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College of Engineering



Investigation Biaxial Creep of Woven Fabrics of Composites Materials

A Thesis

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(Polymers Engineering)*

By

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيمِ

((يرفع الله الذين آمنوا منكم والذين
أوتوا العلمَ دَرَجَاتٍ وَاللَّهُ بِمَا تَعْمَلُونَ خَبِيرٌ ١٠))

صدق الله العلي العظيم
المجادلة (11)

الخلاصة

أغلب المواد المركبة التي تصنع حديثاً هي من الألياف المختلفة (الهجينة). وهذه المواد تكون معرضة إلى تأثير عدم التماثل في الخواص (anisotropic properties) في الاتجاهات المختلفة للمادة لعدم وجود مستويات تناظر لخواص المادة ذلك السلوك يقود الى صعوبة في التصميم وصناعة هذه المواد بسبب عدم توقع الاختلافات التي تحصل في خواص تلك المواد مثل مقاومة الزحف و الانبعاج في اتجاهات مختلفة الخ.

لأسباب أعلاه فان مشروع الدراسة الحالية يركز على دراسة ظاهرة الزحف الثنائي في المواد المركبة والمقواة بنسيج ذو ألياف مختلفة (Hybrid) هنالك عدة طرق لمعرفة سلوك المادة تحت حالة معقدة من الاجهادات (complex stresses) , في هذه الدراسة استعملت تقنية واحدة للفحص وهي طريقة الفحص الثنائي في المستوي (in-plane biaxial testing). التحميل الثنائي على العينات الصليبية في الدراسة الحالية منفذ بواسطة طريقة العناصر المحددة (FEM) بواسطة نظام التحليل (ANSYS 10). لتحقيق من دقة النموذج الرياضي تم تنفيذ الجانب العملي. في هذه الدراسة استخدمت مادة البولي اثيلين النقي المنخفض الكثافة كمادة أساس (matrix) ونسيج يتألف من ألياف البولستر والنايلون تمت حيакته بشكل (plain weave).

يتضمن الجزء العملي تطوير وصناعة أداة تجريبية لدراسة سلوك الزحف الثنائي (biaxial creep behavior) للمواد المركبة ذات ألياف مختلفة (هجينة) المحاكاة بشكل (plain weave) تحت شد ثنائي متماثل وبشكل متعامد في درجة حرارة الغرفة.

الخواص المبدئية للمادة الأساس والألياف كمقاومة الشد ومعامل المرونة لمكونات المادة المركبة تم حسابها بواسطة جهاز فحص الشد أحادي المحور نوع (tensometer 10 machine).

النتائج العملية أظهرت أن مقدار الزحف للمادة المركبة ذات الأنسجة المحاكاة باتجاه ألياف النايلون يكون أكبر من مقدار الزحف للمادة باتجاه ألياف البولستر. كذلك أظهرت بان قيمة الزحف التجريبية تكون اكبر من قيمة الزحف النظرية للبولي اثلين منخفض الكثافة .

ABSTRACT

Most of composite materials which are newly fabricated from hybrid fibers ,these materials are mannequin to effect of anisotropic in behavior because there are no planes of symmetry for the material properties that behavior leads to difficulty in the designing and fabricating of these materials because of variation in their properties such as strength , creep and warping in different direction.....etc will not be expected.

For the causes hereinbefore the present work is a proposal to the study of the biaxial creep phenomena to the hybrid woven fabrics composite materials. There are many methods to study material behavior under state from complex stresses, the current study one technique for investigating material behavior is used in – plane biaxial testing . Mostly cruciform specimens are used of in-plane biaxial testing .In this study the cruciform specimen under in-plane biaxial loading is carried out by using the finite element technique implemented by ANSYS (10)code. To verify this model in the prediction anisotropy effect an experimental work is conducted. This research is applied to the pure low density polyethylene as matrix and plain weave from nylon and polyester fibers.

The experimental work includes development and fabrication of an experimental device for assessing biaxial creep behavior of hybrid woven fabrics composite materials under Biaxial symmetric tension at room temperature.

The initial properties of matrix and fibers such as tensile strength and modulus of elasticity are evaluated in universal uniaxial (tensile test tensometer10 machine type) .

The experimental results show the creep value of woven fabrics of composites materials in the direction of polyester fiber which is lower than the creep value in the direction of nylon , and they also show that the creep value of experimental work is higher than numerical value of pure low density polyethylene.

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Finally ,I would like to thank all my friends for their encouragement.

Wisam N. AL- Aaragie

Examining committee

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I dedicate this thesis to:

My parents,

&

My brothers

*For their encouragement, support,
and love.*

Wisam

Chapter One

Introduction and Literature Survey

(1-1) Introduction

The rapidly expanding applications of composite materials in the recent past years have provided much optimism for the future of engineering design and technology. With the recent advances in modern industrial materials , such as high polymers and polymeric base composite materials , and their extensive application in aerospace and other industries. (the high technology of composites have been in the aerospace industry only in the last thirty years) [1,2].

The advantages of composite include high strength to weight ratios, good fatigue and creep resistance , good corrosion resistance. These advantages of composite spurred the development of high strength and low ductility materials such as fiber reinforced matrix composites. The properties of composites are usually different from those of original materials[1,3].

Both the fibers and matrix retain the physical and chemical identities. Yet they produce a combination of properties that cannot be achieved with any of the constituent acting alone [1 , 4].

In general, fibers are the principal load carrying members , while the surrounding matrix keeps them in the desired location and orientation acting as a load transfer medium between fibers and protecting them from environmental damage [1 ,4,5,6].

Fiber reinforced composite materials may offer a combination of strength and modulus that are comparable to or better than many of the traditional materials . Traditional structural materials such as steel and aluminum alloys are considered "isotropic " since they exhibit nearly equal properties irrespective of the direction of measurement [1].

The fibers may be oriented randomly within the material , but it is also possible to arrange them to be oriented preferentially in the direction expected to have the highest stresses. Such a material is said to be "anisotropic"(different properties in different directions).In general the properties of fiber reinforced composites depend strongly on the direction of measurements [1,3].

The composite perform is obtained from the assemblage of unrigidized fibrous material (fibers yarn or fabrics)and its architecture can vary from a simple planar sheet to complex 3D net shape [7,8].

It is also well known that the textile fabric composites have been attractive for industrial application as a reinforcement of composite materials. For example the composite materials reinforced with woven and braided fabric performs have been considered for potential structural applications in the aircraft and automotive industries . Fabric- reinforced textile composites potentially have better out-of plane stiffness, strength, and toughness properties than laminates composed of plies. Among these textile fabrics ,tri-axial woven fabrics have many attractive properties . It has been stated that tri-axial woven fabrics have more isotropic responses to both tensile and shear deformation compared with the convntional biaxial fabrics .In addition , the tri-axial woven fabrics can also be individually used in some composite structures such as satellite dish [9,10].

Textile structural composites have been the focus of many aircraft and automotive manufactures for more than two decades . They offer a good alternative to develop composite primary structures for commercial transport airplanes with costs that are completive with those of current metallic airplanes. Textile composite were considered for many components to improve structural performance and to reduce costs. Boeing and Lockheed martin evaluated textile composites for fuselage frames [7,11].

Polymer composites are viscoelastic in nature (i.e. their behavior is a combination of viscous and elastic behavior). While being used for load bearing structural application , polymer composites exhibit time dependent degradation in modulus and strength .As a consequence of viscoelasticity of the polymer matrix .The time dependent modulus and strength of composite materials are measured by creep and creep rupture tests respectively .Since characterizing the time dependent modulus and strength for the entire service life is impossible, accelerated testing and

extrapolation procedures are used to extrapolate creep data obtained over a short time to time frame beyond the experimental time window .

Composites used in aerospace industries are either multidirectional or textile composite .Since fiber orientation in a multidirectional composite varies from layer to layer , characterizing each composite laminate lay-up sequence for time dependent strength and modulus is costly and time consuming . The preferred route by many researchers is to measure creep and creep rupture data for unidirectional composites and use them with suitable model (such as lamination theory), to predict creep and creep rupture data of multidirectional and textile composites [12].

(1-2) Literature Survey

(1-2-1) Literature survey of manufacturing biaxial testing rig and studied biaxial behavior

The biaxial studies are cited in the literature .It has an active area in mechanical behavior research in the past few decades .The following is a listed of some studies by researchers about bi -axial test of composite materials with woven fabrics .

1-Clulow and Taylor (1963) designed the first bi-axial testing rig for the investigation of biaxial stress - strain relations in plain - weave cloth using a manual /motor driven screw system. They primarily investigated repeated stressing of woven cloth using a cruciform sample with a 100*100 mm central section . The cloth was gripped by two rectangular steel bars screwed firmly together by three bolts . Tension was measured by the deflection of stiff springs via a transducer . Dimensional changes were measured by the relative displacement of needle points inserted in the cloth . The maximum load that could be applied was 900 N . Continuous cycling was achieved by setting relays to reverse the drive direction . In each axis , both arms moved simultaneously ; this has the advantage of keeping the sample central , but restricts the versatility of the instrument . The grip design meant that the applied tension was not entirely in the plane of the cloth ; this necessary condition is hard to achieve for flexible samples [13].

2-M.ZALAWSKKY(1969) studied bi-axial creep behavior of polymethyl methacrylate .Biaxial creep tests have been performed on thin -walled tubes of polymethyl methacrylate at 116 F .The results for the range of stress, temperature, and time investigated show : the creep behavior can be described by the form $\epsilon = \epsilon_0 + mt^n$ where ϵ is the strain , ϵ_0 is the time independent portion of the strain , and m and n are constants [14].

3-Robinson (1980) designed a dead weight system to determine the bi-axial properties of coated woven glass-fiber materials , used in the construction of fabric structures such as canopies. Loads in the order of

(2 KN) were applied to the arms of a cruciform sample , approximately 720 mm square in the central section . Extensions were measured using a combination of dial gauges and photogrammetry , resolution of - 0.025 and - 0.35 mm. Respectively . The sample grips consisted of an aluminum bar inserted along each edge of the fabric , where it had been folded and heat bonded to form a sleeve . This grip design gives true in -plane loading and a more even distribution of load along the sample [15].

4-Russell and berger(1982) designed the first bi-axial tensile tester specifically for investigating canvas paintings [16]. The tester used a dead weight system for tensioning the canvas . The canvas was not held in grips ; instead , fiberglass threads were attached along each side of the canvas , using plasticized epoxy adhesive . The other ends of the threads were attached , using epoxy adhesive ,to four separate bars . in each axis , a bar was attached to the dead weight system . This tester held 50 *50 cm square canvas samples . The original design was modified to incorporate a micrometer screw - driven assembly [17]. and an automotive data acquisition system. Strain was measured by the displacement of the bar using the micrometers (one quarter turn of the screw producing a 0.1 % change in the distance between the bars). A resolution of 0.02 % of the total length of the sample is quoted . A load cell in each axis was measured the applied load , with an average tension of 200 Nm^{-1} , with the assumption that the central region of the sample is under uniform load . with the advent of Berger and Russell 's rig , paintings were tested under realistic loading conditions for the first time [18].

5-Greenwood and Myles(1986) reported that most of the creep values for woven polyester fabrics are considerably higher than the values for the yarn , and for polypropylene , the creep results for woven and nonwoven fabrics are of the same general appearance [19].

6- D.E.DUVALL AND D.B.EDWRDS (1993) presented method for evaluating the creep and stress rupture response of polyethylene sheet under equal bi-axial loading is presented . Specimens have been tested at 23,60,80 °C .both creep data and stress vs. Failure time data have been obtained [20].

7-Boeler(1994) designed a screw - driven tester specifically for anisotropic materials , using flat cruciform samples , with applied loads up to 100N .The system is servo-controlled , to enable a variety of testing conditions and operations . Under either displacement or load control . The most interesting feature of this design is the implementation of an off axis testing devise . Tests can be performed where the principal directions of the applied loads do not coincide with the axes about which the material has symmetry , for example with the weft and warp in a canvas . The aim of such a device is to obtain homogeneous stress strain fields in the samples under test [21].

8-Lindem(1994) designed a screw-driven tensile tester to assess the bi-axial stress as paper dries , in response to a need for better process control in the paper making industry .The investigated how controlled shrinkage in both axes affects the final dimensions and properties of the paper .A sheet up to 180 mm square was held along four edges by pneumatically operated clamps.To avoid breaking of the paper due to stress concentrations around the clamps. Heating elements in the clamps preheated the paper locally . Typical applied tensions for this tester were the order of 14 Nm^{-1} (an order of magnitude lower than for canvas) [22].

9-C.szostkiewicz-Chtain and Hamelin (1996) studied material with a polyester plain – woven fabric coated with PVC .They presented three numerical textile composite micro-structure models .They are integrated in stiffness calculation software programs which are used to identify linear elastic characteristics for a coated fabric sample . The first two models are based on the laminated thin plate theory ;the fabric is represented by a stacking of uni directionally – reinforced layers ,or by the the "crimp model". The third one considers geometrical approach to the basic cell of the fabric ;the elastic characteristics are calculated by assembly of the meshing elements .In addition, an inverse and experimental stiffness identification method ,based on biaxial tensile tests conducted (in orthotropic directions),is proposed .Load – controlled tests are conducted on cross-shaped samples with different loading ratios in warp and weft directions :1/1,1/2,2/1.

The biaxial test experimental set-up cannot directly give stresses as a function of strain .On one hand ,stress-time curves are obtained by the processing load cells .On the other hand ,strain – time curves are tracked by the software visidef .Only the quasi – linear parts of the curves are considered [23].

10-Bathgate et.al. (1997) investigated tensile creep behavior of woven fabric composite stitched through the thickness with carbon threads along the loading direction. Creep tests were conducted at various temperatures. It was found that through-thickness stitching significantly improved resistance to creep deformation and creep rupture of stitched composites [24].

11- Tushar K. Ghosh, Xie Zhengheng, and H. Dattani (1997) developed an instrument for the evaluation of biaxial stress-strain response of fabrics . The results of initial evaluation of the instrument is encouraging. Test results show significant influence of load and extension ratios on stress- strain response of some commercially available nonwoven fabrics to biaxial loading. The results can be used for understanding the nature of failure in biaxial tensile loading and thereby design fabrics for particular applications [25].

12-Christina R.T.Youn and RogerD.Hibberd(1999) studied the practical application of bi-axial testing of canvas as the first step in getting further into the mechanical properties of the complex composite structure of a canvas painting .The long term of this study is to aid conservators in the selection and development of conservation treatments and methodologies [26].

13- p.BOisse,K.buet,A.Gasser,J.Launay(2001) studied the mechanical behavior under bi-axial tension . The study results are obtained for a set of fiber fabric reinforcements that show the consequences of undulations and interactions at the mesoscopic scale. For those experimental results it is possible to validate and identify models for the fabric behavior [27].

14- PHILIPS,KRISTIE(2002) studied stress relaxation of tufted carpets components .This research seeks to analyze the various components play relaxation .Since a carpet which is always in the phenomena of stress stretched simultaneously in both dimensions during installation .The results of this work are that fabrics may have higher creep and stress opportunities for movement in the relaxation values due to the greater fibers within the yarns may be fabric structure since the yarns and the able to shift positions in order to alleviate stress [28].

15-Prof. Dr. Josep Llorens(2004) studied a bi-axial test protocol to generate response surfaces to describe in-plane bi-axial fabric behaviour. Biaxial tensile testing of a plane cruciform specimen was carried out using a purpose built test rig. The fabric was conditioned such that the behaviour measured was not the initial behaviour but the typical behaviour of an in-situ fabric. The effect of load history on the response of the fabric has been investigated. As a result, the PTFE/glass-fibre fabric showed a very discrete response envelope, The behaviour dominated by crimp interchange with little extension of the stiff glass yarns. In contrast, the polyester yarns were more easily extensible giving a greater range of possible strain states [29].

16- S.V.Lomov,A.Willems,M.Barburki*,TzStoilova,I.verpoest(2006)

They studied experimental techniques for prediction shear, bi-axial tension, bending properties of woven fabrics ,tension of fabrics can be characterized on KES-F tensile tester for low loads (up to 5 N/cm). The tests on fabrics of different orientation were performed with different ratios of deformation on the machine axes .The results show that ,woven fabrics of bias orientation (-45/+45)the test goes in the direction in - between the fibers (so called 'bias extension test"). Stitching serves as "hinges" between the two fiber systems in the plies .This ensures extremely strong link between the two tension directions .In all other cases fibers lie in the directions of the tension of orientations (0/90),(0/-45, 90/45).Non linearity of the initial stage of deformation is explained by waviness of the fibers in the plies . Fibers undergo straightening before receiving full load of the tension . At the end of the diagrams apparent stiffness reduces because of on - set of the slippage in the grips [30].

(1-2-2) Literature survey of modeling creep behavior

There are fewer reviews of the modeling of creep in polymeric composites. Among the earlier investigations are the articles by Halpin(1968),Schapery(1968),Chan(1988),Dillard(1991),and Brinson and Lin(1998).Most of this literature utilizes linear viscoelastic models to describe the creep behavior of the composite .

A thermodynamically consistent theory of non linear viscoelastic and viscoplastic materials was developed by Schapery (1997).This model considers the nonlinear viscoplastic response of materials as a particular case of non linear viscoelasticity corresponding to infinite retardation times .Experimental methodology for complete material characterization

in the framework of this model was presented by Megins and Varna(2003).

A another approach to the modeling of creep is formulated based on plasticity theory ,which was applied initially to metal matrix composites by Perzyna(1966)and later by Liu and Krempl (1979).This approach can be expanded to include the time dependent behavior for a laminated structure by including phenomenological macroscopic analysis for each particular laminate lay-up based on laminate theory type of analysis that describes the inelastic response of laminates based on inelastic stress-strain relationships of a layer.

