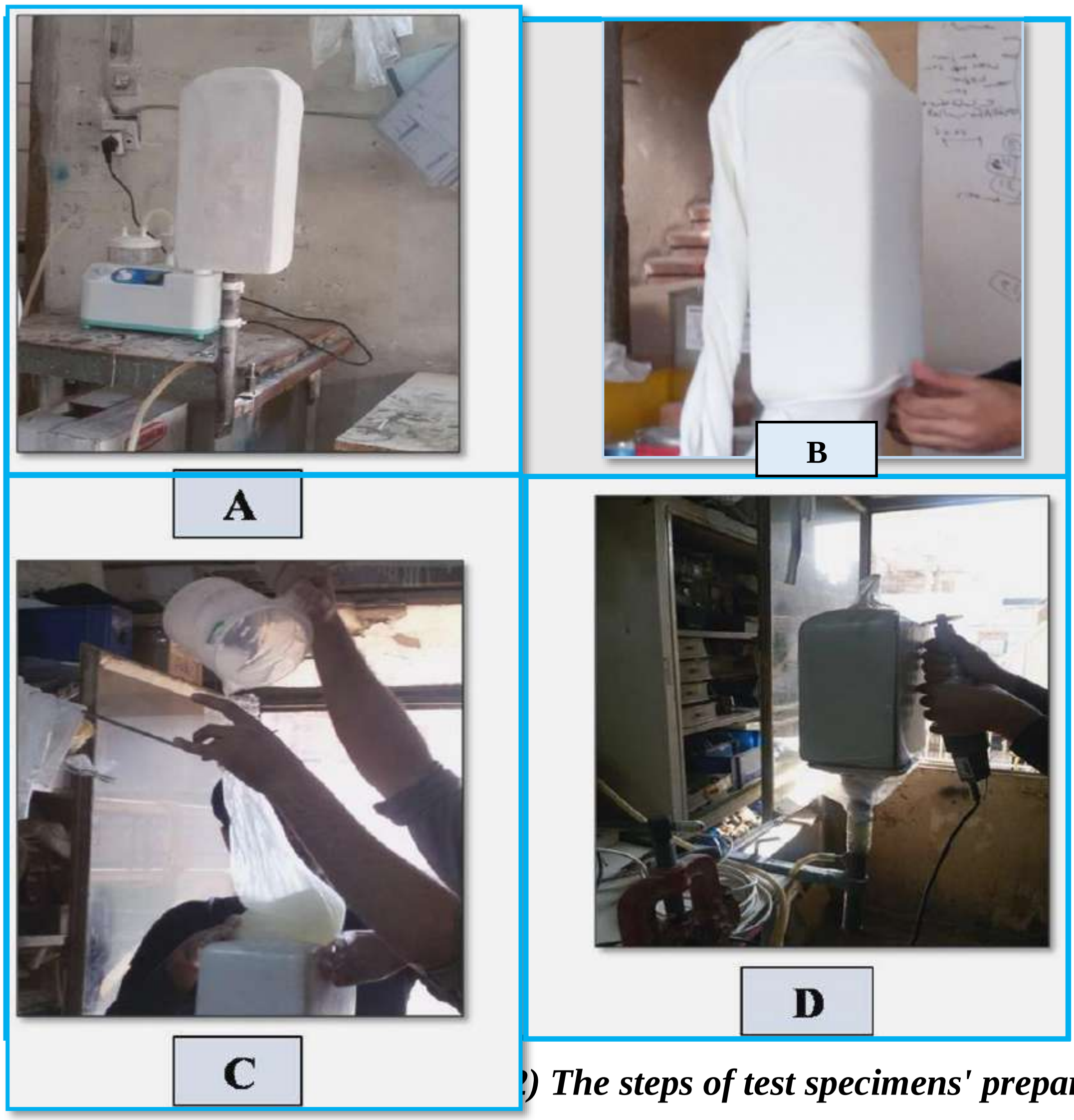
Groups	No. of Layers	Lamination arrangement	Description of Layers	Thickness (mm)
A	**10**	**10**	**Perlon fiber as (reinforcement)**	**4.7**
B	**12**	**5-2-5**	**(5Perlon& 2Carbon fibers &5 Perlon fiber) (reinforcement)**	**4.9**

The Preparation of Test Specimens is as follows:-

1- The mass of the reinforcement material (perlon fiber) for a composite testing sample are measured using digital sensitive weighting device according to the required volume fractions.

2- Placing the mold on the device stand and connects it to the vacuum forming system and pull the inner (PVA) bag in the mold and open the pressure valves to value of approximately (0.06 MPa) at room temperature as shown in figure (4.2.A).
3- Putting the perlon fibers of the first group according to the lamination arrangement mentioned in table (4.1) as shown in figure (4.2.B) and pulls the outer polyvinyl alcohol (PVA) bag on the mold then using cotton string to tie off the (PVA) bag.
4- Mixing Acrylic resin (725 ml) with (25 gram) hardener according to the standard ratio for each (100 part) of acrylic resin mixed (2-3) part of hardener, then putting the resulting matrix mixture inside the outside PVA bag slowly and distributing the matrix homogenously over the entire area of mold as shown in figure (4.2.C).
5- Keeping a constant vacuum until the composite material mold cool down; a cubic composite material is obtained which it will be cut according to required dimensions of specimens.
6- The mass of a composite testing sample are measured using digital sensitive weighting device

The manufacturing steps are repeated for group (B) of composite with (800 ml) acrylic resin and (26.96) gram hardener.



) The steps of test specimens' preparation.

4-4 The Experimental Buckling Rig

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. The experimental rig consists of the following parts:

1. Hydraulic press ((10 ton) capacity): a device which operates on the principles of hydrostatic pressure to generate a concentrated compressive force as shown in figure (4.3).

Figure (4.3) Hydraulic Press

2. Load Cell (SS 300 model with (2 ton force capacity)): a sensor or a transducer that converts a load or force acting on it into an electrical signal as shown in figure (4.4).

Figure (4.4) Load Cell

3. Digital load Indicator (model: SI 4010 R): is a weighing indicator that amplifies signals from a load cell, converts it to digital data and displays it as a force value as shown in figure (4.5).

Figure (4.5) Digital load Indicator & Digital Temperature Controller.

4. Set of Jaws: It is made of tool steel. It was manufactured with groves according to special design to fix the sample without any movement as shown in figure (4.6).

Figure (4.6) Set of Jaws.

4. Dial Gage Indicators: it is an instrument used to measure accurate a small distance. The dial was mounted to magnetic base used to fix the dial and allowing adjusting it to a different directions and positions. It is used to measure the deflection of a column as shown in figure (4-13).

6- 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 a suitable space to be able to include all the required parts such as (load cell, dial gauge with its magnetic base, the fixing jaws and the testing specimen). The 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 (4.7).

b- Heater (400 watt): it is used to produce the heat and raising the temperature to the required temperature inside the chamber as shown in figure (4.8).

c- Thermo Couple (type K): is a sensor used to measure temperature .It was calibrated in the laboratory by team of experts for standardization and quality control at room temperature (25°C) as shown in figure (4.3).

d- Fan: it used to distribute the heat uniformly inside the aluminum chamber as shown in figure (4.8).

e- Ducting: ducting system inside the chamber is used to distribute the heat homogenously as shown in figure (4.8).

f- Digital Temperature Controller (model (AI K3)): it used to [- 50°C to 200°C] with allowance of (± 1°C) control the temperature inside the chamber as shown in figure (4.5).