For uniaxially reinforced polymeric composites ,Sun and Chen (1997) ,Yoon and Sun and Chang (1992) developed a simplified single parameter plasticity model for creep. This model was subsequently extended to laminated plates by Sun and Zhu(2000) and included thermal effects by Gates (1992,1993a,b).Rate dependence was included by means of a viscoplastic model by Gates and Sun (1995)and later by Thiruppukuzhi and sun (1998,2001) [31].

(1-3) Definition of the problem

The phenomenon of creep is the source of many problems in design, foremost amongst these is the need for the generation of ways of predicting whether components operating in the creep range will sustain the life required of them. The useful life could be terminated

A)-when the creep range deformation becomes excessive.

b)-when rupture occurs.

For most practical applications predictive methods must be capable of accounting for complex loadings which vary with time .

(1-4) Aim of study research

The variation in the material property which causes anisotropic behavior that behavior is undesirable in most of applications such as airframe structure ,automobile structure ,tires...etc therefore the knowledgement of this effect is very important to prevent and treatment these defects of structure during the design process.

The present study aims to:

1-Carry out the numerical model to predict the biaxial creep of pure low density polyethylene .

- 2-Manufacturing biaxial creep tester apparatus.
- 3-Conduct the experimental work of biaxial creep testing of this materials low density polyethylene .
- 4-Comparison between numerical and experimental analysis to verification from the accuracy and validity of this model and apparatus to study this phenomena.
- 5-Conduct the initial testing such as tensile for the composite constituents to valuate the initial properties of the composite materials constituents .
- 6- Conduct the experimental work of biaxial creep testing of this material (pure low density polyethylene)as matrix and plain weave from nylon and polyester fibers .

Chapter Two

Creep behavior of Fiber Reinforced Composites

(2-1) Fiber Reinforced Composites

General

The term composite refers to an assembly of different materials; which when used together Enables them to reflect properties not obtainable by either constituent materials. The term advanced composites(PMCs) refers to the group of materials usually used in the aerospace industry. Composite materials were developed because single. Homogeneous structural material could be found that had all of the desired attributes for a given application in the aerospace [1].

Composite materials that exist today can be categorized into five major classes according to matrix used ,which include ceramic matrix composites(CMCs),metal matrix composites(MMCs),intermetallic matrix composites(IMCs),carbon carbon composites(CCCs) and polymer matrix composites [1,3].

There are two important types of polymer matrix composites, short fiber and continuous fiber composites. Continuous fiber composites, made up of several prepreg layers(a prepreg is a single layer of continuous fiber in a matrix) are divided into three types:-[12].

- 1)-Unidirectional composite- fiber are parallel to each other.
- 2)-Multidirectional composite- fiber orientation varies from layer to layer.
- 3)-Textile composite- fibers are woven like textile cloth.

Textile composites represents a class of advanced materials which are reinforced with textile performs for structural or load bearing application. Presently, textile structural composites are part of a larger category of

composite materials textile composites [7].

Textile composites can be defined as the combination of resin system with a textile fiber or fabric system.

(2-2) Materials constituent

Fiber reinforced plastics(FRP) have two major constituents; the matrix which forms continuous media and the fibers which act as a reinforcement that are added to the matrix to improve the matrix properties. The fibers surface is usually chemically treated or coated with every thin layer to enhance the bonding with the matrix, protect the fibers from moisture or chemicals reacting with the matrix at high temperature [5].

The overall properties of the composite are a function of many variables, including the amount and type of reinforcement and matrix, the orientation of the reinforcing particles or fibers, the processing method used in fabricating the composite ,and so on. Some of these materials show isotropic mechanical behaviour ,others show anisotropic behavior. The fiber-reinforced composites, such as those used for rocket-motor cases and for some structural components of aircraft, show anisotropic behavior-dependent on the orientation of the load [1,5].

The thickness of the lamina is usually in the range of 0.1 to 1.0 mm. If continuous fibers are used in making a lamina. They may be arranged in unidirectional or in bidirectional orientation as shown in Figures (2-1 a and b).A lamina can be constructed using discontinuous (short)fibers in a matrix - the fibers can be arranged in a unidirectional orientation or in random orientation see Figures ((1- c) and (1-d)) . Discontinuous fiber reinforced composites have lower strength and modulus than continuous fiber composite . However. with random orientation of fibers. It is possible to obtain nearly equal mechanical and physical properties in all direction in the plane of lamina.

The thickness required to support a given load or maintain a given deflection in a fiber-reinforced composite structure is obtained by stacking and welding together a number of sheets (laminates). Each has the fibers oriented either in one direction or in different directions to form a laminate (see Figure(2-2) [1].

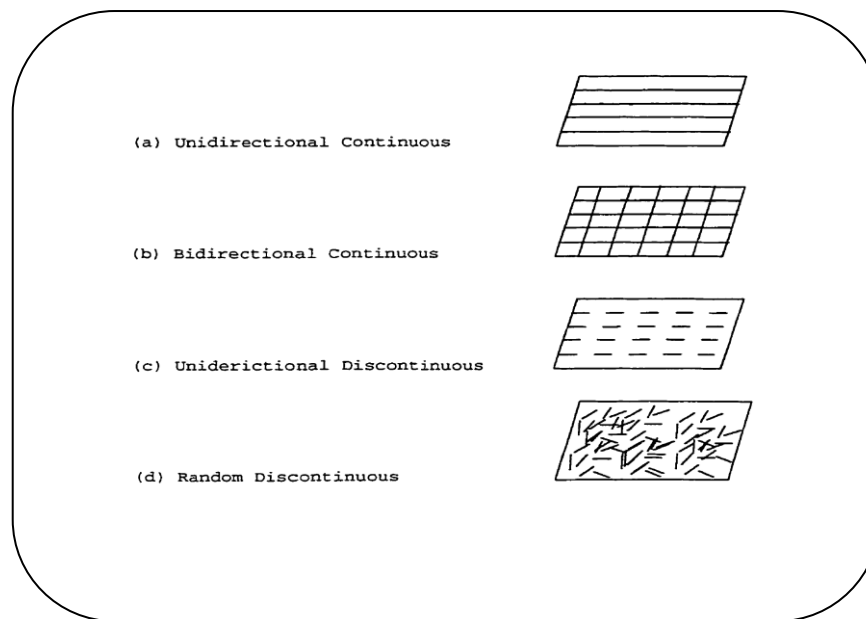


Figure (2-1): Fibrous composite lamina [1].

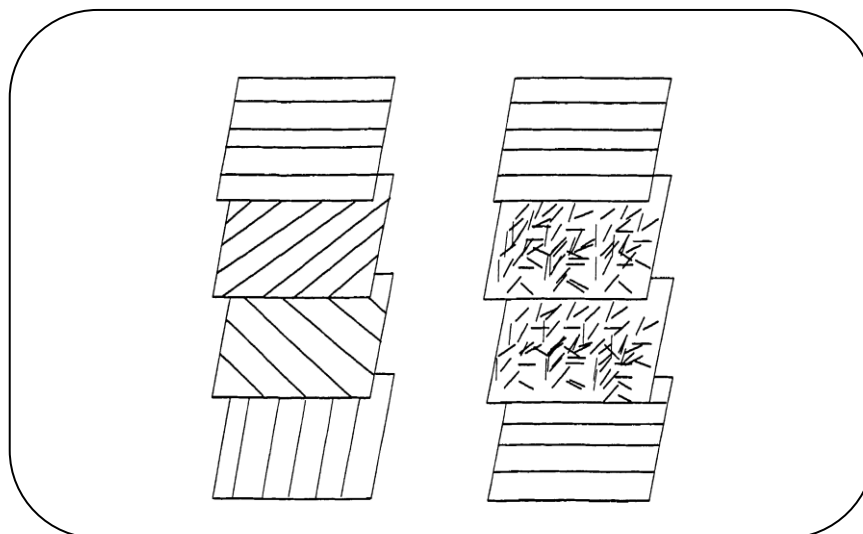


Figure (2-2): Typical Laminates [1].

(2-2-1)Fibers

Fibers are the main load-carrying component in fiber reinforced composite material. The effectiveness of fiber reinforcement depends on the types, length, volume fraction and orientation of the fibers in the matrix. The proper selection of these fiber parameters is very important as they influence the density , strength , modulus , fatigue performance, thermal properties and the cost of the fiber reinforced composite [1,32] .

One of the most commonly used fibers among the new composite materials is the carbon fiber. This fiber is manufactured from rayon or PAN fibers. It can also be made from pitch fibers which are produced directly from oil or coal. Carbon and graphite materials are quite new. The first commercial fiber were produced in the early 1970s. Among the advantages of carbon fibers are their exceptionally high tensile strength to weight ratio as well as tensile modulus to weight ratios, high fatigue strength and very low coefficient of linear thermal expansion, where they can maintain their strength up to 2000 °C. Thus providing the dimensional stability required in space application. Due to the high cost of these fibers, they are mostly used in the aerospace industry where weight saving is more critical than cost [1].

Class fibers commonly used are the E-glass and S-glass. In addition to these glass types, there are others that are not usually included in advanced composites because they are used in different fields.

Another new fiber gaining wide acceptance is Kevlar this man-made material manufactured by DuPont has many attributes of the carbon fiber because of its high strength and high modulus. It also has a unique property to a degree which neither carbon nor glass fibers have, that is adequate fracture toughness. There are two types of Kevlar: Kevlar 29 and Kevlar 49. It is of equal strength but has a higher modulus than Kevlar 29 unlike carbon fibers. Kevlar does not conduct electricity. It also has a low compressive strength and modulus compared to high tensile properties. Kevlar acts more as a glass fiber to transmit electric radiation such as radomes and antenna windows. The diameter of Kevlar fibers and the way they are handled are similar to both carbon and glass fibers. But the form in which the material is available differs [1].

(2-2-2) matrix

We use the term matrix here to include the material between the fiber surface. The composite matrix is required to fulfill several functions. The matrix binds the fibers and holds them in the desired dimension and acts as a stress transferring media to the fibers and protects the fibers from the mechanical damage, chemical and moisture attack. The matrix has a minor role in the longitudinal strength and modulus of unidirectional continuous fiber composite [1, 32, 33].

There are mainly five types of matrices in composite: polymeric, metallic, ceramic, intermetallic and carbon. Polymeric matrices are two types, thermosetting resins and thermoplastic resins. Thermoset polymers

epoxies, vinyl esters and polyesters. Phenolics and polyamides are also thermoset polymers which are used for high temperature applications. Thermoset polymers are characterized by having low viscosity (i.e. liquid-like polymers) which are suitable for long continuous fibers. Thermoplastics such as polypropylenes and nylons have high viscosity even at high temperature. Therefore, thermoplastic polymers are used more commonly with short fibers because of the difficulty of processing high viscosity resin with continuous fibers. Thermosets are more thermally stable and chemically resistant than thermoplastics. Therefore, thermosets are more suitable for (FRP) chimneys applications [32].

(2-2-3) Fiber matrix composite

Fiber alignment in matrix can be unidirectional, of two directions, three directions or random (discontinuous fibers). Continuous fibers are used in filament - winding, pultruded or laminated structures in which the fibers can be oriented precisely. Two directional fiber alignment is used with laminated composite and three dimensional is usually used when delamination is anticipated to be a problem. The unidirectional arrangement provides the most effective use of the fibers when the load is acting in the fiber direction. For such arrangement, the strength and the modulus in the transverse direction of the lamina are very low compared to those in the longitudinal direction (such composite is highly anisotropic). Randomly oriented fibers give equal properties in all directions on plane of the lamina (almost isotropic). In a two dimensional alignment, fibers are woven in both 0° and 90° directions which bring the lamina properties in the two directions to be identical if the fiber content is the same in the two directions [32].

(2-3) Processing and manufacturing of composites

Various processes have been developed for manufacturing composite materials and composite structures. Composite materials are fabricated using Hand lay-up, filament winding, prepreg, resin transfer molding, sheet molding compounds, Bag molding process and autoclave molding. The early manufacturing method for fiber-reinforced composites used hand lay-up are a liable processes. It is by nature very slow and labor intensive. In recent years, particularly due to the interest generated in all types of industry, there is more emphasis on the development of manufacturing methods that can support high production rates [1].

(2-3-1) Prepreg process

In this process, fibers may be in the form of continuous rovings, mat, or woven fabric. Epoxy is the primary matrix material in prepreg sheets. The width of the prepreg sheet may vary from less than 25mm to over 457mm. The thickness of the ply cured from prepreg sheets is normally in the range of (0.13 to 0.25) mm. Most prepreg sheets are made by hot-melt process see Figure(2-3) [1,34].

The fabrication of a laminated structure with prepreg sheets evolves simply by "laying - up" the sheets at the required orientation on a mold, stacking layers of tape in the required stacking sequence, and then curing the assembly under elevated temperature and pressure. Towards the end, the prepreg sheets are backed up with a release film or waxed paper. The back up material is separated from the prepreg sheet just before it is placed in the mold. The normal storage life before molding is 6 to 8 days at 23 °C [1].

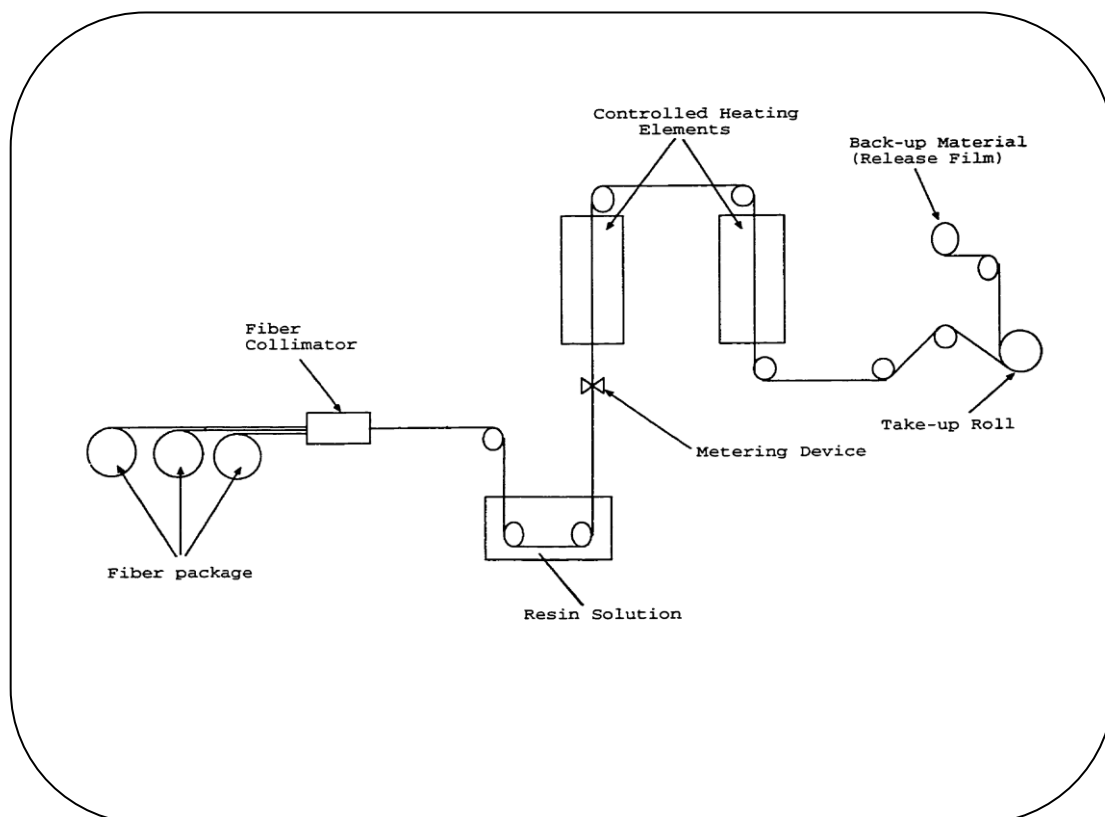
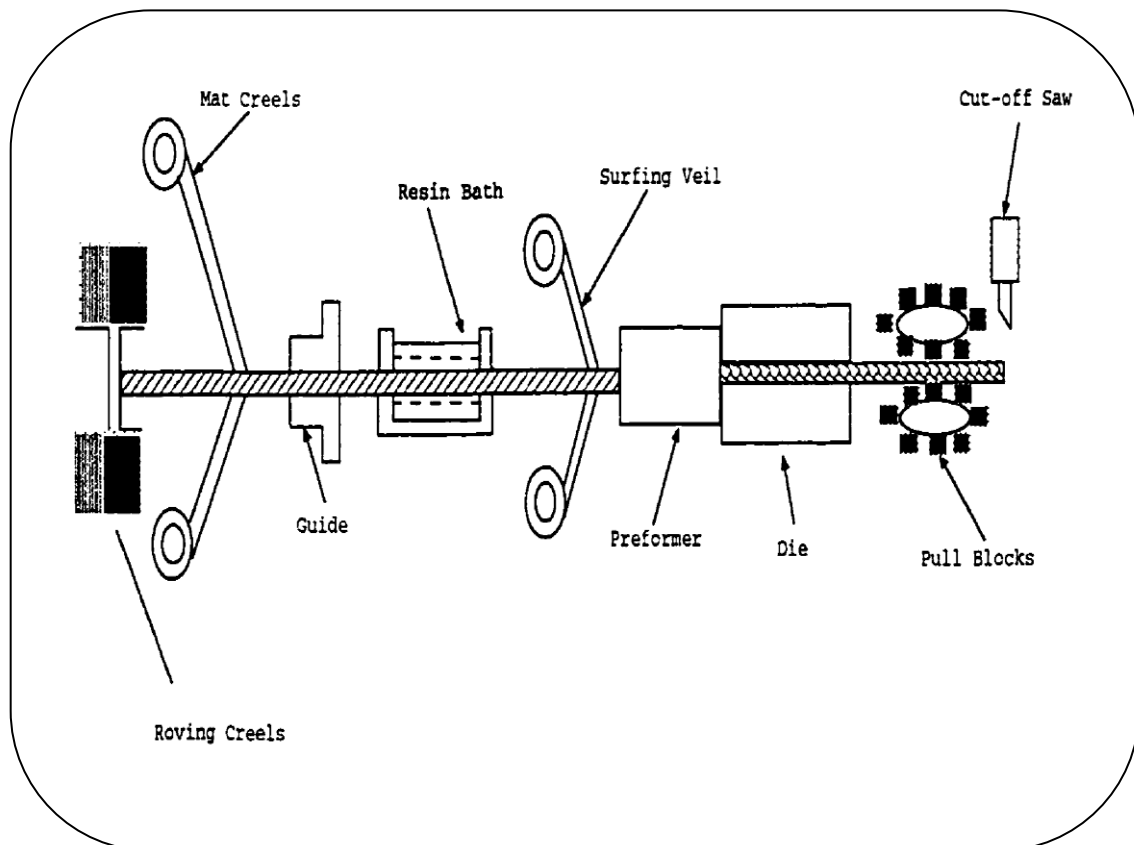


Figure (2-3): Schematic of Prepreg manufacturing [1].

(2-3-2) Pultrusion process

In this process fiber reinforcement in the form of rovings, stitched fabric, mat, etc are pulled from a creel through strand-tensioning device into a resin impregnation resin chamber where they are wetted by resin supplied under pressure. The wet reinforcement passes through the performer into a die where curing takes place at prescribed temperature. Once the curing is done, the composite part is pulled continuously and cut by an appropriate saw to the required length as shown in Figure(2-4) [1,35].



Figure(2-4):Schematic of pultrusion process [1].

(2-3-3) Compression molding

Compression molding is often referred to as matched metal die molding see Figure (2-5). To start the compression molding operation, first the material containing the fiber and resin are placed in a metal cavity. Then, The composite is compressed under pressure and heated by a top metal punch (or cavity) to compact, flow, and cure the material to a rigid shape having the form of the metal cavity. Finally, The mold is opened and the part is removed, often with the aid of ejector pins [1].

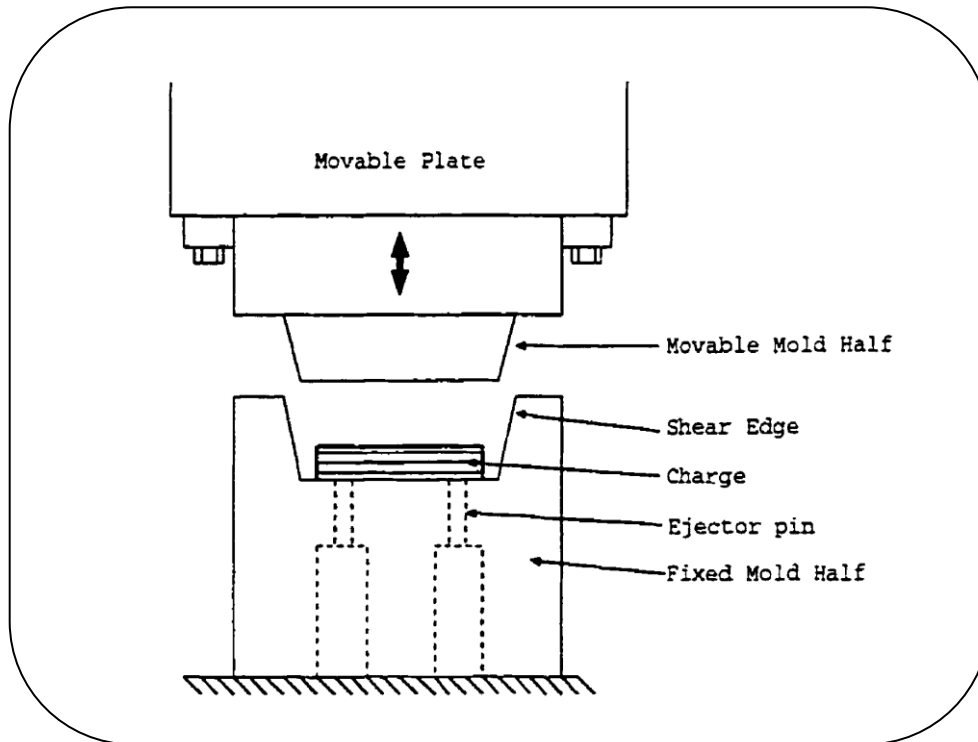


Figure (2-5): Schematic of a Compression molding Process [1].

(2-4) Woven fabrics of composite materials

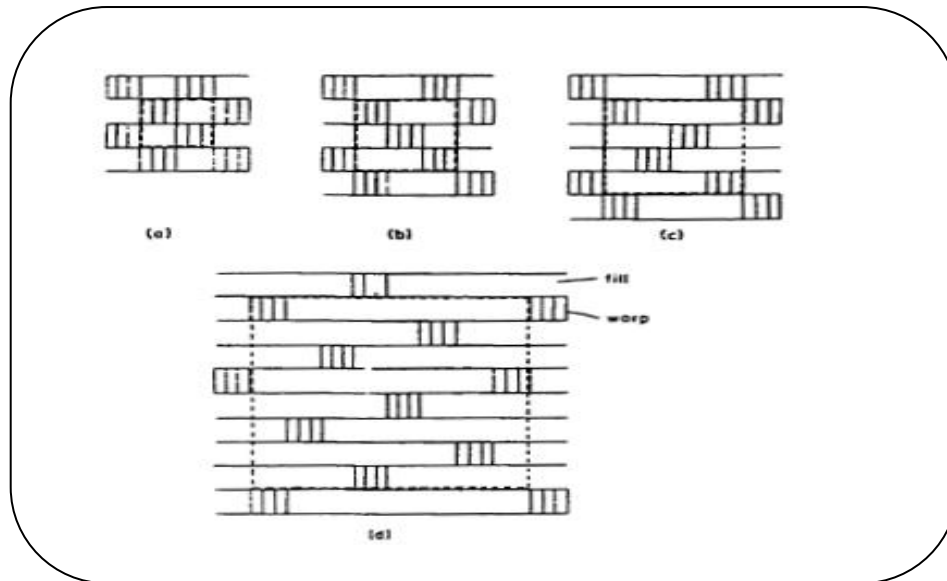
Woven fabrics are now considered to be a more important reinforcing material in the composite technology than a decade ago. Although the structure efficiency of fabric composites is not as high as that of the unidirectional laminates, their handling properties and low fabrication costs have made fabric composites attractive for structural application[36,37].

Woven fabrics can be described as two or more sets of yarns interlaced at same angle to each other to form a fabric. When two yarns are interlaced at 90 to each other, the fabric is called an orthogonal 2-D fabric. The yarn running the length of the weave is termed the fill or weft yarn. The different weave styles can be identified by the repeating pattern of the interlaced regions as shown in Figure (2-6). There are several ways in which the yarns can be interlaced, resulting in a number of different weave styles. These can be characterized by the geometric quantities n_g and n_g denotes a warp yarn interlaced with every n_g fill yarn and n_g denotes a fill yarn interlaced with every n_g warp yarn. [35-36]

One condition for which a weave fabric is considered unbalanced is $n_g \neq n_g$. further, if the yarns are of dissimilar size or exhibit different length

undulation , then the weave is said to be unbalanced . When the two sets of yarns composite dissimilar materials , the fabric is termed a hybrid weave [37].

The most common patterns of woven fabrics are plain weave ($n_g=2$) twill weave($n_g=3$)crowfoot stain or 4-harness stain($n_g=4$).5 harness stain ($n=5$) and 8-harness stain ($n_g=8$).Figures shows some examples of woven fabrics patterns(10)[7].



Figure(2-6): Examples of woven fabric patterns :(a)-Plain weave ($n_g=2$)b-Twill weave($n_g=3$):c-4-Harness stain($n_g=4$):(d)-8-Harness stain($n_g=8$) [36].

(2-5) Fabric Types and Constructions

In polymeric composite terms, a fabric is defined as a manufactured assembly of long fibers of carbon, aramid or glass, or a combination of these, to produce a flat sheet of one or more layers of fibers. These layers are held together either by mechanical interlocking of the fibers themselves or with a secondary material to bind these fibers together and hold them in place, giving the assembly sufficient integrity to be handled. Fabric types are categorized by the orientation of the fibers used, and by the various construction methods used to hold the fibers together. The four main fiber orientation categories are: Unidirectional, $0/90^\circ$, Multi axial, and Other/random [38].

(2-5-1) Unidirectional fabrics

A unidirectional (UD) fabric is one in which the majority of fibers run in one direction only. A small amount of fiber or other material may run in other directions with the main intention being to hold the primary fibers in position, although the other fibers may also offer some structural properties. While some weavers of 0/90° fabrics term a fabric with only 75% of its weight in one direction as a unidirectional, at SP Systems the unidirectional designation only applies to those fabrics with more than 90% of the fiber weight in one direction. Unidirectional usually have their primary fibers in the 0° direction (along the roll – a warp UD) but can also have them at 90° to the roll length (a weft UD). True unidirectional fabrics offer the ability to place fiber in the component exactly where it is required, and in the optimum quantity (no more or less than required). As well as this, UD fibers are straight and uncrimped. This results in the highest possible fiber properties from a fabric in composite component construction. For mechanical properties, unidirectional fabrics can only be improved on by prepreg unidirectional tape, where there is no secondary material at all holding the unidirectional fibers in place. In these prepreg products only the resin system holds the fibers in place [38].

There are various methods of maintaining the primary fibers in position in a unidirectional including weaving, stitching, and bonding. As with other fabrics, the surface quality of a unidirectional fabric is determined by two main factors: the combination of often and thread count of the primary fiber and the amount and type of the secondary fiber. The drape, surface smoothness and stability of a fabric are controlled primarily by the construction style, while the area weight, porosity and (to a lesser degree) wet out are determined by selecting the appropriate combination of fiber tex and numbers of fibers per cm. GTC-1-1098 - 33 Warp or weft unidirectionals can be made by the stitching process (See information in the 'Multi axial' section of this publication). However, in order to gain adequate stability, it is usually necessary to add a mat or tissue to the face of the fabric. Therefore, together with the stitching thread required to assemble the fibers, there is a relatively large amount of secondary, parasitic material in this type of UD fabric, which tends to reduce the laminate properties. Furthermore the high cost of set up of the 0° layer of a stitching line and the relatively slow speed of production means that these fabrics can be relatively expensive [38].

(2-5-2)0/90° fabrics

For applications where more than one fiber orientation is required, a fabric combining 0° and 90° fiber orientations is useful. The majority of these are woven products. 0/90° fabrics can be produced by stitching rather than a weaving process and a description of this stitching technology is given below under 'Multiaxial Fabrics' [38].

0/90° fabrics can also be made by a stitching process, which effectively combines two layers of unidirectional material into one fabric. Stitched 0/90° fabrics can offer mechanical performance increases of up to 20% in some properties over woven fabrics, due to the following factors:[38]

1. Parallel non-crimp fibers bear the strain immediately upon being loaded.
2. Stress points found at the intersection of warp and weft fibres in woven fabrics are eliminated.
3. A higher density of fiber can be packed into a laminate compared with a woven.

In this respect the fabric behaves more like layers of unidirectional.

Other benefits compared with woven fabrics include:[38]

1. Heavy fabrics can be easily produced with more than 1kg/sqm of fiber.
2. Increase packing of the fiber can reduce the quantity of resin required.

(2-5-3)Multiaxial fabrics

In recent years multi axial fabrics have begun to be favoured in the construction of composite components. These fabrics consist of one or more layers of long fibers held in place by a secondary non-structural stitching thread. The main fibers can be any of the structural fibers available in any combination. The stitching thread is usually polyester due to its combination of appropriate fiber properties (for binding the fabric together) and cost. The stitching process allows a variety of fiber orientations ,beyond the simple 0/90° of woven fabrics, to be combined into one fabric [38].

(2-6)Overview of textile structural

The mechanics of textile composites can be best studied by taking into account their hierarchical organization .There are usually four important levels in the manufacturing process of textile composites :

Fiber>yarn>fabric>composite

The choice of the fibers represents the first step in the fabrication of textile structural composites products must be made from high modulus fibers e.g. glass, graphite, aramid, ceramic or steel fibers [39].

The second step of the manufacturing process consists of grouping together the fibers (or filaments) in a linear assemblage to form a continuous strand having textile- like characteristic. The group of filaments is then impregnated with resin (for non-hybrid fabrics , the resin is the same for all the strands and usually the same for the perform and the resulting tubular form is called yarn . Figure(2-7) shows different examples of idealized models of various yarn structure.

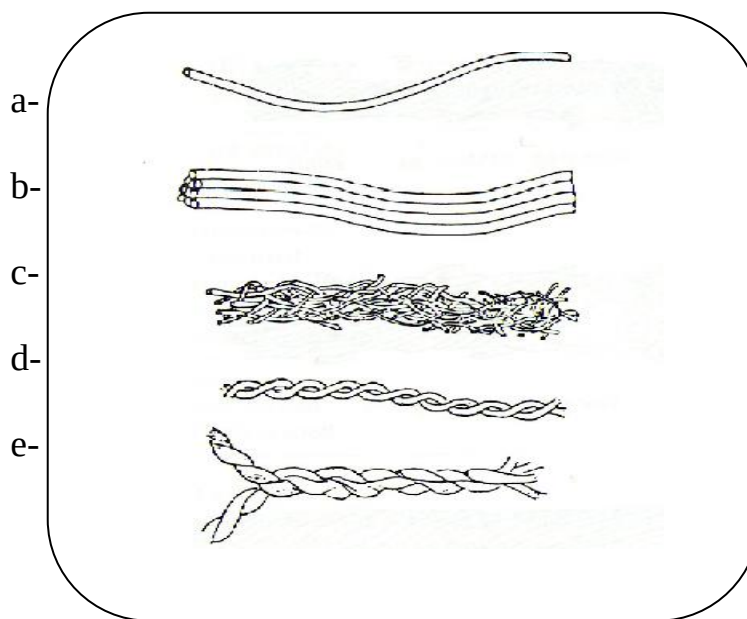


Figure. (2-7) Idealized models of various yarn structures [39].

All by the Figure , yarns may be composed of one a)- or more b)- continuous filaments , or even discontinuous chopped fibers c)-and finally , two or more single yarns can be twisted together to form ply or plied yarns (d and e). Thus, the manufacturing process of yarns it self can involve rather complicated shapes [39].

Yarn structural features are characterized by several geometrical parameters , as the number of filaments the diameter of the filaments (assuming the fibers have a cylindrical shape),(d_f) and the yarn packing density , (pd) defined as the ratio of the fibers volume to the yarn overall volume.Yarn structure plays a dominant role in the translation of fiber properties into yarn properties [39].

Fiber obliquity (orientation relative to the yarn axis) and the fiber entanglement in the various structural forms. For multifilament untwisted

yarn structures , the strength translation efficiency ratio is closed to 100% therefore the behavior of these yarns is very close to that of the fibers themselves . The loss of strength in the fiber direction is mostly due to degradation during yarn processing and lack of toughness .Also, the fibers are usually assumed to be transversely isotropic and resin isotropic, such that untwisted yarns can be considered as transversely isotropic.

The third step in the textile structural composites manufacturing process consists of bonding interlocking the yarns together to produce a flat sheet with a specific pattern .Fabric types are categorized by the orientation of the yarn used , and by the various construction methods used to hold the yarns together.The periodicity of the repeating pattern in a textile fabric can usually be used to isolate a small repeating unit cell (RUC) which is sufficient to describe the fabric architecture [39].

The four basic fabric structure categories are woven ,knits, braids, and non woven as described in Figure(2-8).

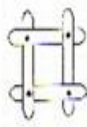
	Woven	Knitted	Braided	Nonwoven
Geometry				
Cell model				
Composition	yarn	yarn	yarn	fibers
Formation	interlace	interloop	intertwine	bond

Figure. (2-8) Comparison of basic fabric structures [39].

The interlacing of the yarns in a fabric leads to yarn undulation "crimp".[7]

(2-6-1) wovens

Woven fabrics are produced on a loom by the interlacing of warp (0) and fill (90) yarns in a regular pattern or weave style .The fabrics integrity is maintained by the mechanical interlacing of the yarns . Drape, surface smoothness and stability of the fabric are controlled primarily by the weave style Figure (2-9) shows miscellaneous

woven fabric structures , currently the most common construction are plain ,twill, basket and stain weaves. " [7].