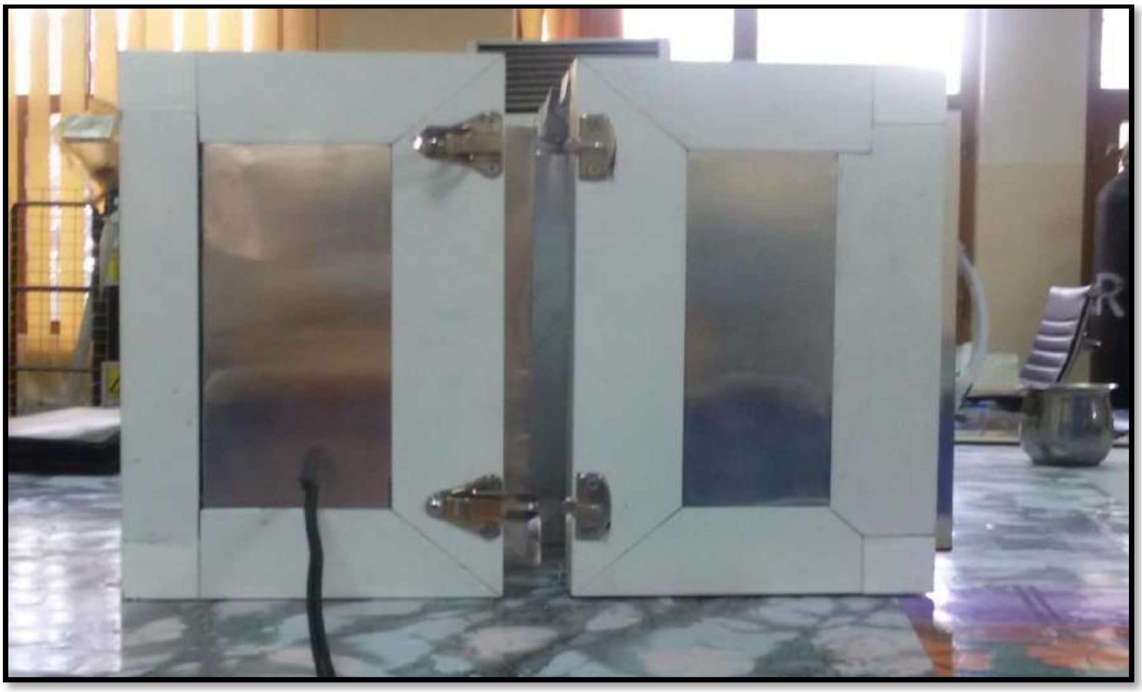


Figure (4.7): Thermal Chamber.

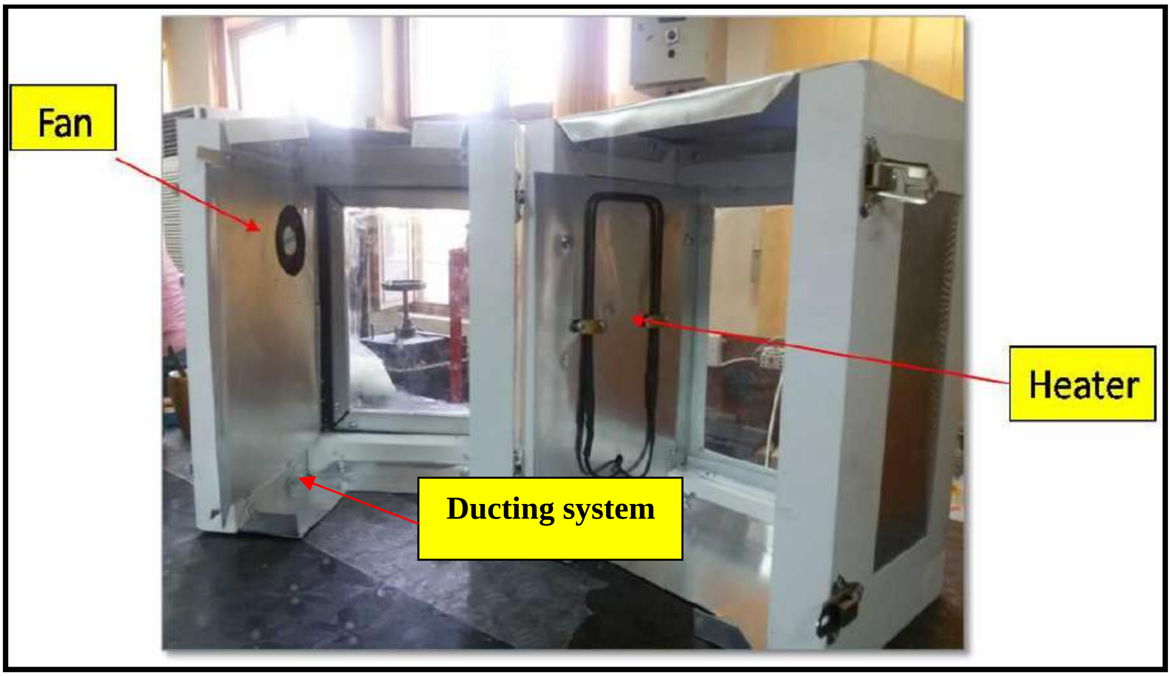


Figure (4.8): Thermal Chamber containing (A) Heater (B) Fan

4-5 Specimens for Thermal & Mechanical Properties

Three types of specimens were prepared for this study, these types are used to find the mechanical properties, thermal properties and buckling behavior:-

1. Mechanical test specimens.
2. Thermal test specimens (to find thermal expansion coefficient).
3. Buckling by thermal loading.

4-5-1 Specimens for Mechanical Properties

Mechanical properties were measured as follows:

1- The tensile specimens are cut using CNC machine as shown in plate (4.1) according to a standard of tensile test of ASTM (D-638 type IV) [48] as shown in plate (4.2).

2- 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) as shown in plate (4.3).

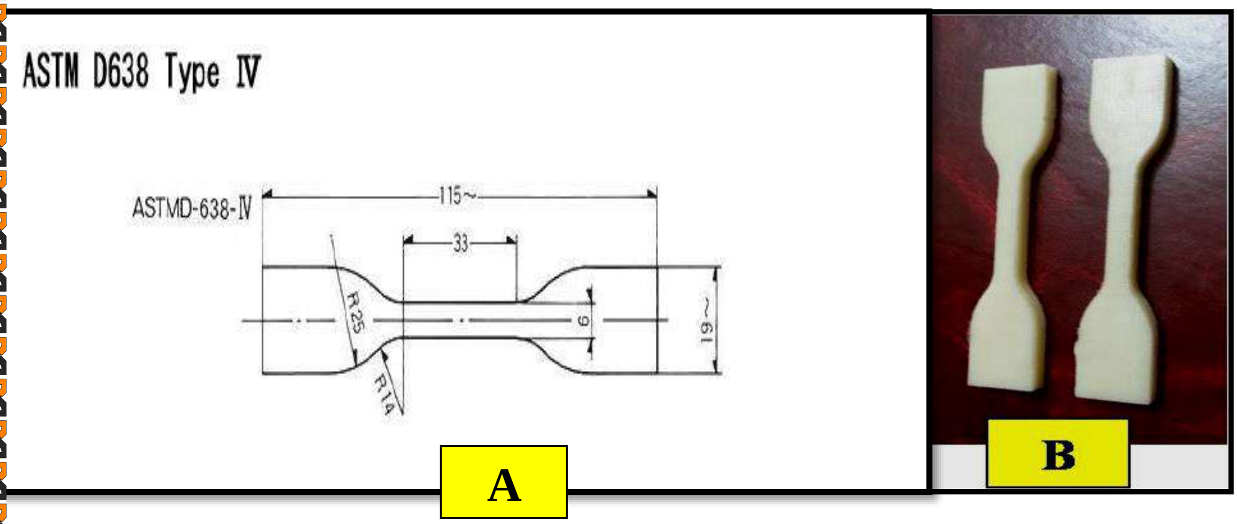


Plate (4.1) CNC (C. Tek) Machine

Plate (4.2) (A) The standard specimen for the tensile test, (B) Tensile specimens.

Plate (4.3) Tensile tests using universal testing machine.

4-5-2 Thermal Property Tests (Thermal Expansion Coefficient Measurement):

The thermal property of composite material required in this study is the thermal expansion coefficient. Thermal expansion is the tendency of matter to change in length or volume of material in response to a change in temperature. When heat is subjected to most materials causes the material to expand.

The linear thermal expansion coefficient is the fractional change in length per degree of temperature change. It can be evaluated using the following equation [49]:

$$\alpha = \frac{\Delta L}{L\,.\,\Delta T} \qquad \ldots(4-1)$$

Where:

α = Thermal Expansion coefficient (m/m.°C)
L = Original length of the sample (m)
ΔL = Change in length of the sample (m)
ΔT = Temperature change (°C).

An experimental evaluation of the thermal expansion coefficient was carried out using the same testing buckling specimen with dimension of (170 mm × 50 mm) with thickness of (4.7,4.9)(mm)for group (A,B) respectively.

Determination of the coefficient of thermal expansion of a given Sample Procedure:

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) according to (ASTM D_696) [50].

The increment in length was measured using an accurate dial gauge. Thermal expansion coefficient is then calculated using equation (4-1).

4-5-3 Buckling by Thermal Loading Test:

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

The specimens were cut into a specific dimension (200 mm × 50 mm) as shown in figure (4-9). To apply Euler buckling equation of a long column, the specimens dimensions must ensured that the slenderness ratio was greater than critical slenderness ratio, after applying those equations these dimensions were chosen to initiate this study, all the equation of calculation are presented in appendix (A) .

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. Enclosing 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. Appling 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 ℃ and 50 ℃).
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.

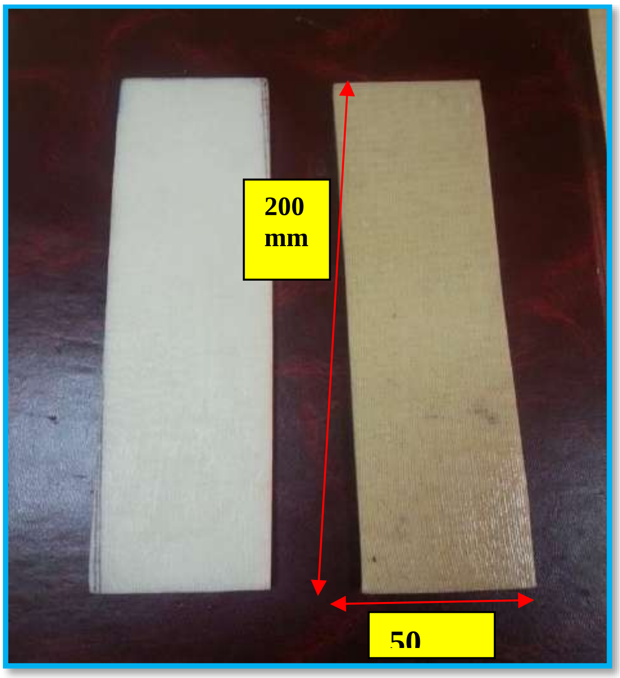


Figure (4-9): Specimen for Buckling Test.

The overall experimental rig is shown in figure (4 – 10) which is used in this research to study the thermal buckling. This figure shows the main items of the experimental rig which are:

1. The hydraulic press.
2. The thermal chamber.
3. The digital load indicator.
4. The digital temperature controller.
5. The dial gauge.
6. The load cell.
7. The test specimen, and
8. The other items mentioned in paragraph (4 – 4).

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.

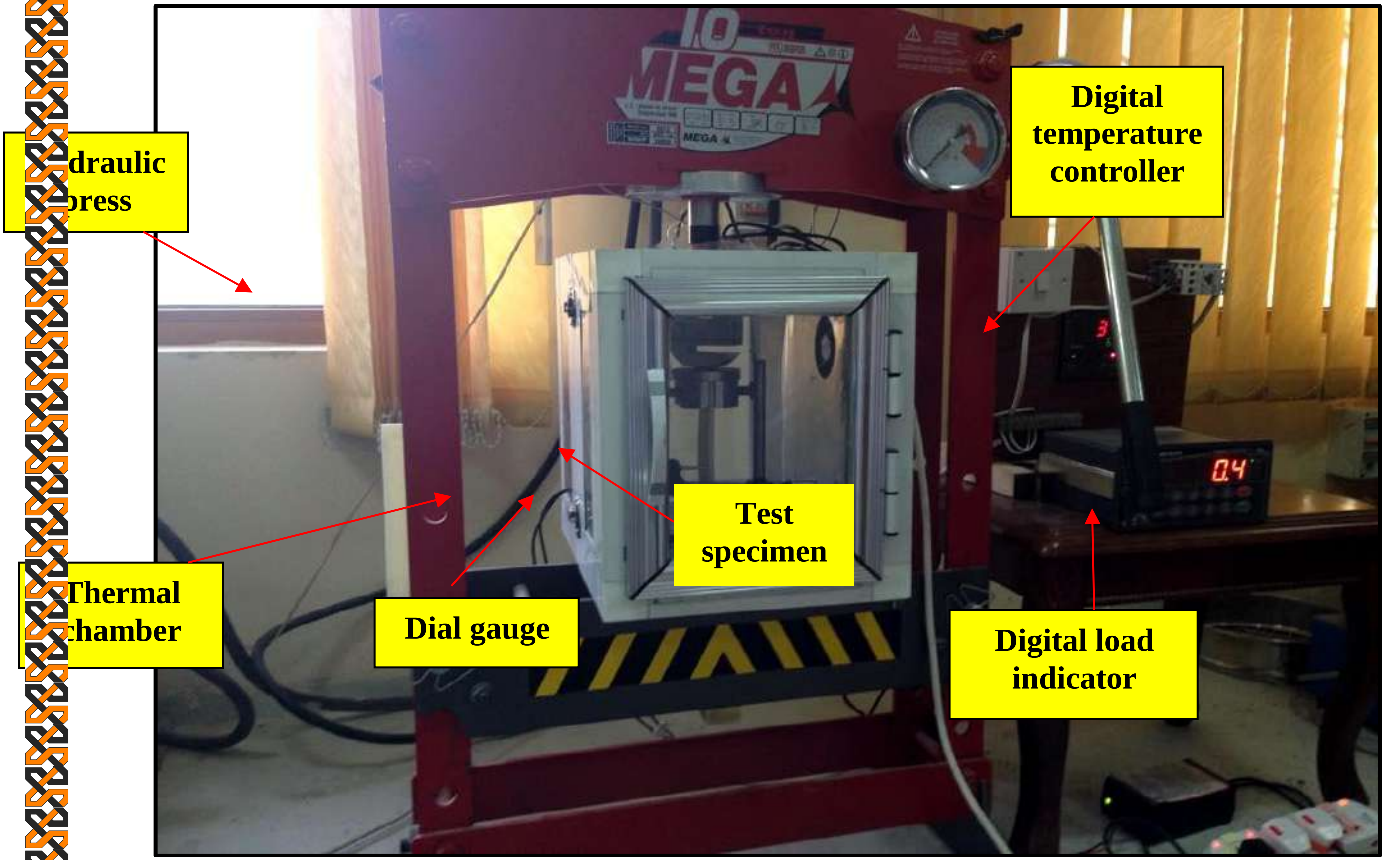


Figure (4-10): Buckling Test Device.