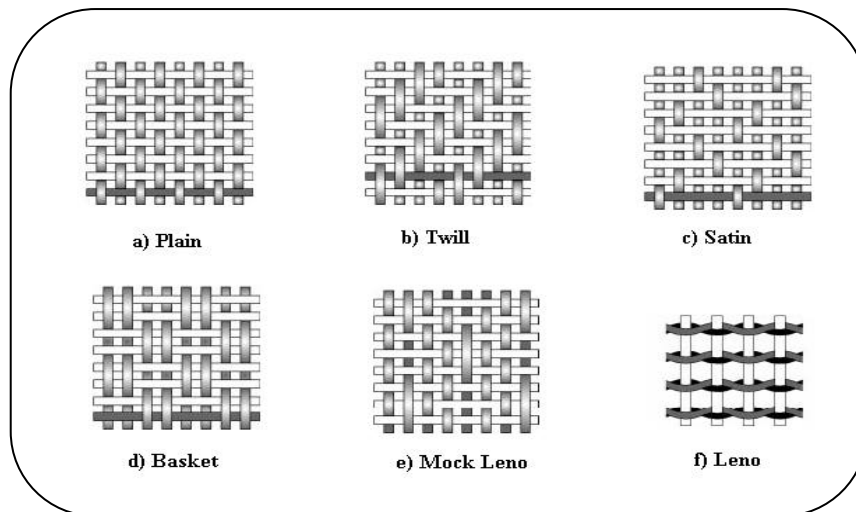


Figure. (2-9) Comparison of most common woven fabric structures [40].

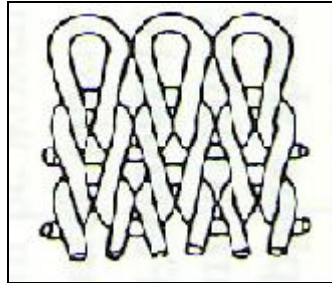
Table(2-1) described weave styles-comparison of properties [38].

Weave Styles - Comparison of Properties						
Property	Plain	Twill	Satin	Basket	Leno	Mock leno
Good stability	****	***	**	**	*****	***
Good drape	**	****	*****	***	*	**
Low porosity	***	****	*****	**	*	***
Smoothness	**	***	*****	**	*	**
Balance	****	****	**	****	**	****
Symmetrical	*****	***	*	***	*	****
Low crimp	**	***	*****	**	**/*****	**
***** = excellent, **** = good, *** = acceptable, ** = poor, * = very poor						

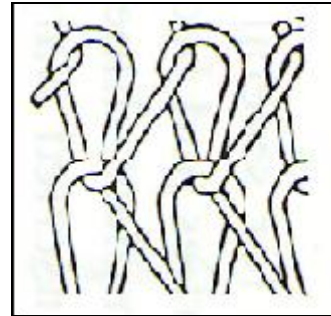
(2-6-2)knit knits fabrics are usually made by interlacing one or more yarns and offer a much wider range of forms and behaviors that wovens . Simple fill (or weft) and warp knit construction. Figure (2-10a) provides considerable extensivity in all directions and therefore are quite suitable for deep- draw molded composites . They can also be added to a woven or braided perform for specific directional extensibility and good stability . In

this case , the knitting threads are passed a round the primary yarns and one another in interpenetrating loops as shown in Figure (2-10b) [7].

a)-



Weft knit



warp knit

b)-

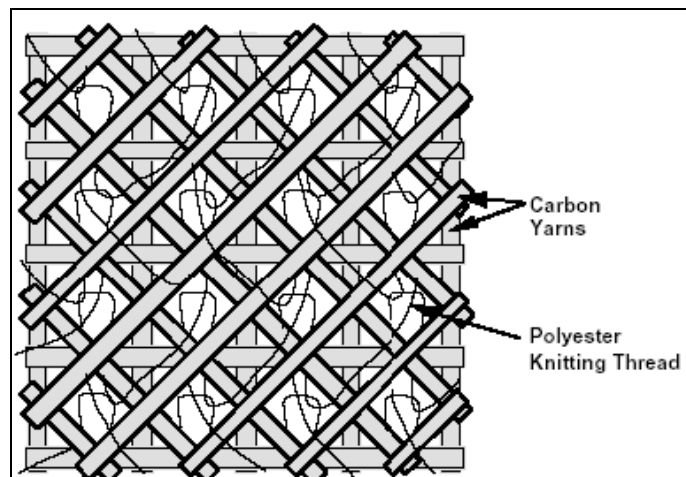


Figure. (2-10) (a)- Simple warp and weft knits ; (b)- Multi-axial warp knit Insertion [41].

Knit fabrics offer higher yarn to fabric tensile strength translation efficiencies , greater in-plane shear resistance and better handling than comparable wovens . The process of knitting can also be used to provide through-thickness reinforcement in composite structures . The process, called "stitching", significantly enhances damage tolerance and often represents a helpful step in the fabrication of textile structural composites. Figure (2-11) shows the two forms of stitching that are of interest for structural applications: the modified lock stitch and chain stitch [7].

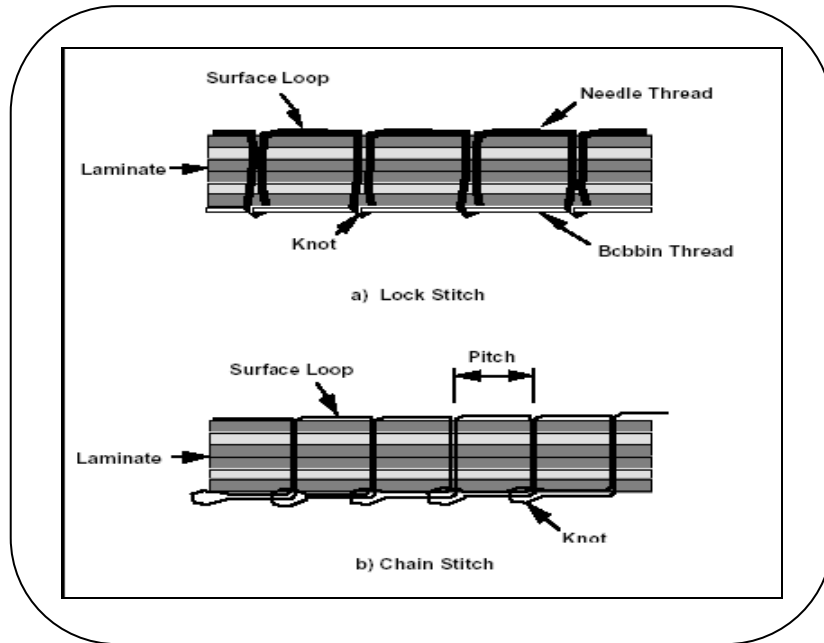


Figure. (2-11) Types of stitching used for through-thickness reinforcement [41].

(2-6-3)Braid

Braided performs are fabricated over a cylindrical mandrel Figure (2-12) . Yarns are intertwined together in a spiral nature to form a tubular fabric. The braid angle is usually noted (θ_b) and is controlled by the rotational speed of the yarn carriers relative to the transverse speed of the mandrel . The braider yarns follow the ($\pm \theta_b$) directions and usually interlace in either a (1*1) or (2*2) pattern. Triaxial braided fabrics can be designed by inserting axial yarns between the braider yarn in the longitudinal or vertical direction .Braids can be found in such composite components as mats , antennae, drive shafts and other tubular structures that require torsional strength [7].

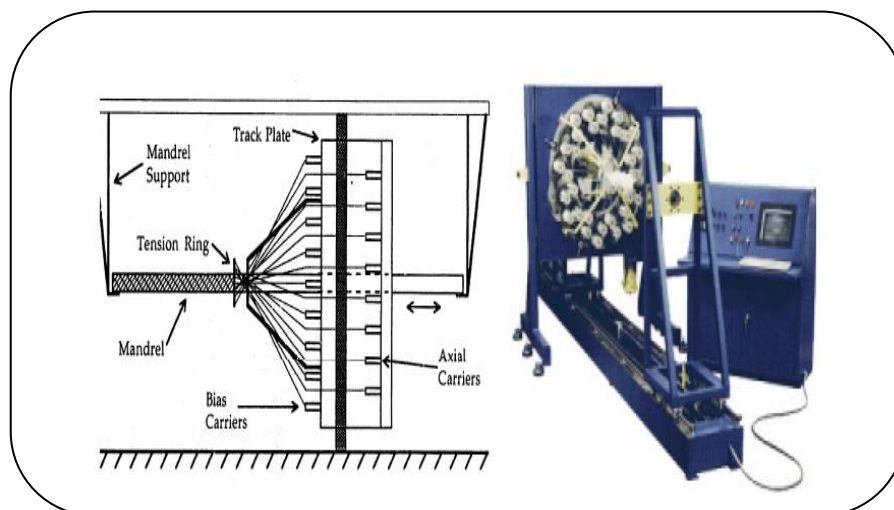
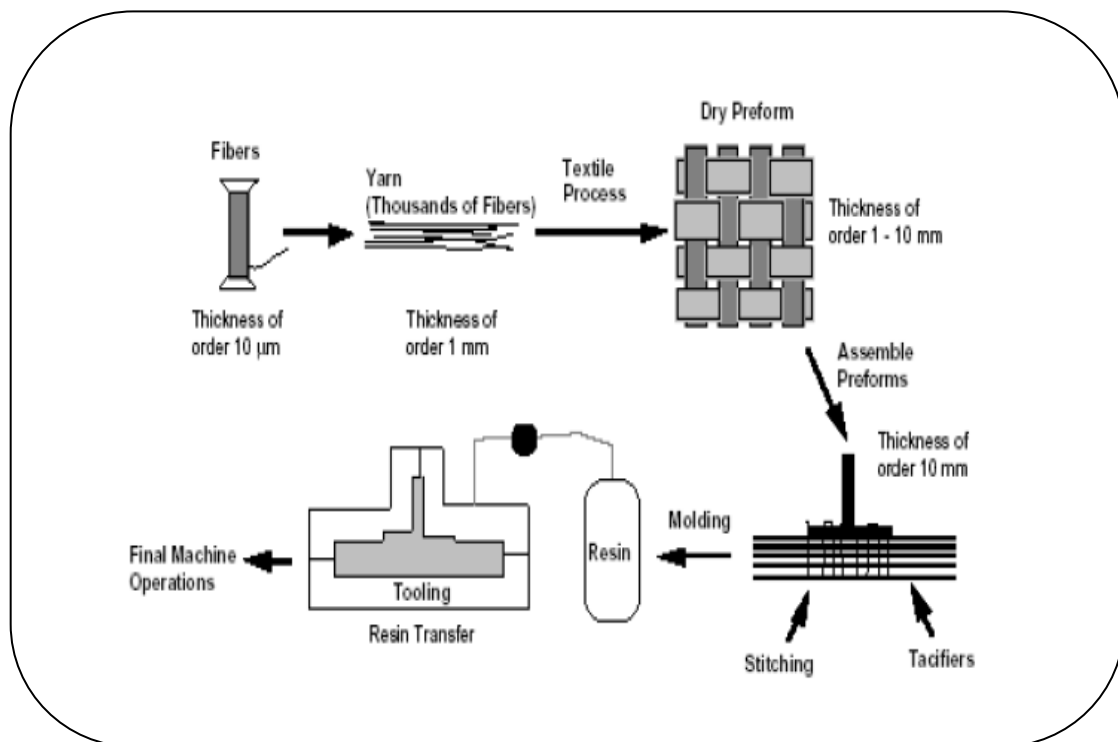


Figure (2-12) Schematic view and photo of a cylindrical mandrel [41].

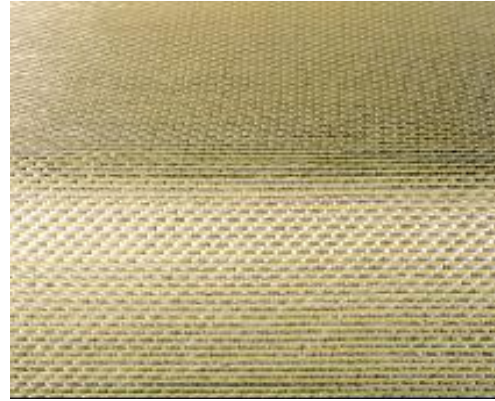
(2-6-4) Non woven

Non woven fabrics consists of randomly bonded yarns such as a fiber mats, stitch bonded ,xyz, and adhesively bonded fabrics . They are characterized by slight conformability , very short yarns and rigid entanglements . As the yarns are bonded together, these fabrics offer no substantial directional extensibility and often low in_ plane shear resistance.

The fourth step of the textile composites manufacturing process consists of assembling several layers of fabrics in a laminate - like manner. The un rigidized textile dry preform is then molded to a final shape and infused with a matrix (e.g. resin transfer molding) (RTM) or resin film infusion (RFI) .Figure(2-13) illustrates scales in one textile process .The part shown is an integrally formed skin/ stiffener assembly. The first processing step is the formation of yarns from fibers . In the second step, the yarn are woven into a plain weave fabric . The cloths are then laid up in the shape of the skin and stiffener and stitched together to create an integral perform ,Finally , the composite part is consolidated by the infiltration of resin and cured in a mold [7].



Figure(2-13)Steps in the production of a textile composite structure [41].

(2-7) Hybrid fabrics

Figure(2-14) Describe the hybrid woven fabrics[38].

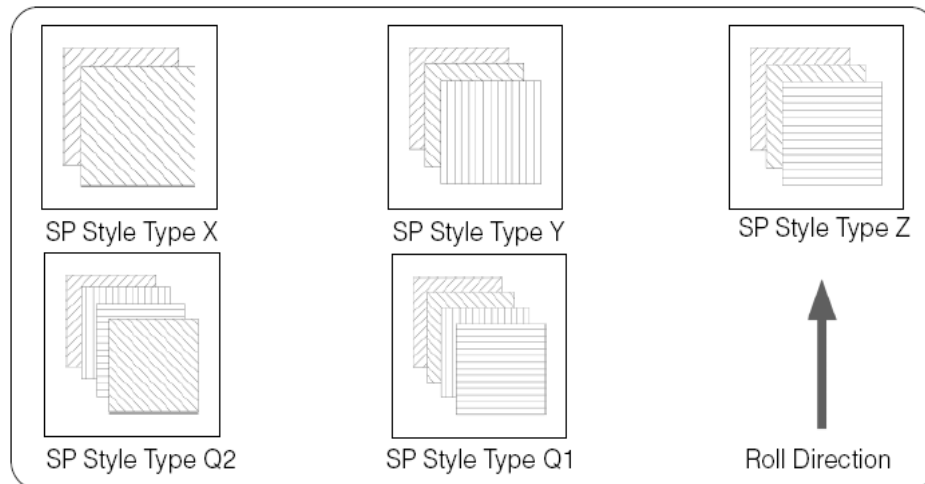
The term hybrid refers to a fabric that has more than one type of structural fibre in its construction. In a multi-layer laminate if the properties of more than one type of fibre are required, then it would be possible to provide this with two fabrics, each containing the fibre type needed. However, if low weight or extremely thin laminates are required, a hybrid fabric will allow the two fibres to be presented in just one layer of fabric instead of two. It would be possible in a woven hybrid to have one fibre running in the weft direction and the second fibre running in the warp direction, but it is more common to find alternating threads of each fibre in each warp/weft direction. Although hybrids are most commonly found in 0/90° woven fabrics, the principle is also used in 0/90° stitched, unidirectional and multi axial fabrics [38].

Table(2-2) The most usual hybrid combinations:[37] .

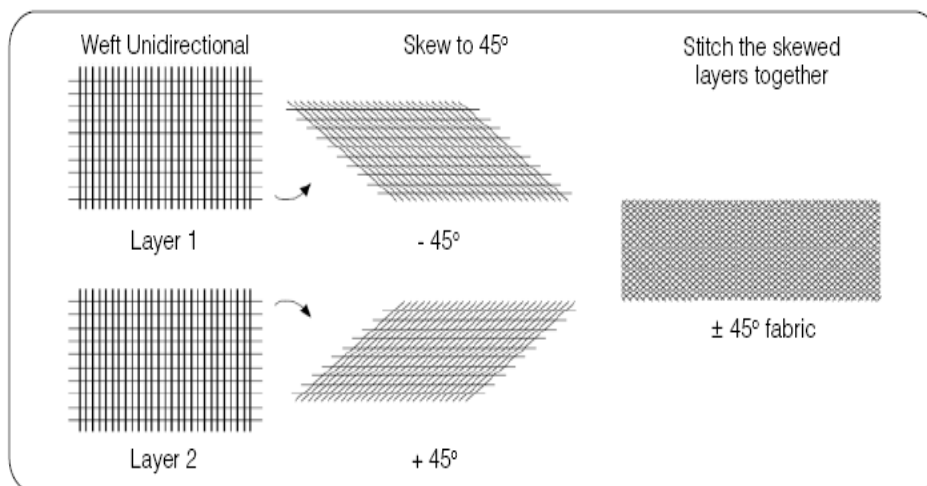
1-Carbon / Aramid	The high impact resistance and tensile strength of the aramid fibre combines with high the compressive and tensile strength of carbon. Both fibres have low density but relatively high cost.[38]
2-Aramid / Glass	The low density, high impact resistance and tensile strength of aramid fibre combines with the good compressive and tensile strength of glass, coupled with its lower cost.[38]
3-Carbon / Glass	Carbon fibre contributes high tensile compressive strength and stiffness and reduces the density, while glass reduces the cost.[38]

(2-8) Fabric construction

The most common forms of this type of fabric are shown in the following Diagrams(2-15):[38]



There are two basic ways of manufacturing multiaxial fabrics: 'Weave & Stitch' method the $+45^\circ$ and -45° layers can be made by weaving weft unidirectionals and then skewing the fabric, on a special machine, to 45° . A warp unidirectional or a weft unidirectional can also be used un skewed to make a 0° and 90° layer. If both 0° and 90° layers are present in a multi-layer stitched fabric then this can be provided by a conventional $0/90^\circ$ woven fabric. Due to the fact that heavy rovings can be used to make each layer the weaving process is relatively fast, as is the subsequent stitching together of the layers via a simple stitching frame.



Figure(2-16)Describe the 'Weave & Stitch'

To make a quad axial (four-layer: $+45^\circ$, 0° , 90° , -45°) fabric by this method, a weft unidirectional would be woven and skewed in one direction to make the $+45^\circ$ layer, and in the other to make the -45° layer. The 0° and

90° layers would appear as a single woven fabric. These three elements would then be stitched together on a stitching frame to produce the final four-axis fabric [38].

(2-9) Fabric models

Recently, there are normally five different models which are then employed to approximate the elastic and strength behavior of composites: one model for laminated composite and four models for woven fabric composite.

In the first model for woven fabrics, known as the mosaic model, a fabric composite is idealized as an assemblage of a symmetrical cross-ply laminates. Based upon the assumptions of the (iso- stress) and (iso- strain), bounds of elastic moduli are derived and they provide an approximate method for predicting the elastic moduli:

In the second model for woven fabric, the mosaic model is modified to take into consideration the effect of fiber undulation and continuity on composite stiffness. A one-dimensional strip of the fabric composite forms the basis of the analysis and the classical laminated plate theory is applied to each infinitesimal piece of the composite plate. This model has been extended to investigate the bi-linear of knee behavior of the stress-strain relations of plain weaves composites [36].

The concept of the third model for woven fabrics is developed based on the findings of load transfer in stain weave composites. The region with straight threads surrounding an undulated interlaced region has higher local in-plane stiffness than the latter and acts as a load-transferring bridge. This model has also been extended to the analysis of the knee behavior in stain weave composites where the same assumptions about internal failure are employed. This model has been also modified for treating hybrid woven composites and as action of the third model is preserved, although the geometry of this fourth model is much involved due to the complexity in the hybrid fabric structure. This model provides a significant improvement of the predictions of the bound results [36].

And last model for woven fabrics is called the sub-ply model which has been proposed for the characterization of thermo-elastic properties for any deformed woven fabric composite [36].

(2-9-1) Laminated mechanical model

In the case of laminated composites, Stiffness components are calculated by laminated mechanical model.

The generalized Hooks' s law relating stresses to strains can be written in contracted notation as :

$$\sigma_i = C_{ij} \varepsilon_j \quad \dots\dots\dots (2-1) [36]$$

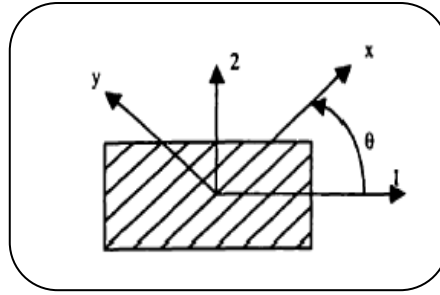
where σ_i are the stress components, C_{ij} is the stiffness matrix and ε_j are the strain components. The stiffness matrix C_{ij} has 36 constants. However due to symmetry ($C_{ij} = C_{ji}$). Only 21 of the constants are independent. A lamina is under a plane stress state when $\sigma_3 = \sigma_4 = \sigma_5 = 0$. And therefore only $\sigma_1, \sigma_2, \sigma_6$ are presented. On axis stress-strain relation can be expressed by following:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_s \end{Bmatrix} = \begin{bmatrix} Q_{xx} & Q_{xy} & 0 \\ Q_{yx} & Q_{yy} & 0 \\ 0 & 0 & Q_{ss} \end{bmatrix} \cdot \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_s \end{Bmatrix} \quad \dots\dots\dots (2-2) [36]$$

The principal directions of orthotropy in an orthotropic material do not always coincide with the directions of the applied load. In fact. This would be the exception rather than the rule and quite often we need to use some transformation relations in order to express the stresses in the required directions, i.e. The directions of orthotropy. This can be done using the following relations:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \sigma_r \end{Bmatrix} = \begin{bmatrix} \cos^2 \theta & \sin^2 \theta & 2 \sin \theta \cos \theta \\ \sin^2 \theta & \cos^2 \theta & -2 \sin \theta \cos \theta \\ -\sin \theta \cos \theta & \sin \theta \cos \theta & \cos^2 \theta - \sin^2 \theta \end{bmatrix} \cdot \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} \quad \dots (2-3) [36]$$

where θ is the angle between the fibers and the loading direction. An example of lamina orientation is given in Figure (2-17) or we can write off-axis stress-strain relation for unidirectional composite in terms of stiffness as following way:



Fig(2-17)Principal material coordinates of a lamina [36].

$$\begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_6 \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & Q_{16} \\ Q_{21} & Q_{22} & Q_{26} \\ Q_{61} & Q_{62} & Q_{66} \end{bmatrix} \cdot \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_6 \end{Bmatrix} \dots\dots\dots(2-4) [36]$$

where :

$$\begin{aligned} Q_{11} &= Q_{xx} \cos^4 \theta + 2(Q_{xy} + 2 Q_{xx}) \sin^2 \theta \cos^2 \theta + Q_{yy} \sin^4 \theta \\ Q_{12} &= (Q_{xx} + Q_{yy} - 4 Q_{xx}) \sin^2 \theta \cos^2 \theta + Q_{xy} (\sin^4 \theta + \cos^4 \theta) = Q_{21} \\ Q_{22} &= Q_{xx} \sin^4 \theta + 2(Q_{xy} + 2 Q_{xx}) \sin^2 \theta \cos^2 \theta + Q_{yy} \cos^4 \theta \\ Q_{16} &= (Q_{xx} - Q_{xy} - 2 Q_{xx}) \sin \theta \cos^3 \theta + (Q_{xy} - Q_{yy} + 2 Q_{xx}) \sin^3 \theta \cos \theta = Q_{61} \\ Q_{26} &= (Q_{xx} - Q_{xy} - 2 Q_{xx}) \sin^3 \theta \cos \theta + (Q_{xy} - Q_{yy} + 2 Q_{xx}) \sin \theta \cos^3 \theta = Q_{62} \\ Q_{66} &= (Q_{xx} + Q_{yy} - 2 Q_{xy} - 2 Q_{xx}) \sin^2 \theta \cos^2 \theta + Q_{xx} (\sin^4 \theta + \cos^4 \theta) \end{aligned}$$

[Applying the classical lamination theory. coefficients A_{ij} . B_{ij} . D_{ij} can be determined from the coefficients Q_{ij} :

$$\begin{aligned} A_{ij} &= \sum_{K=1}^N (\overline{Q}_{ij})_K (Z_K - Z_{K-1}) \\ B_{ij} &= \frac{1}{2} \sum_{K=1}^N (\overline{Q}_{ij})_K (Z_K^2 - Z_{K-1}^2) \\ D_{ij} &= \frac{1}{3} \sum_{K=1}^N (\overline{Q}_{ij})_K (Z_K^3 - Z_{K-1}^3) \end{aligned} \dots\dots\dots(2-5) [67]$$

where :

N : total numbers of ply (or Layer)

k : the k -th layer.

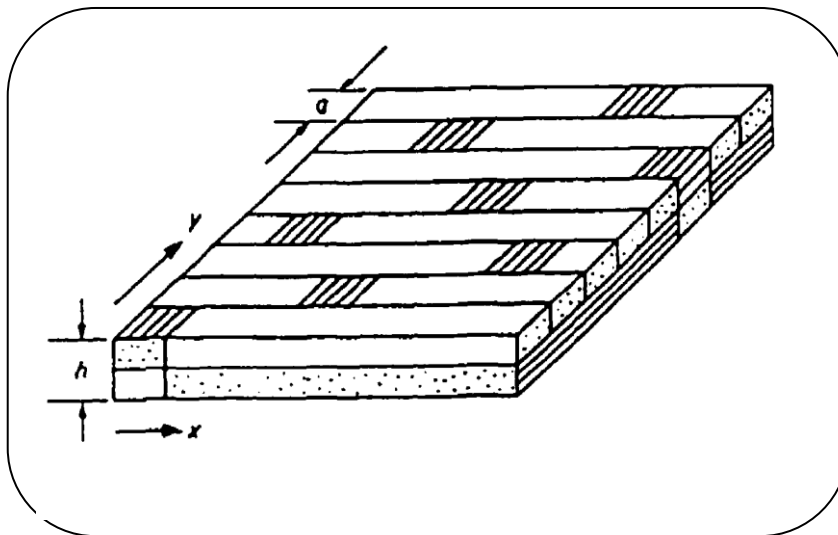
z : position of ply in z -direction.

The A_{ij} are called extensional stiffness. The B_{ij} , are called coupling stiffness and the D_{ij} , are the bending stiffness. If the coupling stiffness are non-zero. Then we should expect an in plane loading to produce a coupled effect of bending as well as extension. This coupled effect could be prevented by constructing laminates which are symmetrical with respect to the middle surface (plane). In which case B_{ij} reach zero values.

Classical laminate theory is based on the assumption that inter-laminar stresses are negligible and. Therefore, lamina stresses do not change if the stacking sequence is changed as long as the entire laminate remains symmetrical. However. It was observed experimentally that different stacking sequences produce different lamina stresses in symmetrical laminates which may indicate that inter laminar stresses have a rather measurable effect on the behavior of laminates [36].

(2-9-2)Mosaic model

This model has been proposed by Chou. It can only be used in the case of woven fabrics consisting of two sets of yarns interlaced at (90°) angle orthogonal woven fabrics (or non-deformed woven fabrics). Woven fabric is simplified as the Figure (2-18) by repetitive order of cross-ply laminates $(0/90^\circ)$. According to each pattern of cross-ply laminates that is defined by geometrical parameter (n_g) . Otherwise, the effect of fiber undulation and continuity on composite stiffness in this model were neglected. Average stresses (N_i) and moments (M_i) are defined by :



Figure(2-18)Idealization for the mosaic model [36].

$$(\overline{N}_i, \overline{M}_i) = \frac{1}{n_g} \left[\int_0^a (N_i, M_i) dx + \int_a^{n_g a} (N_i, M_i) dx \right] \dots\dots\dots(2-6) [36]$$

Where $n_g a$ is a unit of length and h is a thickness of fabric . Substituting (N_i) and (M_i) , into equation (2-4). It is obtained the rigid coefficient (A_{ij}, B_{ij}) and (D_{ij}) that can be expressed by :

$$\left. \begin{array}{l} \overline{A}_{ij} = A_{ij} \\ \overline{B}_{ij} = \left[1 - \frac{2}{n_g} \right] B_{ij} \\ \overline{D}_{ij} = D_{ij} \end{array} \right\} \dots\dots\dots(2-7) [36]$$

We can see that $(\overline{A}_{ij}, \overline{B}_{ij} \text{ and } \overline{D}_{ij})$ can be calculated from the $(A_{ij}, B_{ij} \text{ and } D_{ij})$ of laminates eq (2-5) B_{ij} represent the coupling stiffness between bending and extension when $n_g = 2$ $\overline{B}_{ij}$ is equal to zero. Chou has shown that with the mosaic model , the results were only correct for $n_g > 4$ [36].

(2-9-3) Fiber undulation model

Because the mosaic model can only apply for woven fabrics with $n_g > 4$, in order to use in the case of plain weave fabrics $n_g = 2$, chou has proposed a second model which is called the fiber undulation model . In this model , the effect of fiber undulation and continuity on composite stiffness have been considered .

This model based on the micro-mechanical behavior of woven fabrics, permits to integrate undulation form of structure . This undulation form is defined by three geometrical $(h_1(x), h_2(x) \text{ and } a_u)$ as shown in Figure (2-19).

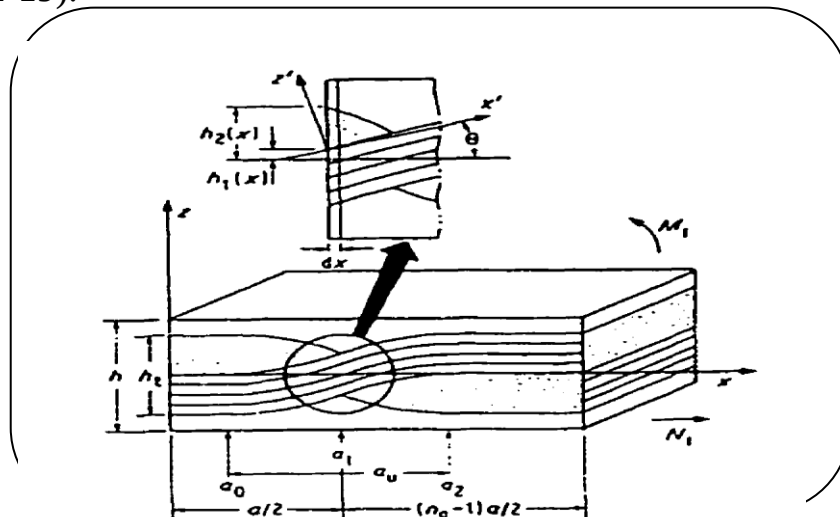


Figure (2-19)Fiber undulation model [36].

Where $h_1(x)$ and $h_2(x)$ vary between $-h_t/2$ and $h_t/2$. and in the undulation region ($a_2 \geq x \geq a_0$). they vary according to sinusoidal equation.

The fundamental assumption is that the classical lamination theory is applicable to each infinitesimal piece of the strip along the undulation direction . the average coefficients of compliance are calculated by:

$$\left. \begin{aligned} \overline{a_{ij}} &= \left[1 - \frac{2a_u}{n_g a} \right] a_{ij} + \frac{2}{n_g a} \int_{a_0}^{a_2} a_{ij}(x) dx \\ \overline{b_{ij}} &= \left[1 - \frac{2}{n_g a} \right] b_{ij} + \frac{2}{n_g a} \int_{a_0}^{a_2} b_{ij}(x) dx \\ \overline{d_{ij}} &= \left[1 - \frac{2a_u}{n_g a} \right] d_{ij} + \frac{2}{n_g a} \int_{a_0}^{a_2} d_{ij}(x) dx \end{aligned} \right\} \dots\dots\dots(2-8) [36]$$

Where $a_{ij}(x)$, $b_{ij}(x)$ and $d_{ij}(x)$ are calculated from the (a_{ij} , b_{ij}) and d_{ij} of laminates which is modified the position (x) and volume ratio between the fiber and the resin .

This model can be used for woven fabrics $n_g < 4$ and gave the good result. Obviously , using this model is more difficulty than using the mosaic model .But it is efficient specially for plain weave and it is also only used for orthogonal woven fabric composite [36].

(2-9-4) The sub – plies model

Figure(2-20) shows the sub-ply model .In this model the fabric, consisting of warp and a weft, is replaced by four fictional unidirectional lamina with orthotropic properties that are laid up in an anti symmetric configuration ($0h_1/90h_2/0h_2/90h_1$). By choosing adequate thickness for the sub- plies, the stiffness coefficient (A_{ij} , B_{ij} and D_{ij}).Of the fabric composite can be obtained . Since the configuration of the sub- plies model is anti symmetric , the thickness of the plies can be defined by a fictive thickness, which is a function of the fabric thickness and the geometrical parameter (n_g)of the fabric [36].

$$e = t_o \sqrt{\frac{1}{n_g}} \dots\dots\dots(2-9)[36]$$

The stiffness coefficients of the sub-ply's laminate. ($\overline{A}_{ij}$, $\overline{B}_{ij}$ and $\overline{D}_{ij}$), can then be obtained from the classical laminated plates theory.

To predict the failure envelope of the composites made ,the strength coefficient of the constituents ply such as :longitudinal tensile and compressive strengths (x,x). Transverse tensile and compressive strengths (y,y) and shear strength (s) are needed [36].

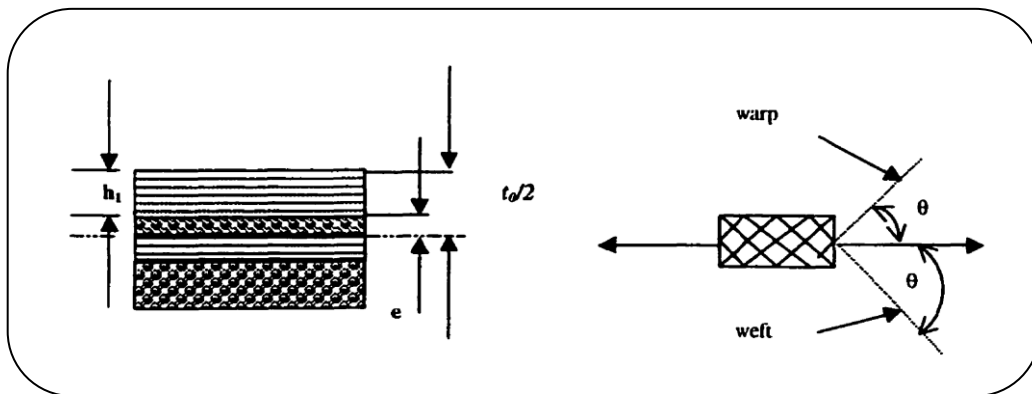


Figure (2- 20)Sub-ply's model [36].

(2-9-5) The bridging model

This model is desirable in view the fact that the interlaced regions in a stain are separate from each other. The geometry of the model is shown in Figure (2- 21).