Figure (4 – 11) is shows the procedure of the experimental work in the following flowchart:

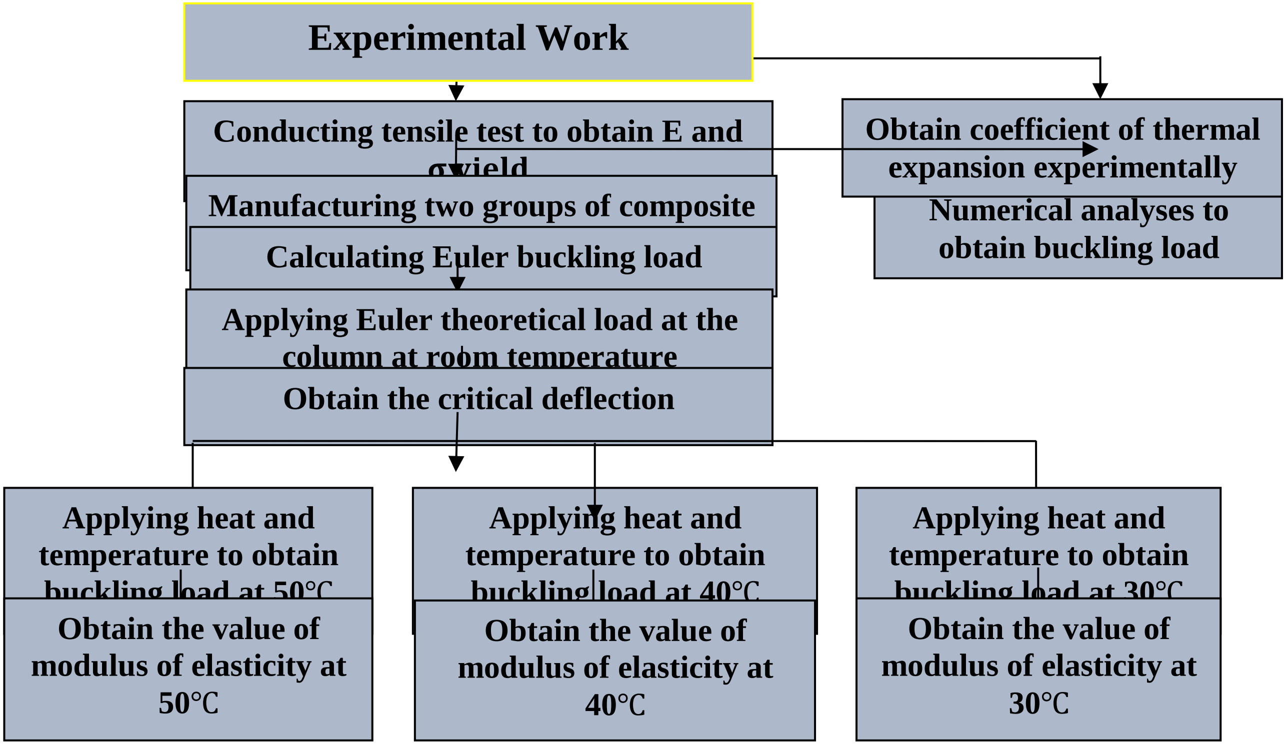


Figure (4-11): The Main Steps of Experimental Work.

Chapter Five

Results and Discussion

5-1General

Theoretical, experimental and numerical results are evaluated and discussed. Mechanical properties obtained by the tensile test were used as input data in determining the dimensions of buckling test specimens. The results obtained from the numerical analysis by ANSYS software program were used to predict buckling load and to compare them with the theoretical results.

5-2 The Mechanical and Thermal Test Results

5-2-1 Tensile Test Results

The results of tensile test for these groups are shown in figure (5-1).

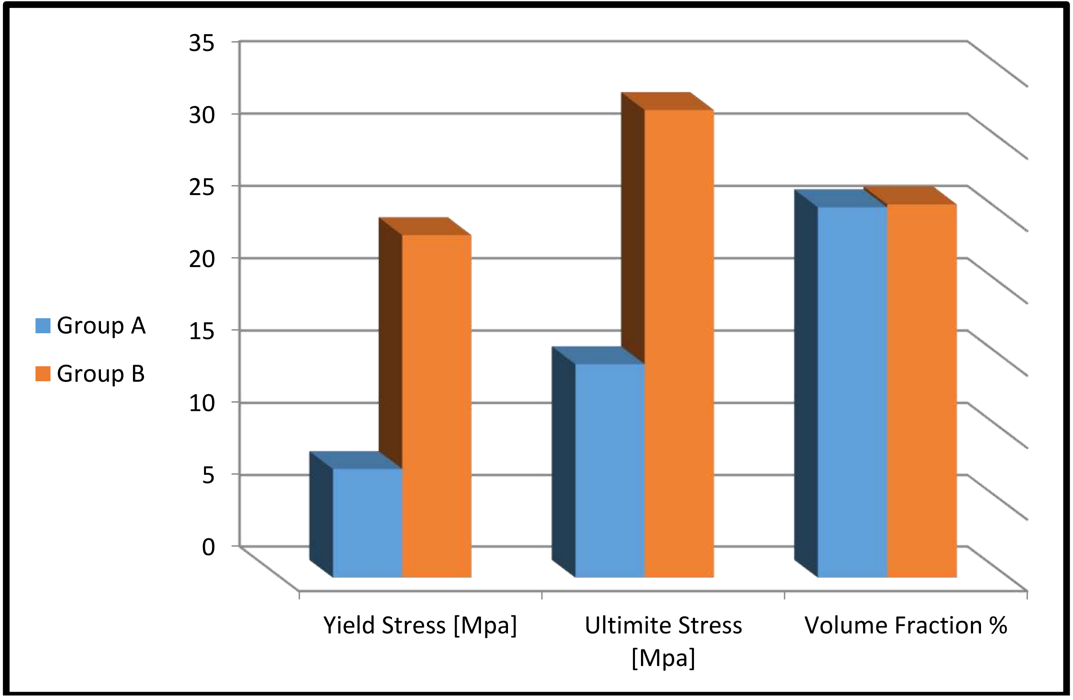


Figure (5-1) Tensile properties (Yield Stress, Tensile Stress and Volume Fraction) of both composite groups.

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 from figure (5-1) that reinforcing composite materials with carbon fiber improves their strength and stiffness properties and this combination of properties would eventually enhanced the overall performance of composite materials. Also it is noted that reinforcing with perlon fibers gives low tensile properties, meaning that perlon improve the mechanical properties of matrix material to a small extent.

The increase in the number of reinforcement materials has increased the absorbing ability of matrix material and the results of volume fraction strongly support this analysis [the results of calculating volume fraction are presented in appendix (B)]. For that reason the higher strength coming from changing fiber material and number of reinforcement layers.

5-2-2 Determining the Coefficient of Thermal Expansion (CTE)

The value of the linear coefficient of thermal expansion was experimentally evaluated by heating both groups to temperature range from (room temperature to 60°C) and recording the resulting elongation. The results were tabulated in table (5-2)

Two graphs were plotted between the (ΔT) against the dimension change which is shown in figures (5-2) and (5-3) for both groups (A, B) respectively.

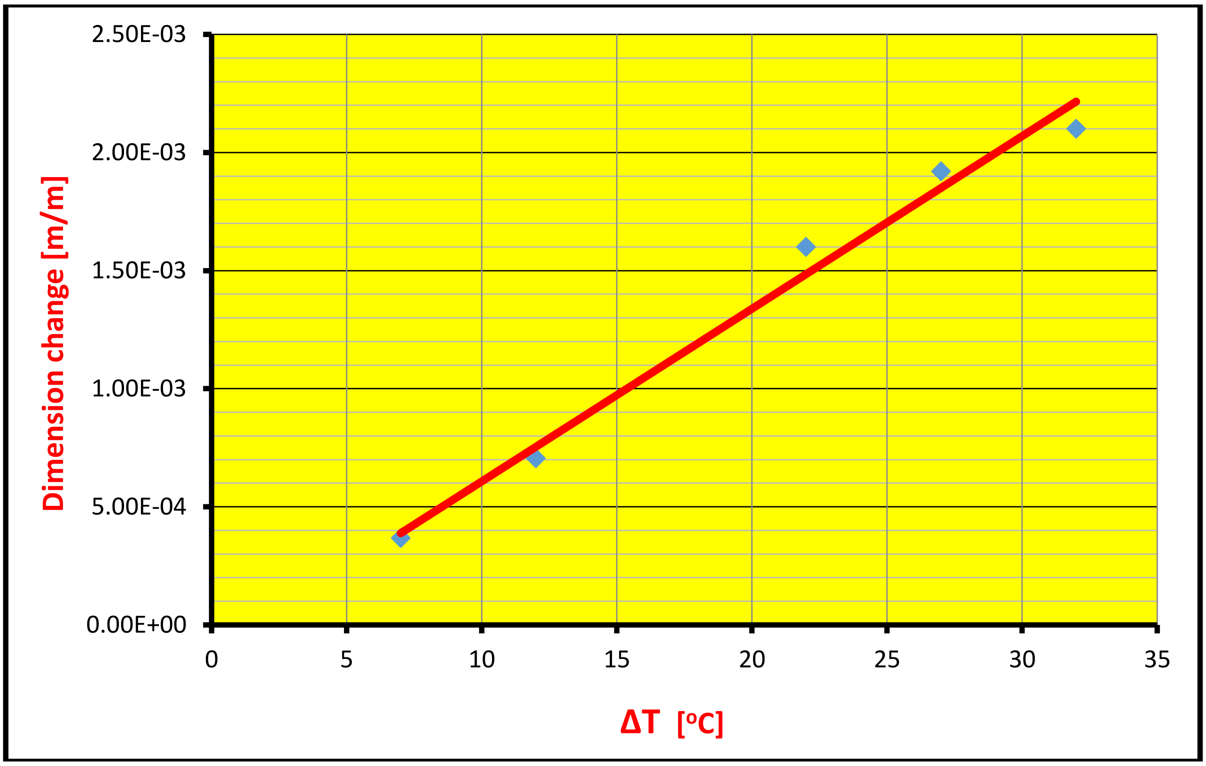


Figure (5-2) Coefficient of thermal expansion of group (A) materials.

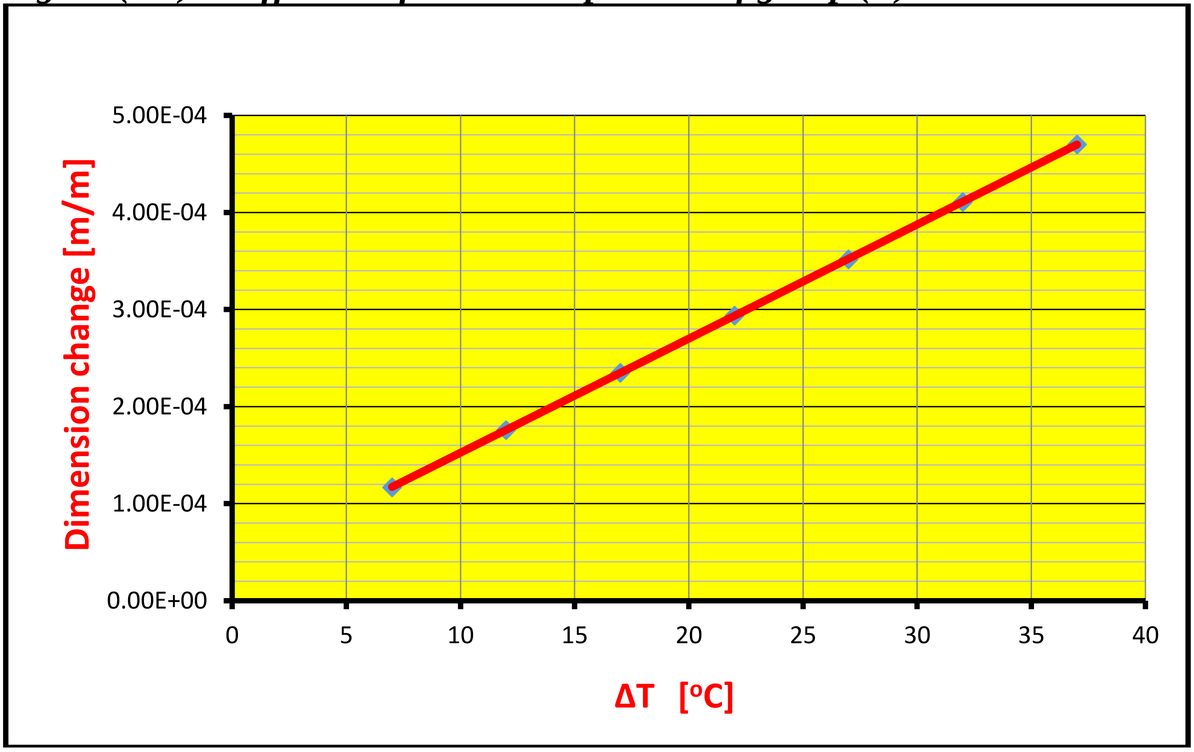


Figure (5-3) Coefficient of thermal expansion of group (B) materials.

The (CTE) was evaluated as the slope of those graphs.

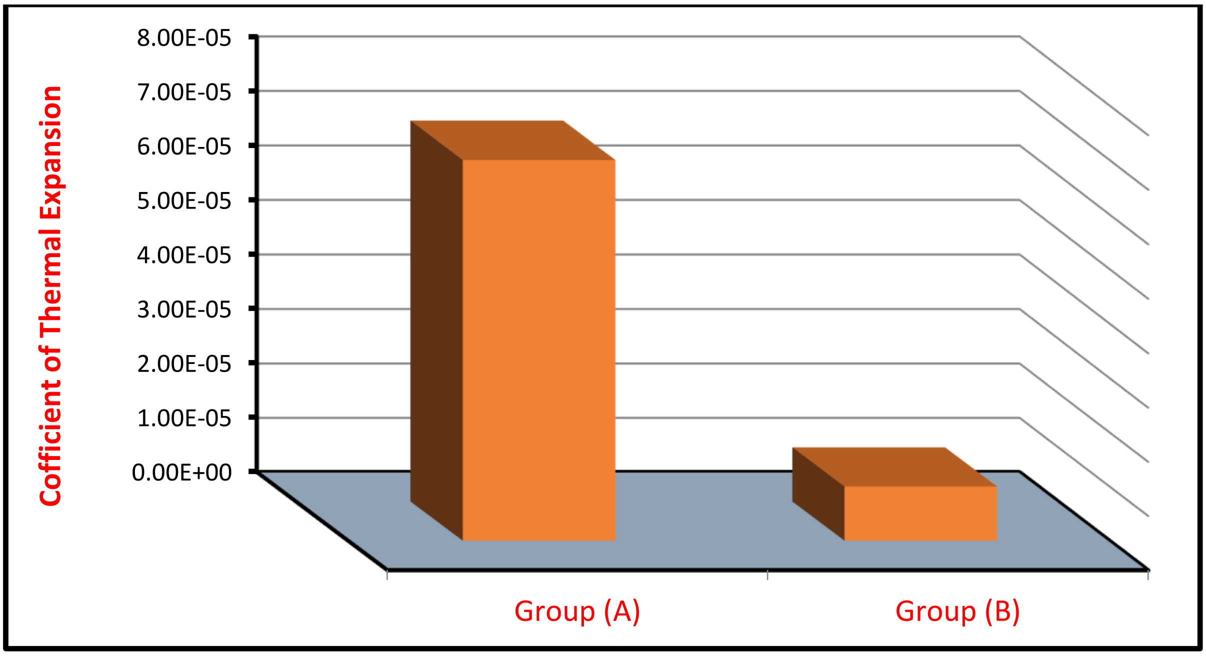


Figure (5-4) CTE comparison among different composite laminates

Coefficient of thermal expansion that was obtained compared with the standard (CTE) of composite materials and it seems to be within the range of fiber reinforced material [49]. A comparison of (CTE) among group (A), group (B) is presented in figure (5-4), the graph shows that group (A) has a higher CTE of [7×10^{-5} m/ m·°C] whereas group (B) has small CTE of [1×10^{-5} m/ m·°C]. 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, As the temperatures increase from room temperature to (60 **°C**) the value of (CTE) for this group increases. Thus, the higher thermal expansion coefficient is considered as non-desirable for a wide range in structural applications.

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 [as in appendix (C)] and tabulated in table (5-1).

Table (5- 1) Euler buckling load

The Groups	**Theoretical buckling load [N]**

Group (A)	827.56
Group (B)	2327.73

Because composite material test specimens tend to be relatively thin, buckling failure mode is a concern when specimens are loaded in compression. The load at which buckling occurs depends on the stiffness of composite materials.

A stiff material is sensitive for high resistance to buckling. From table (5-1), 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 and that seem to make them the best candidate to use in the structural application where high buckling resistance are required. The reduction in stiffness property resulted by using perlon fibers as a reinforcement material in group (A) decreases the buckling resistance.