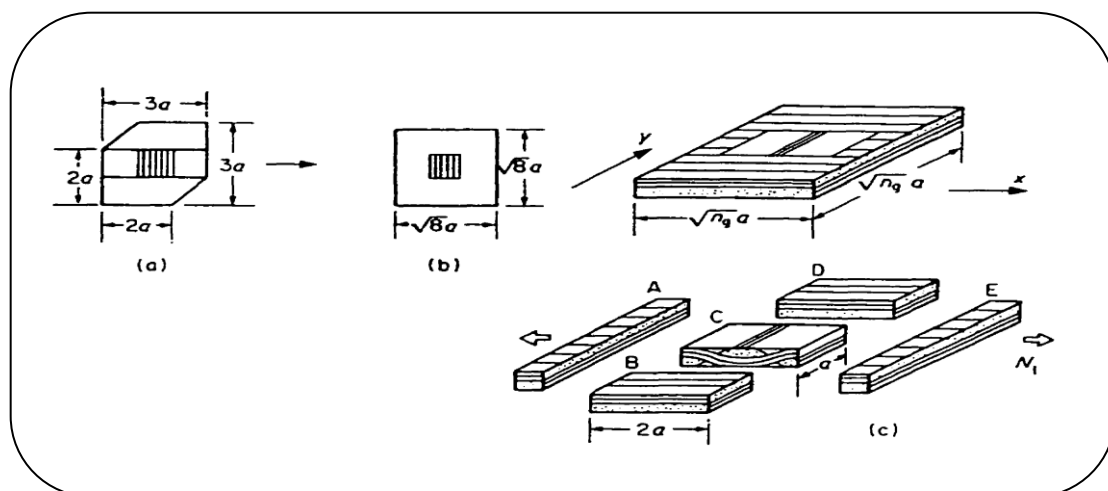


Figure (2-21) Bridging model a)- Shape of repeating unit of 8-harness stain; b)-Modified square shape and c)- Basic idealization [36].

Where the shapes of the reaping regions are modified. This model is valid for only stain weave where ($n_g > 4$). The four regions labeled by (A,B,C,D) consists of straight fill thread, and hence, can be regarded as pieces of cross- ply laminates of thickness (h). Region © has an undulation fill and continuity and undulation in the warp are ignored. The letter effect is expected to be small because an applied load is in the fill direction. The in- plane stiffness in region © where ($n_g = 2$) is found to be much lower than that of cross - ply laminate where ($n_g \rightarrow \infty$) therefore. Regions(Band D) carry higher loads than region©, if we assume these three regions have the same averaged strain and curvature.

The reason why the fiber undulation model is effective for plain weave composites whereas the bridging model is valid for stain weave composites can be explained as following :

There are no straight thread regions surrounding on interlaced region and the one-dimensional distribution of in - plane stiffness is identical in each thread in a plane weave composite. It can be expected; Therefore, that no bridging effect occurs in the plain weave composite and that each thread carries the same in - plane force. Hence, the one dimensional and bridging approaches are suitable for plain and stain weave composites, respectively [36].

(2-10) Tensile properties Of woven fabrics

It was understood that the woven composites behave non-linearly only at the initial stage (typically $< 0.2\%$) of the tensile test. After the initial non linear range, the material behaves almost linearly, similar to that of the yarn alone, except for a greater shrinkage in the direction perpendicular to the loading direction.

Generally, the load-strain curve of the woven composite fabric can be roughly divided into three stages. First, the fabric has every small initial tensile modulus (the slope of the load – strain curve) until a strain level at about 0.8% , which is due to the undulation of fiber yarns in the fabric. Secondly, from the strain level of 0.8% to about 2.3% , the load-strain curve is approximately linear with a high tensile modulus, then due to the breakage of some fibers in the fabric, the load – strain curve becomes very non linear and has a much smaller tensile behavior of a single yarn, on the

contrary, is quite different from that of a fabric. As shown in Figure (2-22) there is no initially soft stage in the load –strain curve of the yarn. The tensile modulus of the yarn is much larger than that of the fabric. The fiber breakage at a bout 0.6% strain level immediately results in the loss of loading capacity in the yarn [42].

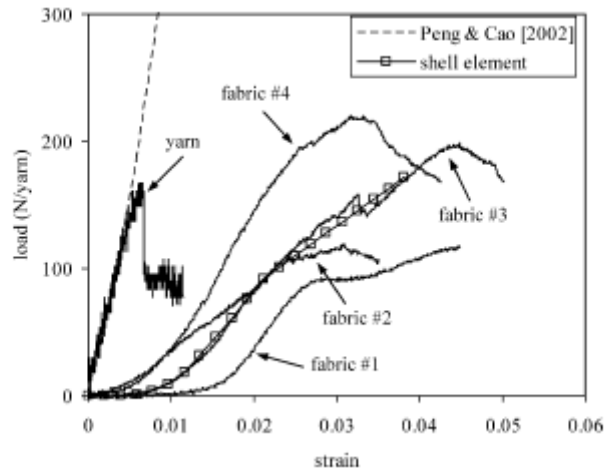


Figure (2-22) Uniaxial tensile test results on plain weave composite fabric [42].

Therefore, the classical rule of mixtures of unidirectional composite and a simple and straightforward analytical techniques can be applied to approximately determine the tensile properties of woven composites.

The tensile properties of a composite material depend on the properties of the constituents and their contribution. The longitudinal stiffness of a unidirectional composite yarn can be predicted by

$$E_1 = E_f V_{fp} + E_m (1 - V_{fp}) \quad \dots\dots\dots (2-10) [43]$$

Where V_{fp} is the fiber packing fraction in a yarn. This equation indicates that the contributions of the fiber and the matrix to the average composite properties are proportional to their volume fractions. The prediction of transverse modulus by the Halpin Tsai equation is:

$$E_2 = \frac{(1 + \xi_\eta V_{fp}) E_m}{1 - \eta V_{fp}} \quad \dots\dots\dots (2-11) [43]$$

Where $\eta = \frac{(E_f / E_m) - 1}{(E_f / E_m) + \xi}$, and is a measure of reinforcement that Depends on the fiber geometry, packing geometry, and loading conditions.

The value of $\xi=2$ has been suggested for fibers with a circular or square cross section .

Major and minor Poisson's ratios of a composite with unidirectional fibers reinforced can be expressed as the functions of the fiber packing fraction ,The Poisson's ratios and the Young's moduli of the fiber and the matrix i.e.

$$\nu_{12} = \nu_f V_{fp} + \nu_m (1 - V_{fp}) \dots\dots\dots (2-12) [43]$$

$$\nu_{21} = \nu_{12} \frac{E_2}{E_1} \dots\dots\dots (2-13) [43]$$

From equations (2-11) ,(2-12) ,the Young's modulus of the yarn a long the longitudinal and the transverse directions ,as well as the Poisson's ratios can be obtained .

Then ,tensile properties of the unit cell in the elastic range can be approximately determined by:

$$D_{11,u}^e = \frac{\beta_4 E_1}{1 - \nu_{12} \nu_{21}} \dots\dots\dots (2-14) [43]$$

$$D_{12,u}^e = \frac{\beta_4 \nu_{12} E_2}{1 - \nu_{12} \nu_{21}} \dots\dots\dots (2-15) [43]$$

The adjustable coefficient β_4 is introduced to reflect the effect of yarns normal to the loading direction on the tensile properties .It dependent on the undulation of the yarn in weave architecture. β_4 could be determined by an uniaxial tensile test for woven composite .Usually ,It ranges from(1 to 1.2) .

$$D_{11,s}^e = D_{11,u}^e \frac{A_Y}{A_S} \dots\dots\dots (2-16) [43]$$

$$\dots\dots\dots (2-17) [43] D_{12,s}^e = D_{12,u}^e \frac{A_Y}{A_S}$$

Where the subscript ,s, denotes shell element ;u and y correspond to unit cell and yarn ,respectively . The cross-sectional areas of the yarn and the shell element are A_Y and A_s , respectively.

Within the initial non-elastic range ,the main deformation mechanisms are linked to un crimping of the yarns under tensile loading. This leads to the nonlinear behavior ,which is related to the geometric parameters of the fabric architecture and the imposed strain ratio .Based on our previous study, it was known that the tensile stiffness of the material, D_{11} , will increase gradually and approach a constant .Therefore ,the tensile stiffness along the loading direction can be expressed as a function of the geometric parameters of the fabric architecture and the equivalent strain as follows:

$$\dots\dots\dots(2-18) [43] \quad D_{11} = \frac{D_{11,S}^e}{1 + e^{f\varepsilon}}$$

Where f is a function of the microstructure parameters ,such as yarn undulation ,yarn thickness ,yarn width and inter-yarn gap in a unit cell . The function f describes the effect of the weave architecture on the non-linear tensile property .For the plain weave structure studied,

$$\dots\dots\dots f = -\frac{(w_o + g_o)^2}{Uh^{\frac{3}{2}}} \dots\dots\dots(2-19) [43]$$

Where U . is the yarn undulation , h the yarn thickness , w_o the initial yarn width and g_o the initial inter-yarn gap between adjacent parallel yarns. D_{11} will approach $D_{11,S}^e$ with the increase of the deformation .Eq(2-18)is suitable for the entire deformation process ,including the initial non-linear stage and the linear stage afterwards .The function D_{12} ,which is determined by eq ((2-15)and (2-17)),can be taken as a constant during the deformation process [43].

(2-11) Creep

When designing any system, there is a number of mechanical behavior of materials questions that must be answered . Among them are fracture, yield , fatigue , stress , corrosion cracking , and creep , just to scratch the surface , some of these considerations , like fracture and yield are well recognized mechanical behavior problems. The other phenomena are more subtle and happen over longer time periods[44].

Creep is term used to describe the tendency of a material to move or to deform permanently to relieve stresses . Material deformation occurs as a result of long term exposure to levels of stress that are below the yield or ultimate strength of the material . Creep is more severe in materials that are subjected to heat for long periods and near melting point . Creep is often observed in glasses , and there is a direct proportionality between increasing temperature and creep . The rate of this damage is function of

the material properties , exposure time , exposure temperature and the applied load (stress). Depending on the magnitude of the applied stress and its durations , the deformation may become so large that a component can no longer perform its function [45].

Creep deformation of various materials may occur in time under all temperature .i.e. tungsten requires a temperature in thousands of degrees before creep can occur while the ceramic ice Antarctica ice cap creeps even during freezing temperature . Generally (30-40)% of the melting point for metals and (40-50)% of melting point for ceramics are required before creep can occur [45].

This deformation behavior is not only important in systems for which high temperatures are endured . Such as nuclear power plants , jet engines, heat exchangers etc. Lead pipes are not used any more because they can creep at room temperature , also metal paper clips are stronger than plastics because plastics also creep in room temperature [45] . For polymers ,creep is not only an important phenomena in its own right within the framework of viscoelasticity , but also is of great significance in the design of engineering products , as it reflects the long - term load -bearing capacity of structural products . A better understanding on the creep behavior is necessary for reliable assessment of durability to prevent an intolerable amount of deformation or time - dependent failure of polymer structures in engineering applications [46].

Three different approaches have been attempted to describe the time-dependent creep behavior of polymers : engineering approaches , rheological approaches and molecular approaches . In an engineering approach , the goal is set to predict the creep behavior (usually creep strain) for a particular loading situation based on a low number of experiments , and empirical relationships are then proposed . Different relations such as a power law equation have been found to be valuable to describe creep strain for certain polymers under specific loading conditions, although these equations may not have a solid physical base [47].

For the rheological , attempts are directed to extend the linear viscoelastic relations , e.g Boltzmann superposition principle , to a non - linear regime . One way of doing this is to preserve the separability of stress , strain and time in their functional representations , and this leads to the sophisticated form of single integral representations developed by Leaderman, Bernstein , Kearsly and Zapas, Valanis and Landel , and Schapery. Another method is to use multiple integral representations

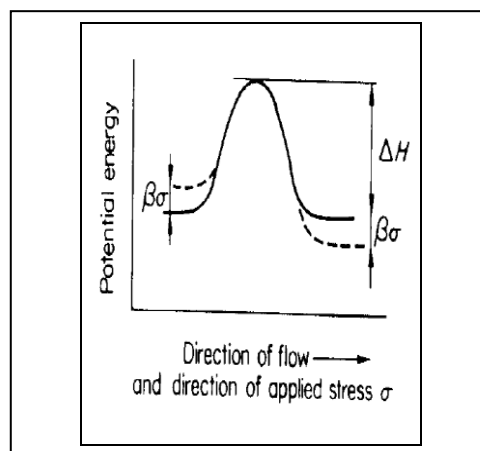
which has led to considerable mathematical complexity [47].

The molecular approach is aimed at incorporating a molecular model that describes the molecular event of creep deformation to a physical property that can be measured experimentally. This approach has the attraction of possible identification of the molecular mechanisms and structural origins responsible for creep. The disadvantages of this approach is the lack of precise mathematical treatment / description as compared with the rheological method. However, this drawback is somewhat balanced by the built-in merit of non-linearity and temperature dependence.

The only molecular model that has been widely used in creep studies was developed by Eyring and co-workers. In this model, the creep deformation of a polymer involves the motion of chain molecules or parts (segments) of a chain molecule over potential barriers, as illustrated in Figure (2-23). The basic molecular processes could be either intermolecular such as chain sliding and/or intra molecular (like a change of chain conformation). With no stress acting upon the material, it is at a state at which chain segments (ν) dynamic equilibrium state, the frequency move across the potential energy barrier (ΔH) can be expressed as:

$$\dots\dots\dots(2-20) \quad \nu = \nu_0 \exp\left(-\frac{\Delta H}{RT}\right) \quad [47]$$

Where (ν_0) is a pre-exponential factor that is dependent upon the fundamental vibration frequency and entropy contribution to the free energy.



Figure(2-23) Molecular mechanism for the Eyring creep model [48].

Applying a stress (σ) to the material produces a linear shift ($\sigma\beta$) of the energy barrier in a " symmetrical " fashion (2-23) . Therefore , a flow in the forward direction (i.e.The direction of the applied stress) is:

$$\dots\dots\dots(2-21)_{[47]} v_1 = v_o \exp\left(-\frac{\Delta H - \beta\sigma}{RT}\right)$$

And the flow in a backward direction is

$$\dots\dots\dots(2-22)_{[47]} v_2 = v_o \exp\left(-\frac{\Delta H + \beta\sigma}{RT}\right)$$

Therefore, the net flow in the forward direction is

$$\dots\dots\dots(2-23)_{[47]} \Delta v = v_o \exp\left(-\frac{\Delta H}{RT}\right) \left[\exp\left[\frac{\beta\sigma}{RT}\right] - \exp\left[-\frac{\beta\sigma}{RT}\right] \right]$$

It is assumed that the net flow in the applied stress direction is directly related to the rate of deformation ,i.e. creep rate ,therefore

$$\dots\dots\dots(2-24)_{[47]} \frac{de}{dt} = e = e_o \exp\left[-\frac{\Delta H}{RT}\right] \sinh\left[\frac{V\sigma}{RT}\right]$$

Where (e_o) is a pre - exponential constant and the symbol (β) is molecular replaced by (v) , which is termed the activation volume for the event . A unique feature of this model is that the parameters in the equation, particular the activation energy and activation volume , can give some indications to the underlying creep mechanisms. The pre - exponential factor , on the other hand , is an representation for the population of potential sites that can contribute to creep (available of creep sites).

The Eyring - rate model has been used initially by Leaderman for the creep studies on silk and other fibers .It was shown that this model gave a good fit over decades of time at a given stress level , by appropriate choice of the parameters for the elements in Figure (2-24a). Sherby and Dorns examined the creep behavior of polymethyl methacrylate under constant stress in a temperature range of (263 - 320) K .The creep rates at different temperatures and stresses were determined by the so - call Sherby -Dorn plot , in which creep strain rate (in logarithmic scale) is plotted against creep strain their results showed a linear relationship between applied stress and creep rate in logarithmic scale . This has been regarded as a specific case of the Eyring - rate equation (equation 2-24) at a higher stresses level , where the sinh function is simplified into an exponential function ,i.e.

$$\sinh(x) = \frac{1}{2} \exp(x)$$

When x is larger than 3.

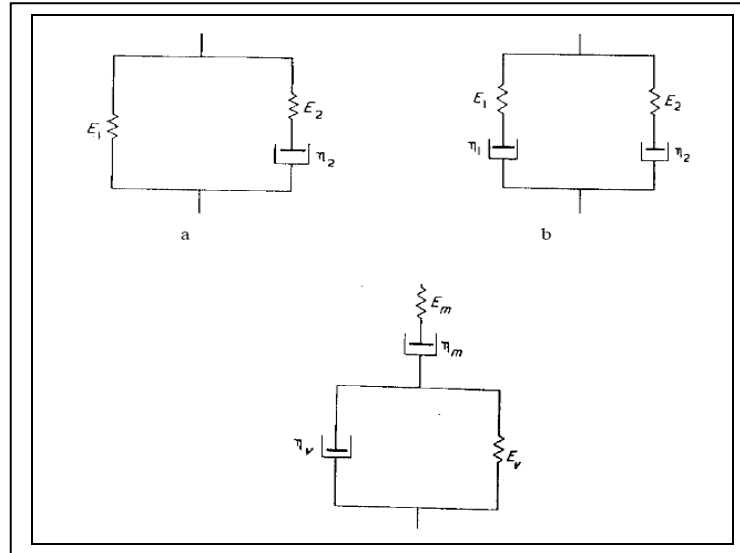


Figure (2-24) Mechanical analogs for (a)- Standard three elements solid with a thermally activated dashpot; (b)- Two Eyring-rate processes model and (c)- Modified two processes Eyring-rate model [47].

This model has also been used extensively in the creep studies of highly oriented polyethylene .Fibers .It has been shown that for low molecular weight samples ,the stress and temperature dependence of the creep rate could be modeled well by a single Eyring-rate process with an activation volume of $(0.08)\text{nm}^3$. This is a reasonable value as it probably means that the activation volume is just the swept – out volume of a single molecular chain moving through the crystal lattice via defect motion. However ,for high molecular weight samples and copolymer samples, two activated Eyring-rate process coupled in parallel ,as shown in Figure(2-24b), had to be used to satisfactorily describe the creep rates ,the two Eyring – rate process differ with regard to the activation volumes and pre-exponential factor ,and it only activates at higher stress level .This process is more related to the crystalline phase of the material .The other process is associated with a large activation volume $(\sim 1.0\text{nm}^3)$ and a small pre-exponential factor ,and it is speculated to represent the deformation of the entangled amorphous net work in the material .