5-3-2 Buckling Results

Generally, the elastic modulus and strength of a polymer drops significantly with increasing the temperature. The effect of the temperature variation may be obtained by investigating the changes in buckling failure load after specimen's exposure for (15 minutes) for different temperatures.

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 (5-2) and (5-3):

Table (5- 2) Experimental results for testing group (A) of composite material (by applying heat and compression load).

Temp. [ºC]	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 (5-3) Experimental results for testing group (B) of composite material (by applying heat and compression load).

Temp. [ºC]	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

From tables (5-2) and (5-3), It is can be seen clearly that mechanical deformations is increased with increasing the temperature due to the mismatch of thermal expansion coefficients of fibers and matrix which can generate internal stresses, causing defects in the microstructure or delamination of their laminas.

Acrylics (poly-methyl-methacrylate) has reasonable mechanical properties at room temperature but with increasing temperatures these properties are decreasing because inter-chain bonding in polymer matrix is weakened allowing deformation at low stresses and leaving only the fibers, but since these fibers no longer provide composite action.

The value of critical buckling load decreases as the temperature increase as shown in tables (5-2) and (5-3). The different in critical buckling load between room temperature to (50 °C) about (63.8 %, 62.1 %) for group (A), group (B) respectively.

This temperature dependent behavior of composite materials reduces their mechanical load carrying capacity leading to structural failure under service loading

1- Buckling Analysis for Group (A)

This group has (10 layers of reinforcement), the 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.

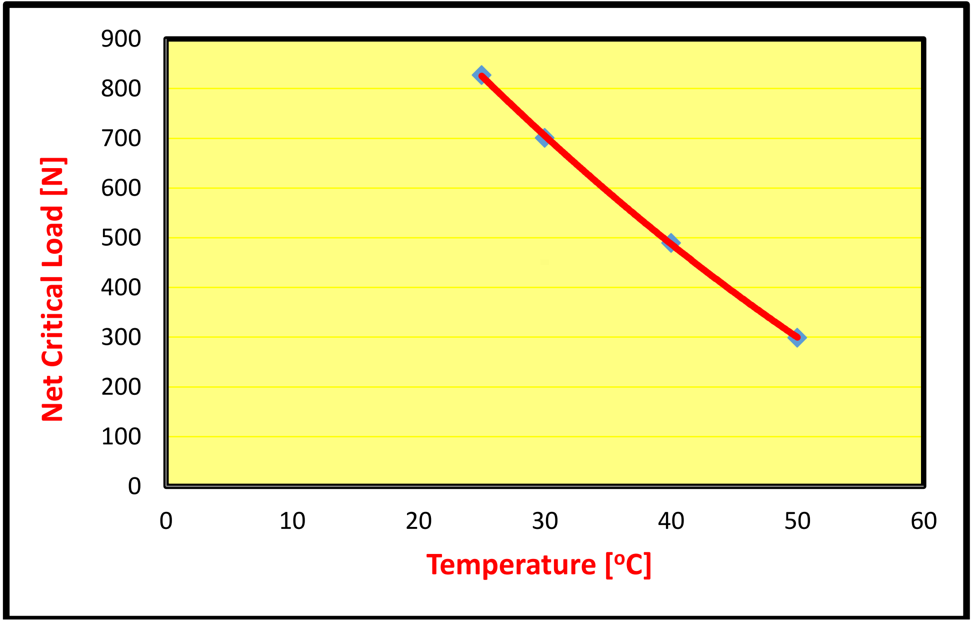


Figure (5-5) Critical Buckling load vs. Temperature.

Using fitting curve, a derived formula for buckling behavior for net critical load as a function of temperature variation was obtained as follows:

$$\mathbf{P_{cr} = 0.150\, T^2 - 32.33\, T + 1539 \qquad 24\,^{\circ}C < T < 50\,^{\circ}C \ \ldots\ (5-1)}$$

Where:

P_{cr} = Net Critical Load [N]

T = Temperature [**°C**].

It can be noticed from graphs, 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 resulting in degradation in the mechanical properties of the laminate as the temperature are increasing.

2- Buckling Analysis for Group (B)

This group has (12 layers of reinforcement) (5 perlon+ 2 fiber carbon+5 Perlon), the buckling occurred by heating the sample to (58 °C) with load (73.5 N) as critical buckling load.

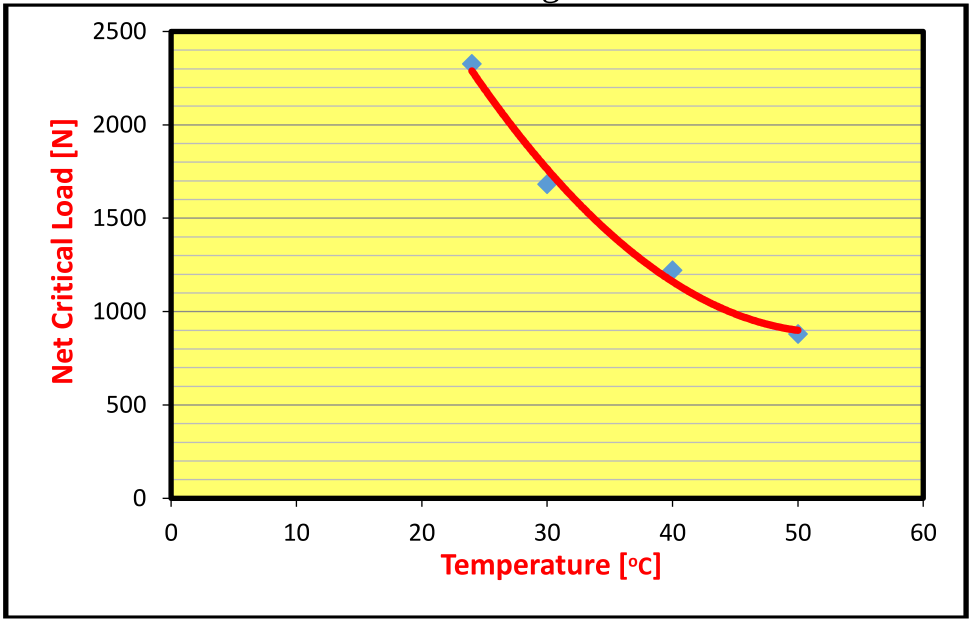


Figure (5-6) Critical Buckling load vs. Temperature.

Using fitting curve, a derived formula for buckling behavior for net critical load as a function of temperature variation was obtained as follows:

$$\mathbf{P_{cr} = 1.706\,T^2 - 179.6\,T + 5618 \qquad 24\,^{\circ}C < T < 50\,^{\circ}C \;\ldots\; (5-2)}$$

Where:

P_{cr} = Net Critical Load [N]

T =Temperature [°C]

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. For (Perlon & Carbon Fibers) composite column, Carbon fibers which tend to exhibit high stiffness and low coefficient of thermal expansion help the damaged Perlon fibers so the column can have an exceptional buckling resistance under the combined effect of temperature and service loading.

5-4 Temperature Effect on Elastic Modulus

Modulus of elasticity is a fundamental measure of the stiffness of the material. The higher modulus of elasticity, the material has more resistant is to be stretched. It is well known that the modulus of polymers depends strongly on the temperature. The degradation of the elastic properties with temperature is accounted for, by using experimental data from the critical load and by adding this load to equation (5-3) [44].

$$\boldsymbol{E = \frac{\mathrm{Pcr}\, L^2}{4\pi^2\, I}} \qquad \ldots (\mathbf{5-3})$$

Where:

E= Modules of Elasticity [MPa]
P_{cr} = Applied load by (compression with heat) [N].
L = length of testing specimen [m]
I = Moment of inertia [m^4]

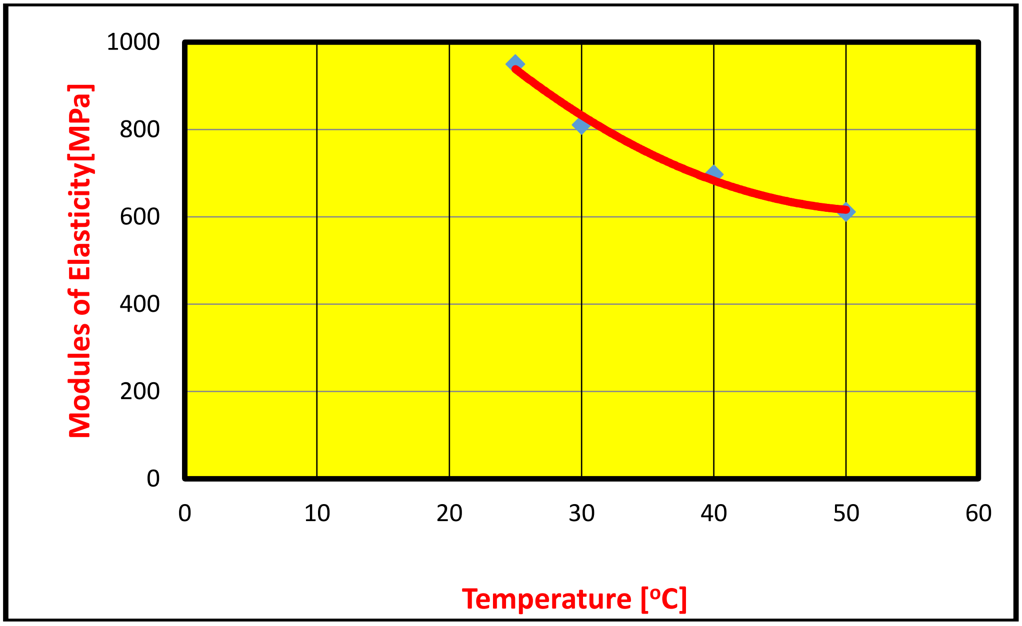


Figure (5-7) **Variation of Modulus of Elasticity with Temperature for group (A) of Composites column**.

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

$$\mathbf{E = 0.413\, T^2 - 43.88\, T + 1777 \quad 24\,^{o}C < T < 50\,^{o}C \quad \ldots (5-4)}$$

Where:

E = Modules of Elasticity [MPa].
T = Temperature [°C].

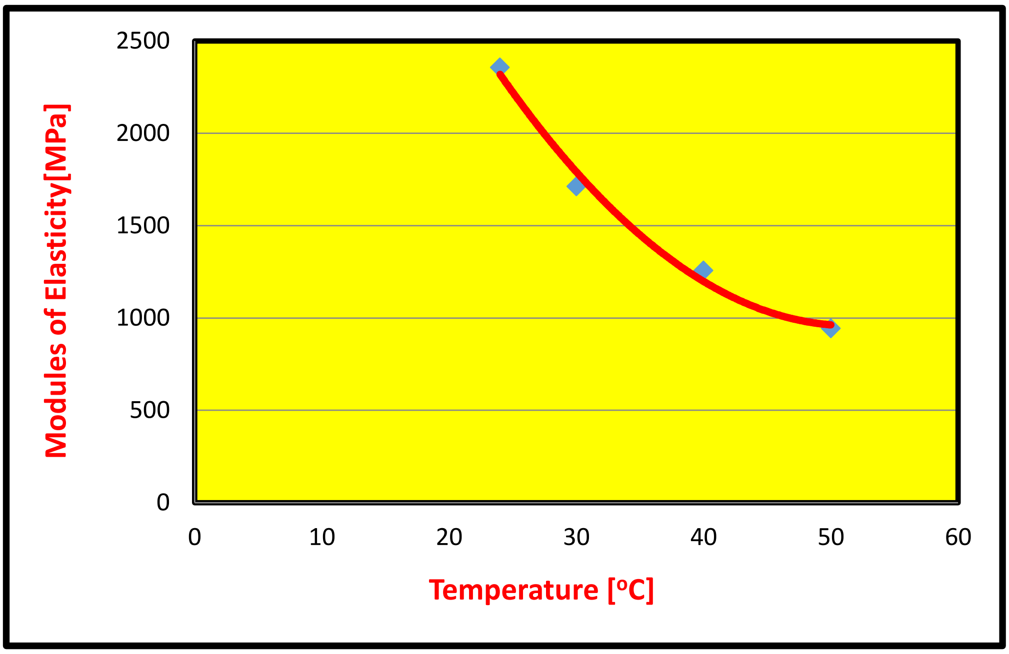


Figure (5-8) Variation of Modulus of Elasticity with Temperature for group (B) of Composites column.

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

$E = 1.791\ T^2 - 184.7\ T + 5721 \quad 24\ ^{o}C < T < 50\ ^{o}C$ … (5 – 5)

Where:

E = Modules of Elasticity [MPa].

T = Temperature [°C].

This method is considered better than stress relaxation method where there is a very large difference and so it cannot be used in composite materials.

Figure (5-7) and (5-8) show that with increasing the test temperature, a significant loss in elastic modules is observed for both types of groups because when fiber reinforced composites are subjected to high temperatures, their mechanical properties, such as the modulus of elasticity, undergo significant changes. Such changes are mainly caused by the glass transition of the resin.

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. While group (A) with perlon fibers as reinforcement materials shows a reduction in the mechanical properties (the elastic modulus and strength) as the temperatures are increased.

5-5 Numerical Results

Buckling failure of an ideal linear elastic structure can by analyzed using a technique well known as linear buckling analysis.The goal of this analysis is to determine the buckling load facter and 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 (5-9) and figure (5-10), in addition to the numerical results of the critical buckling load was tabulated in table (5-4).

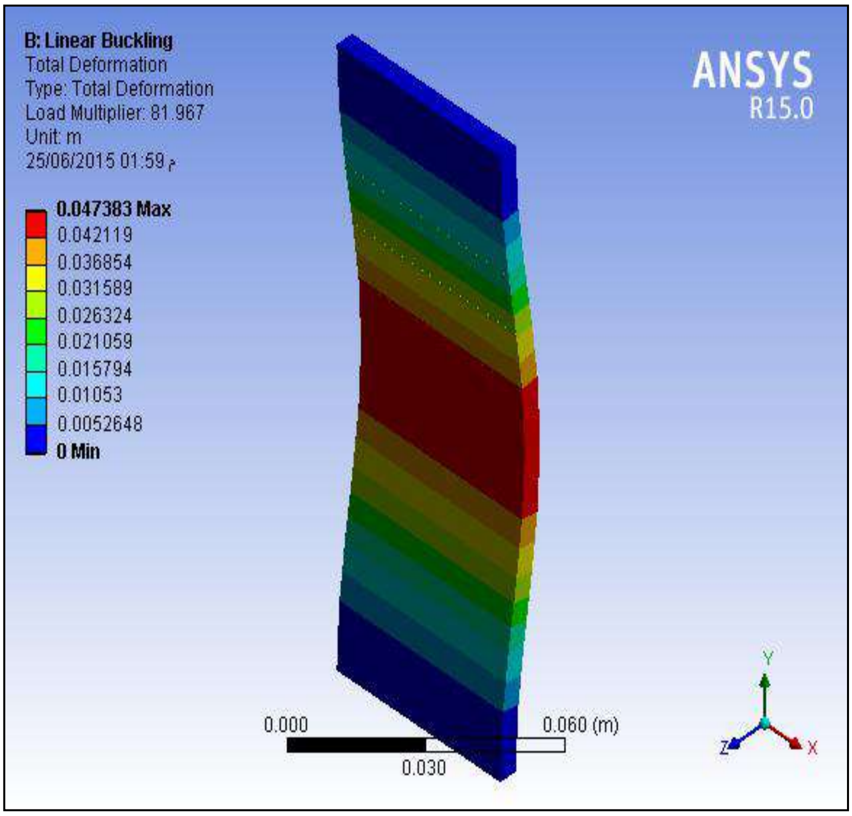


Figure (5-9) The buckling shape of group (A).