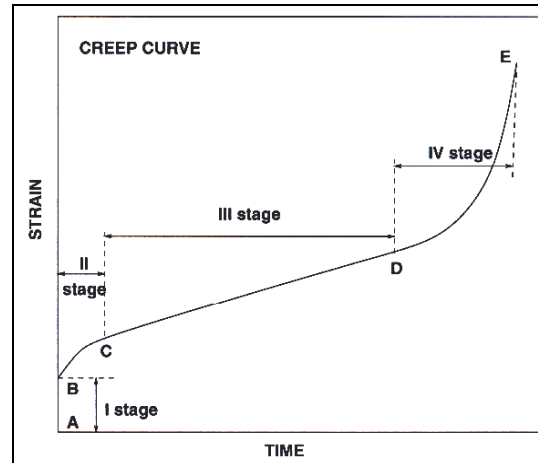
The applicability of the two Eyring-rate process model certainly depends on its capability of providing a comprehensive description of

time-dependent behavior in general. Ward, et al. Carried out an investigation aimed at using the two Eyring – rate process model to describe viscoelastic the behavior of high modulus LPE, including creep as well as stress – relaxation properties .In this study, initial model(Figure (2-24b))was modified into Figure(2-24c)without loosing its significance to a major extent .the modified model is essentially a standard linear solid in series with a dashpot ,and the latter element is introduced to account for the small amount of plastic deformation, which occurred even at small stress. the creep data was fit to the modified model Figure(2-24c) ,and the parameters thus obtained were used to predict the stress relaxation behavior from the original model Figure(2-24b).It was that predicted stress relaxation behavior was in good agreement with that observed experimentally.

Finally, it is worth pointing out that stress relaxation is also a common loading situation in engineering applications, and it is closely related with creep in that both behaviors reflect the same fundamental viscoelastic nature of a given polymer. If a material behaves in a perfectly linear viscoelastic manner, creep compliance and stress relaxation modulus can indeed be coupled with integral transformations. However, since polymers, particularly semi crystalline polymers, tend to be non-linear viscoelastic, the relationship between creep and stress relaxation is complex and has not been studied very often, except for few cases [47].

(2-12) Creep stages

The tendency of a material to undergo plastic deformation under the influence of a stress is often characterized by using a tensile test , which is in general conducted under conditions where the measured properties are independent of time. The details on mechanisms of plastic deformation and creep test have been reviewed in a number of excellent publication . The plastic strain is time - dependent in creep deformation . Most creep data are obtained by measuring the deformation of a bar under constant load and temperature over a period of time . The plastic strain on loading is measured as a function of time . The plastic strain on loading is measured as a function of time and a typical variation of creep strain with time for a specimen subjected to a constant tensile stress is shown in Figure (2-25) [48,49].



Figure(2-25) : General form of strain against time curve. **AB**, elastic extension; **BC**, decreasing creep rate; **CD**, minimum rate of creep; **DE**, increasing creep rate [50].

As shown in Figure (2-25) the slope of the curve is called creep rate ($\dot{\epsilon}$) and the end point of the curve (E) is the time rupture. The creep rate is not ordinarily constant and can be divided into three phases. The region (BC) is commonly considered as primary or transient creep stage. And it starts at a rapid rate and slows with time. The region (CD) stands as secondary or steady state creep, which has an accelerating creep - rate and terminates at the point (E) by failure of material at time for rupture [51].

(2-12-1) Primary creep

During primary creep, the strain rate decreases with time until a constant rate is reached and this tends to occur over a short period [53].

Primary creep strain is usually less than one percent of the sum of the elastic, steady state, and primary strains. The mechanism in the primary region is the climb of dislocations that are not pinned in the matrix. Since the amount of initial strain of a material is due to the number of dislocations initially present, the primary region is strongly dependent on the history of the material. If the material has been heavily worked before the creep test, there would be many more dislocations present and the characterized of the primary creep region would be much different [53].

(2-12-2) Steady state creep

Steady -state creep is so named because the strain rate is constant . In this region , the rate of strain hardening by dislocations is balanced by the rate of recovery .Steady - state creep is roughly centered at the minimum in the plot of the creep rate versus time . The minimum rate is empirically found to be inversely proportional to the time to rupture. This is often called the Monkman-Grant relationship. In which the product of the minimum creep rate and rupture time is found to be constant for a given mechanism [54].

(2-12-3) Tertiary creep

In the tertiary region , the high strains start to cause necking of the material just as in the uni-axial tensile test .This necking causes an increase in the local stress of the component , which further accelerates the strain. Eventually the material will pull a part in a ductile fracture around defects in the solid . These defects could be precipitates at high temperature or grain boundaries at lower temperature [55].

In any case the important of the tertiary region to normal operation and creep design criteria is minimal . In Figure (2-25),above , the time scale of the tertiary region is greatly expanded for the purpose of clarity . Considering the small amount of time in addition to the fact that the tertiary region develops a plastic instability similar to necking , operating in the tertiary region is not feasible .Therefore it is a conservative estimate to approximate the end of serviceable life of any component to coincide with the end of the steady state creep region .Only under accidental conditions may the extra time in the tertiary region be useful to consider.

The primary creep could be described as the work-hardening stage for the material in which the resistance to creep is built up by virtue of its own deformation ; during steady - state creep there is a state of balance between work- hardening and thermal softening ; tertiary creep precedes fracture through cavitations, inter -crystalline cracking or some other damage mechanism [56].

The studies on the primary and steady stages of creep are usually more interesting for engineering analysis. Tertiary a creep is usually associated with the onset of failure (necking ,damage) and is short-lived [56].

Although there are a great number of fundamental theories describing the process of creep deformation and rupture life in different regimes of stress, temperature and strain rate , the theories have not been applied with effect in useful materials of the type used in engineering . This is because practical materials tend to be complex [56] .

(2-13) Biaxial characterization of composite materials

Applied biaxial loading plays a significant in the behavior and failure of laminated composite structures. Due to the biaxiality of most loading conditions and the material anisotropic in composites (i.e. directional dependence), characterization under biaxial loading is enormously important.

Biaxial tests on composites are not commonly performed due to their difficulty, expense (in specimen fabrication and testing) , and requirement for complex and costly infrastructure . Of the biaxial studies cited in the literature, only a limited number of tests are usually performed due to the time consuming nature of these experiments . As such, the vast majority of studies on composites have been performed on laminated coupon specimens under uniaxial loading conditions.

Biaxial tests have been performed on composite laminates in order to determine material properties (elastic, inelastic, and failure), and to study structural effects (laminate geometry, imposed cracks and notches) under complex loading conditions . Biaxial testing , however is most commonly used to generate biaxial failure envelopes for use in design or verification of available failure models. Depending upon the specimen geometry , the envelopes can be defined with respect to a number of applied or material (in - situ) coordinates and by various failure criteria . The failure points are generated by specialized tests which provide the required of biaxiality in Applied stress or strain space [57].

Biaxial testing machines are inherently designed around the geometry and loading requirements of the test specimen .The majority and most successful of these testing facilities can be classified by one of two main test specimen geometries ,a)- The cruciform (planar) specimen, and b)-The thin - walled tubular specimen [57].

The cruciform specimen is the preferred choice for crack growth

studied as 1)- The surface is accessible and visible , 2)- Long crack formation can be accomplished , and 3)- There no curvature effects . The disadvantage with cruciform testing techniques is the difficulty in accurately determining the distribution of stresses in the specimen .This stress distribution is often determined using empirical or numerical methods , and is largely dependent upon the specimen design, configuration of the loading frame , specimen attachment, and actuation method .This accounts for the large number of variations in the reported specimen designs and testing apparatus. For composite materials ,grip attachment and free edge effects further tend to limit the testing to specific laminate geometries and loading conditions .Cruciform type specimens have been used to characterize biaxial under monotonic and cyclic loading [57].

(2-14) General consideration

If the material is isotropic , its behavior under complex stresses can be fully characterized by tensile creep and creep lateral contraction ratio(Poisson's ratio) .If the material is anisotropic or if the properties in tension and compression differ , such information is essential but is insufficient for full characterization of the material .

Practical requirements may demand tests under more complex system, there is no objection to this , but they should be regarded as complementary to, and not substitutes for , the standard recommended tests. Creep tests at several stress levels will normally be necessary because of the non- linear nature of viscoelasticity in plastics.

Creep curves generally show a regular trend and it is often possible to interpolate and provide curves for any particular stress level within the experimental limits. Although interpolation becomes more difficult at high stresses and high temperature, where the creep curves may show a less regular pattern of behavior [58].

(2-15)Long term performance of FRP materials

Polymeric as viscoelastic materials undergo elastic and time-dependent (viscous or creep) deformation . Creep strain of FRP material depends on the stress level , temperature , lay-up of the laminate and the mechanical properties of its constituents , i.e. Fiber and matrix . In general, the creep response in laminate dominated by fibers is less significant than

that dominated by matrix .Therefore , unidirectional laminate stressed in the fiber direction exhibits very low creep strain compared to that with angle - ply ,lay-up. The creep rate of different laminates consisting of various types of fibers acting as a reinforcement for vinyl ester resin have been studied by Yeung and compared with the creep rate of steel .It was reported that carbon fibers composite exhibits the less creep rate .E- glass fibers composite has creep rate comparable with steel while aramid composite (kelvar49) has the highest creep rate. [32]

(2-16) The creep function

Alfrey and doty describe the creep function by considering the sudden application of a stress (at $t=0$) that is held constant .The strain will increase with time according to some function $\varepsilon(t)$.Since for linear viscoelastic material ,the strain at any time is proportional to the stress, then they define the creep function $D(t)$ to be equal to the strain at any time (t) divided by the constant stress value.

$$\dots\dots\dots(2-25)[59] D(t) = \frac{\varepsilon(t)}{\sigma}$$

They describe the voigt _Kelvin model as having a practical relationship to the creep function .If the viscoelastic properties and constants of a material have been specified , then it is relatively simple to calculate the response to a simple constant stress since the behavior of each voigt - Kelvin unit in the sequence can be calculated individually .The strains are simply additive. Therefore , this makes simulating the creep curve a relatively simple task.

creep behavior is non-linear ,linearity only occurs at very low values of (σ,ε) ,as limiting case .therefore , $D(t)$ is $D(t,\sigma)$ [59].

(2-17) Linear and nonlinear viscoelasticity

The time dependent material is often referred to as viscoelasticity . If a constant load (σ_1) is applied to a viscoelastic specimen, the time dependent strain is recorded as (ε_1) as shown in Figure (2-26a). After some period of time , the load is removed . Suppose the specimen is allowed to recover and a larger stress (σ_2) is applied . The time dependence of the strain (ε_2) is shown in Figure(2-26b).

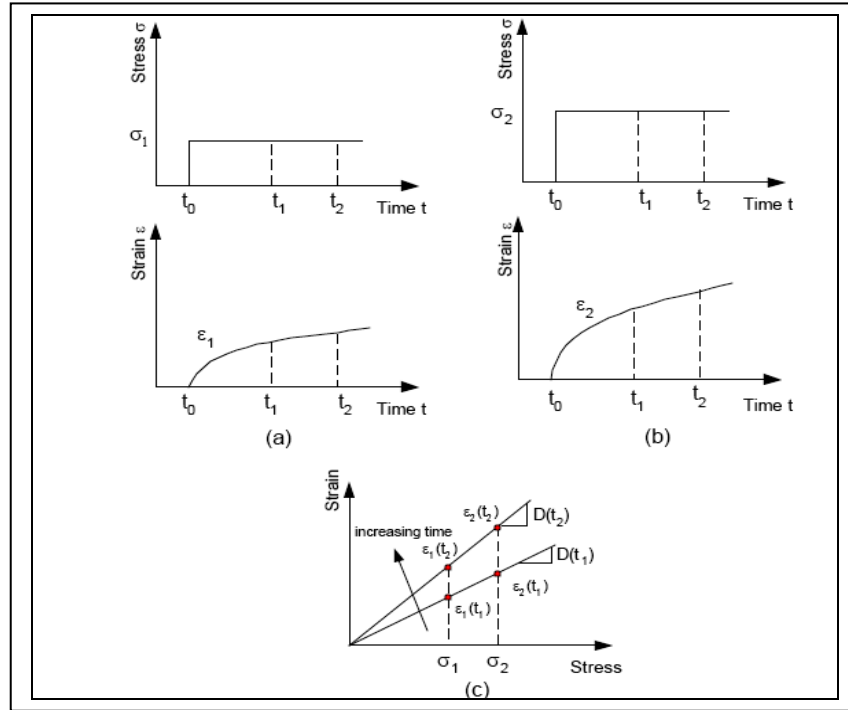


Figure (2-26). Linear viscoelastic creep: (a)- Constant stress σ_1 applied at time t_0 leads to time dependent strain $\epsilon_1(t)$; (b) -A higher stress applied at t_0 leads to time dependent strain $\epsilon_2(t)$; (c)- From (a) and (b) the strains at t_1 and t_2 are linear in the stress [59].

If at a particular time (t_1) and (t_2) after loading, (ϵ_1 and ϵ_2) are linear with the magnitude of correspondent stresses, (σ_1) and (σ_2), the stress strain relationship can be given by:

$$\dots\dots\dots(2-26)[59] \frac{\epsilon_1(t_1)}{\sigma_1(t_1)} = \frac{\epsilon_2(t_2)}{\sigma_2(t_2)}, \frac{\epsilon_1(t_2)}{\sigma_1(t_2)} = \frac{\epsilon_2(t_2)}{\sigma_2(t_2)}$$

Thus, if at an arbitrary time (t), the strains at the two stresses can be expressed as:

$$\dots\dots\dots(2-27)[59] \frac{\epsilon_1(t)}{\sigma_1(t)} = \frac{\epsilon_2(t)}{\sigma_2(t)}$$

The strains in the two experiments are proportional to the imposed stresses. In general, for stress (σ), the creep compliance $D(t)$ can be given as the ratio of strain to stress at a certain time as described by equation(2-25).

This property is often characterized as linear viscoelasticity. In the linear range, the compliance is independent of stress, which means that the compliance is the same whether stresses used in the creep test are σ_1, σ_2 or other stress levels. Figure (2-26c). The strain range in which a specimen

is linear viscoelastic can be determined by a creep test. A transition from linear to nonlinear viscoelasticity is shown in Figure (2-27).

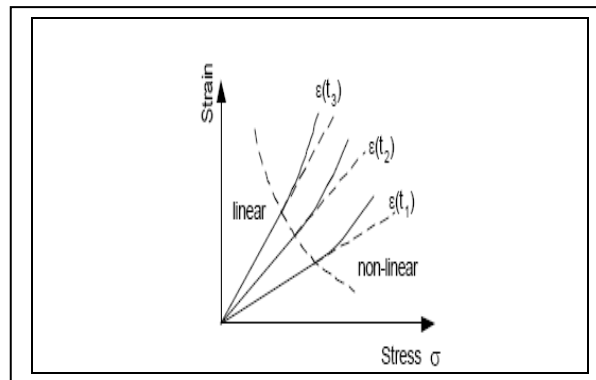


Figure (2-27). Linear-nonlinear transition of stress strain relationship with respect to different time levels
(Isochronous creep curve, data are taken from creep test at different stresses) [59].

However, polymers generally exhibit linear viscoelastic property at low stresses such that the corresponding strain is below $\sim 0.5 \times 10^{-2}$. At higher stress levels, the material will assume nonlinear viscoelastic behaviors which will not obey the linear relation between stress and strain described by equation (3-8).

Since nonlinear behavior is very important to determine material behavior at moderate or higher stress levels, some models have been suggested for different kind of polymers, such as the Eyring model; this model - explains - some aspects, but fails with other ones, and will not be discussed here [59,60].

(2-18) Mechanical behavior of polymeric composite materials

Polymeric - based composite materials are viscoelastic; This makes the time - dependent behavior of such materials one of the most important factors for use in the analysis and design of (FRP) structural systems [60].

(2-18-1) Voigt model

A purely elastic material responds instantaneously to the load and the deformation remains the same in addition, it will recover its initial

shape upon the removal of the load . On the contrary , a viscous liquid will deform as long as the load continues to be applied .Upon the removal of the load , the fluid does not return to its initial position .The response of a viscoelastic material is intermediate between the solid and the liquid (see Figure(2-28)).

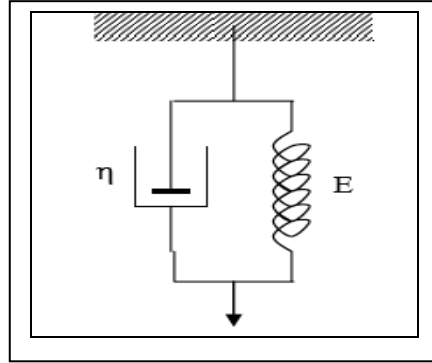


Figure (2-28). A spring and dashpot arranged in parallel [28].

It can use combination of springs (linear elastic behavior) and dashpots(linear viscous behavior) in order to quantify the mechanical behavior of polymeric materials. In Figure (2-28) the voigt element is shown.This is a parallel combination of a spring and a dashpot. The total stress(σ)is distribution between the spring (σ_1) and the dashpot(σ_2), so that:

$$\dots\dots\dots(2-28)[65] \quad \sigma_{total} = \sigma_{spring} + \sigma_{dashpot}$$

However the strains of the spring and dashpot are same , that is

$$\dots\dots\dots(2-29)[65] \quad \epsilon_{total} = \epsilon_{spring} = \epsilon_{dashpot}$$

$$\dots\dots\dots(2-30) \quad \sigma_1 = E \epsilon_1 \quad [65]$$

$$\dots\dots\dots(2-31)[65] \quad \sigma_2 = \eta \frac{d\epsilon_2}{dt}$$

where η : is the viscosity .