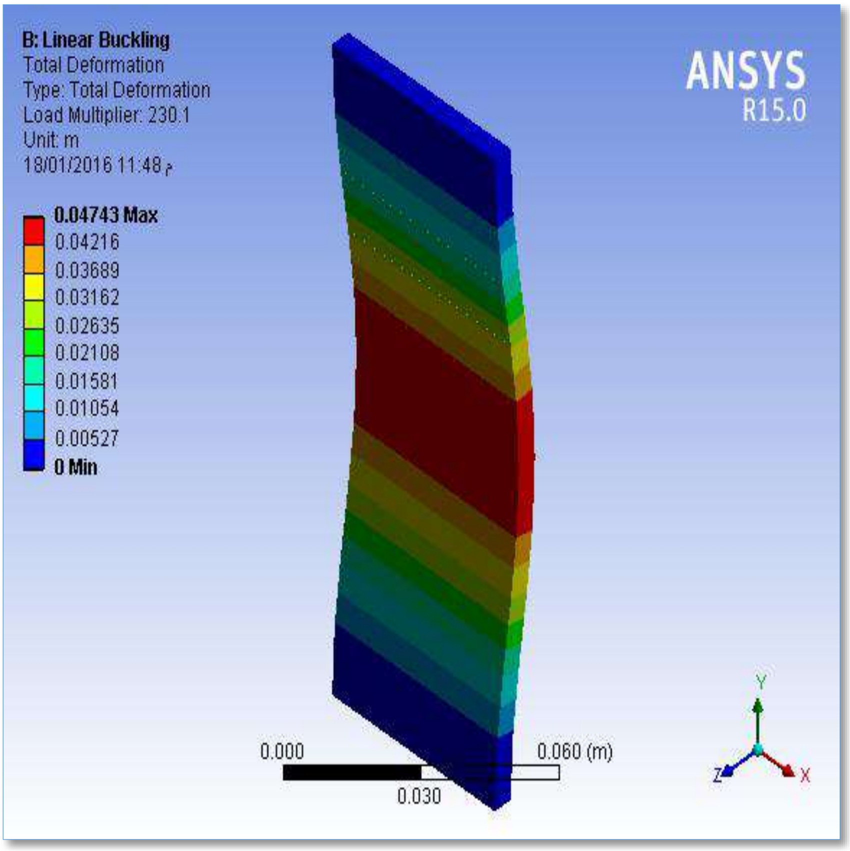


Figure (5-10) The buckling shape of group (B).

Table (5-4) The Numerical results of buckling load.

Groups	**Critical buckling load [N]**
Group (A)	819.57
Group (B)	2301

After setting-up the loads and fixed- fixed boundary conditions under a static structural. Critical loads that induce buckling and possible buckled shapes are presented where critical buckling load is appeared to increase with the number of reinforcement layers and type of lay-up.

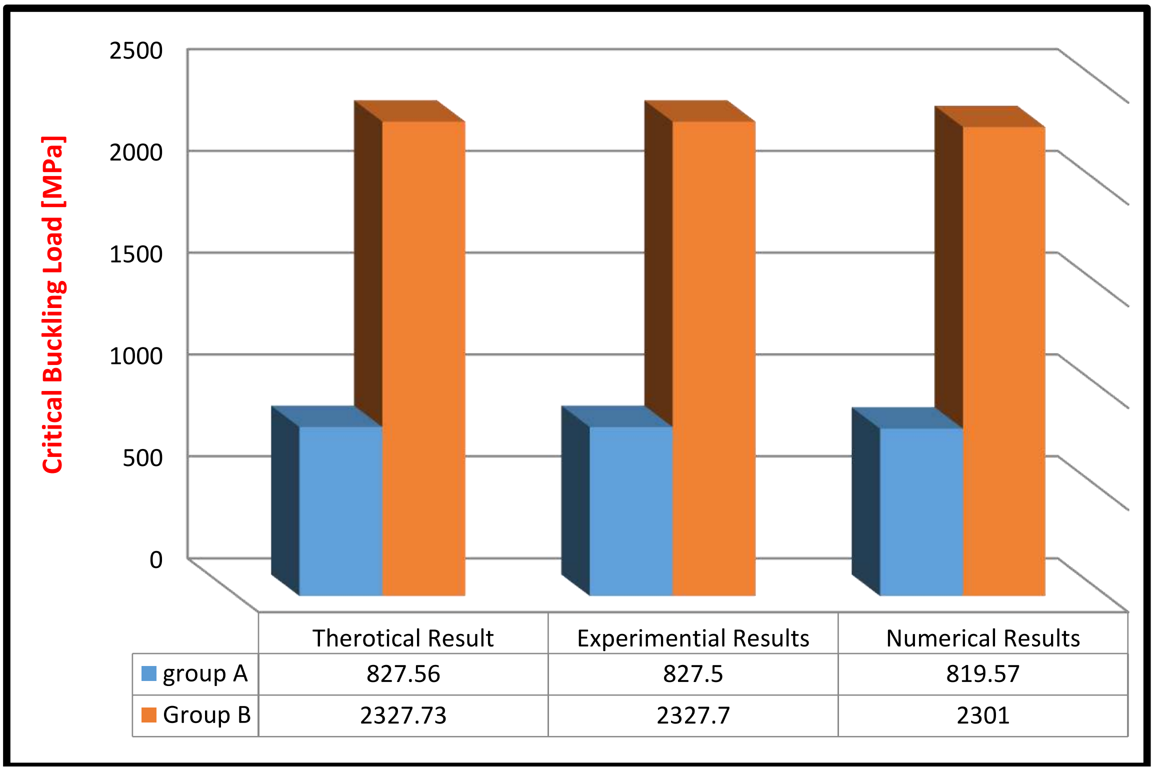
From table (5-4), it is clear that the high elastic modules and low coefficient of thermal expansion Carbon fibers in group (B) make this material especially suitable for wide range of structural applications as they show an attractive resistance property against failure due to axial compression load. While group (A) reinforced by (10) layers of Perlon fibers have low modules of elasticity and as a result buckling failure mode is a concern when composite materials with this type of reinforcement lay-up are loaded in compression.

5-6 Comparison between Experimental, Theoretical and Numerical Results of Buckling Behavior

Figure (5-11) shows the comparison of buckling failure load between the experimental, theoretical and numerical analyses.

It is clear that the classical Euler buckling load and numerical value of (P_{cr}) were very close to the experimential results of (P_{cr}) obtained at room temperature.

The experimental results of buckling load relatively appear higher compared to the numerical results. This is probably due to the significant changes in experimental structural stiffness; however, the numerical model applies to perfect elastic behavior column. This results in the experimential results being greater than those shown in the numerical ones. The buckling modes predicted from the Eigenvalue buckling analyses correlate well with the experimental observations.



	Therotical Result	Experimential Results	Numerical Results
🟦 group A	827.56	827.5	819.57
🟧 Group B	2327.73	2327.7	2301

Figure (5-11) Comparison between the Experimental with Theoretical and Numerical results of Critical Buckling Load.

Chapter Six
Conclusions and Recommendations

6-1 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. Group (B) with (carbon &perlon fibers) as a reinforcement maintains an excellent stiffness characteristic with increasing the temperature and high buckling resistance.
2. The value of modulus of elasticity decreases with increasing temperature for both groups
3. A new experimental formula takes into account the effect of change in temperature on elastic modulus and Euler buckling load was derived.
4. The value of coefficient of thermal expansion increases with temperature, where group (A) with (10 layers of perlon fibers as a reinforcement material) shows a higher coefficient of thermal expansion than group (B).
5. The results of numerical critical buckling load are in a good agreement with the predicted Euler buckling load.

6-2 Recommendations and Suggestions for Future Work

The following Recommendations and Suggestions can be taken into consideration in future work:

1. Applying the same experimental analyses to get the buckling behavior of other types of composite materials under different temperatures.
2. Studying the effect of temperature on buckling behavior for various types of metal alloys.
3. Investigate the effect of shot peening at different time periods on the buckling behavior with a varying range of temperatures.
4. Study of the buckling behavior of welded alloys by friction stir welding with different parameters.
5. Investigating the temperature effect on the buckling resistance of composite material column with different reinforcing layers.

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