Substituting the relationship given by Hooke's and Newton's laws , gives

$$\dots\dots\dots(2-32)[65] \quad \sigma = E \epsilon + \eta \frac{d\epsilon}{dt}$$

where ϵ : is the strain in each of the spring and the dashpot.

If the voigt Kelvin model is considered subjected to constant stress creep, the differential equation for strain with respect to time can be solved to give equation (2-33).

$$\dots\dots\dots(2-33)[65] \quad \varepsilon(t) = \frac{\sigma_o}{E} [1 - \exp(-\frac{Et}{\eta})]$$

For the recovery (relaxation, $\sigma = 0$), obtain

$$\varepsilon(t) = -\varepsilon_o \exp(-\frac{Et}{\eta}) \quad \dots\dots\dots(2-34)[65]$$

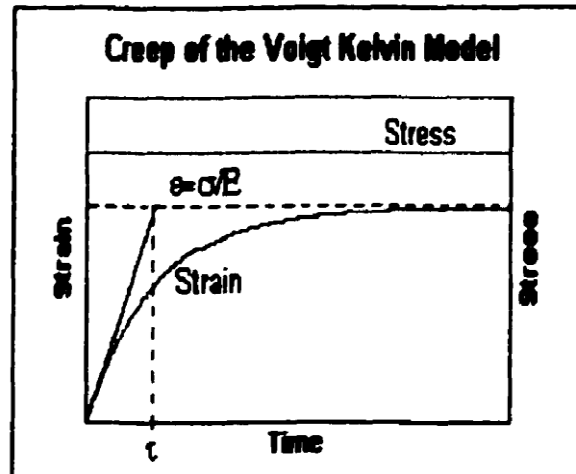


Figure (2-29):Creep at constant stress of the Voigt-Kelvin model [65].

Equation(2-34) agrees qualitatively with the viscoelastic behavior as shown in Figure (2-29), the strain is seen to increase exponentially with time until reaching an asymptotic value at (σ_o/E) . At the time of instantaneous loading to a constant stress ($\sigma = \sigma_o$), the stress is initially supported by the dashpot since the spring cannot extend. Over time, the load is transferred to spring. As the time approaches infinity ($t \rightarrow \infty$), the spring carries the entire stress. This behavior is sometimes called delayed elasticity [65].

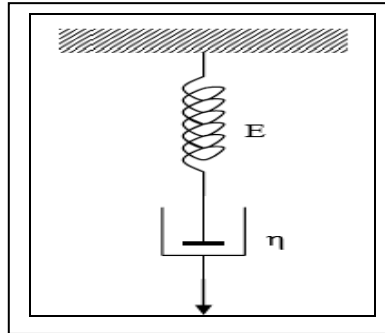
Although the Voigt element and other more complicated combinations of springs and dashpots provide some useful insight into viscoelastic properties of polymers they are inadequate in describing the creep behavior of a real polymeric material. Many empirical equation have been proposed, on which applies to some of common engineering plastics, has the form:

$$\dots\dots\dots(2-35)[65] \quad \varepsilon(t) = K \sigma^n$$

Where n, K are constants for a given polymer and ($0 \leq n \leq 1$). In cases where $n=0$ the material behaves in a purely elastic manner. Alternatively, at $n=1$ the material behaves as a viscous fluid. The rate of (n) obtained from creep data is therefore a measure of the relative contribution, of elastic and viscous deformation to the creep process [60,61].

(2-18-2)Maxwell model

Another simple model to represent viscoelasticity is the Maxwell model which was apparently proposed in the last century by lord Maxwell to explain the time - dependent mechanical behavior of viscous materials. The Maxwell mode consists of spring and dashpot in series as shown in Figure (2-29) [61,62,63,66].



Figure(2-29). Maxwell model. Original equation [28].

The fundamental equations for the stress and strain in Maxwell model are:

$$\dots\dots\dots(2-36)[65] \sigma_{total} = \sigma_{spring} = \sigma_{dashpot}$$

And

$$\dots\dots\dots(2-37)[65] \epsilon_{total} = \epsilon_{spring} + \epsilon_{dashpot}$$

differentiation of equations (2-37) lead us to:

$$\dots\dots\dots(2-38 (a))[65] \frac{d\epsilon_{total}}{dt} = \frac{d\epsilon_{spring}}{dt} + \frac{d\epsilon_{dashpot}}{dt}$$

and when (2-30) and (2-31) are substituted gives

$$\dots\dots\dots(2-38 (b))[65] \frac{d\epsilon_{total}}{dt} = \left(\frac{d\sigma_{spring}}{dt}\right) \frac{1}{E} + \left(\frac{\sigma_{dashpot}}{\eta}\right)$$

The stress -strain - time relationship can be determined from equations (3-21) as one considers the model subjected to different stress- time and strain - time constraints for example , applying a constant stress ($\sigma=\sigma_0$) at ($t=0$) equation (2-38) becomes a first order differential equation of strain such that the relationship of strain with respect to time is :

$$\dots\dots\dots(2-39)[65] \varepsilon(t) = \left(\frac{\sigma_o}{E}\right) + \left(\frac{\sigma_o}{\eta}\right)t$$

The result can be seen in the graph of Figure (2-30) below.

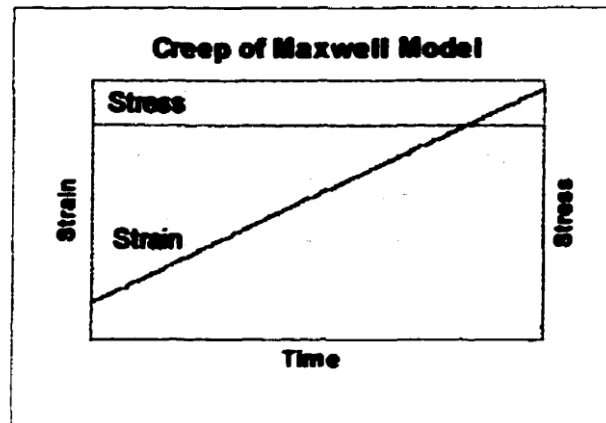


Figure (2-30) : Creep at constant stress of the Maxwell model [65].

(2-18-3)The standard linear solid

We have seen that the Maxwell model describes the stress relaxation of a viscoelastic solid to a first approximation , and the Kelvin model the creep behavior , but that neither model is a adequate for the general behavior of a viscoelastic solid where it is necessary to describe both stress relaxation and creep [62].

Consider again the general linear differential equation which represents linear viscoelastic behavior . From the present discussion it follows that to obtain even an approximate description of both stress relaxation and creep ,at least the first two terms on each side of equation (2-40) must be retained ,i.e. The simplest equation will be of the form,

$$\dots\dots\dots(2-40)[62] a_o \sigma + a_1 \left(\frac{d\sigma}{dt}\right) = b_o \varepsilon + b_1 \left(\frac{d\varepsilon}{dt}\right)$$

This will be adequate to a first approximation for creep (when $(d\sigma/dt=0)$) and for stress relaxation (when $(d\varepsilon/dt=0)$), giving an exponential response in both cases.

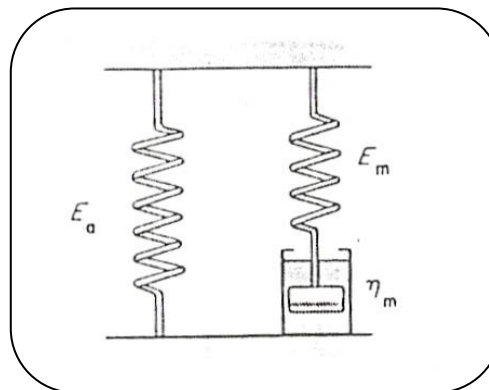
It is very easy to show that the model shown in Figure (2-31) has this form . The stress- strain relationship is.

$$\dots\dots\dots(2-41)[62] \quad \sigma + \tau \left(\frac{d\sigma}{dt} \right) = E_a \varepsilon + (E_m + E_a) \tau \left(\frac{d\varepsilon}{dt} \right)$$

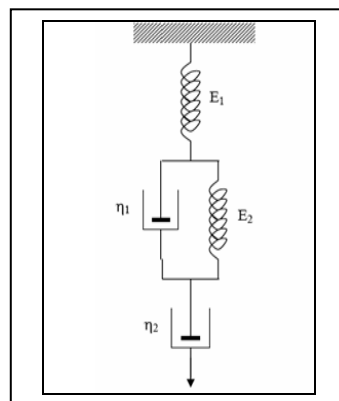
$\tau = \eta_m / E_m$ where

This model is known as the " standard linear solid" and is usually attributed to Zener .It provides an approximate representation of the observed behavior of polymers in their main viscoelastic range . As has been discussed , it predicts an exponential response only . To describe the observed viscoelastic behavior quantitatively would require the inclusion of many terms in the linear differential equation (2-40). These more complicated equations are equivalent to either a large number of Maxwell elements in parallel or a large number of Voigt elements in series (Figures (2-31,2-32)).[62,65]

$$] \quad \dots(2-42) \quad a_0 \sigma + a_1 \frac{d\sigma}{dt} + a_2 \frac{d^2\sigma}{dt^2} + \dots = b_0 \varepsilon + b_1 \frac{d\varepsilon}{dt} + b_2 \frac{d^2\varepsilon}{dt^2} + \dots [\quad [62]$$



Figure(2-31)The standard linear solid model [62].



Figure(2-32)Four-element model from Morton& Hearle [28].

(2-18-4) Viscoelastic model

The constitutive model which proved to be very successful in describing the mechanical response of many polymers and polymer composites developed several years ago by Schapery R.A , based on the notion of internal state. variables and the thermodynamics irreversible processes Based on the one dimensional schapery equation and the elastic hook's law a three dimensional constitutive model is proposed.

The relation between strains and stresses in the one dimensional case is expressed through the Schapery equation as:

$$\dots\dots\dots(2.43)[63] \varepsilon(t) = g_0 D_0 + g_1 \int_0^t \Delta D(\Psi - \Psi') \frac{\partial g_2(\sigma(\tau))}{\partial \tau} d\tau$$

Assuming that the nonlinear creep compliance ΔD can be expressed as

$$\dots\dots\dots(2.44)[63] \Delta D(\Psi) = D_1 \Psi^n$$

Leads to a nonlinear power law expression as

$$\dots\dots\dots(2.45)[63] \varepsilon(t) = \sigma_0 (D_0 g_0 + g_1 g_2 D_1 \left(\frac{t}{a_0}\right)^n)$$

Experimental creep - and relaxation data for the matrix material are provided by BASF and used for determining the parameters in the schapery model [63].

(2-19) Superposition principles

There are two superposition principles , which are important in predicting creep behavior of plastic materials under various test conditions. The first of these is the Boltzman superposition principle ,which describes the response of a material to different loading histories . The second is the time temperature superposition principle or the WLF equation , which describes the equivalence of time and temperature[62].

The Boltzman superposition principle states that the response of a material to a given load is independent of the response of the material to any load , which is already on the material . The deformation of a specimen is directly proportional to the applied stress , when all deformations are compared to equivalent times . It is only valid in linear viscoelastic region. For the case of creep , the total strain may be expressed by:

$$\dots(2-46)[59] \varepsilon(t) = D(t - \tau_1)\sigma_1 + D(t - \tau_2)(\sigma_2 - \sigma_1) + \dots D(t - \tau_i)(\sigma_i - \sigma_{i-1})$$

Or

$$\dots(2-47)[59] \varepsilon(t) = \int_{-\infty}^t (D - \tau) d\sigma(t)$$

where $D(t) = 1/E(t)$ is the compliance function, which is a characteristic of the polymer at a given temperature and initial stress. Figure (2-33) shows the creep curve by boltzman superposition principle [59].

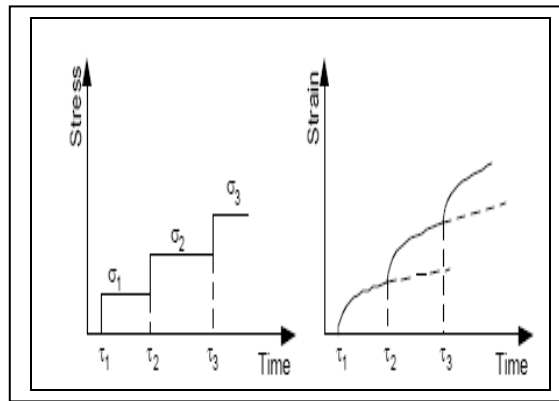


Figure (2-33) Boltzmann superposition principle [59].

at time τ_1 , stress σ_1 is applied and the strain included can be given by:

$$\dots(2-48)[59] \varepsilon_1(t) = \sigma_1 D(t)$$

According to linear viscoelasticity, the compliance $D(t)$ independent of stress, i.e. $D(t)$ is the same for all stresses at a particular time. If stress increment $(\sigma_2 - \sigma_1)$ is applied at time (τ_2) and the strain increase due to stress increment $(\sigma_2 - \sigma_1)$ is

$$\dots(2-49)[59] \varepsilon_2(t) = D(t - \tau_2)(\sigma_2 - \sigma_1)$$

likewise the strain increase due to $\sigma_3 - \sigma_2$ can be given by :

$$\dots(2-50)[59] \varepsilon_3(t) = D(t - \tau_3)(\sigma_3 - \sigma_2)$$

Further strains induced by stress increment which can be given positive or negative, are added to give equations (2-46) or (2-47).

The time - temperature WLF superposition principle describes the equivalence of time and temperature. This superposition is used to describe temperature dependent behavior in stress relaxation [59].

Chapter Three

Numerical Simulation and Experimental Work

(3-1) Numerical Simulation

Numerical simulation plays an indispensable role in the manufacturing process, speeding product design time while improving quality and performance. Recently, analysts and designers have begun to use numerical simulation alone as an acceptable means of validation, in many disciplines, virtual prototyping-employing numerical simulation tools based on finite element methods-have replaced traditional build-and break prototyping, successful designs leading to better prosthetic implants-passenger safety in automotive crashes, packaging of modern electronic chips, and other advances are partly a result of accurate and detailed analysis.

Because of Complexity in modeling creep behavior for hybrid woven fabrics composites materials and design features are included in the cruciform specimen as explained in the hereinbelow section to meet the biaxial test requirements. Therefore, finite element analysis is carried out by using the finite element package ANSYS 10. The simulation is applied on matrix phase which represents the creep response possessed in laminate composites materials.

The problems involved with the phenomenological creep models

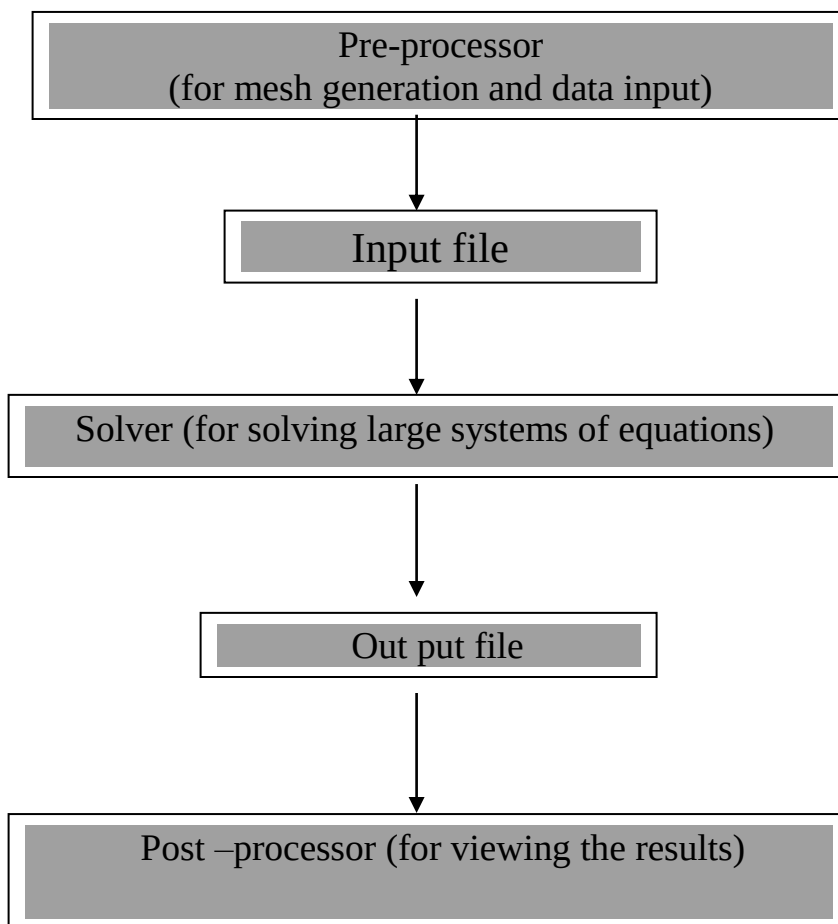
1-The models are simply based on the phenomenological investigation of material properties while the actual behavior of the material is very complex. therefore, inevitably the model contains errors.

2-All these models are limited in their mathematical form and because they are written explicitly ,they require an appropriate set of data for parameter identification .

3- Compared to metals ,composite materials require extra parameters for their characterization like fiber orientation ,volume fraction ,fiber –matrix interface ,etc. these parameters will raise the degree of complexity of the earlier constitutive models.

(3-2) Numerical simulation stages

To carry out a numerical simulation process by using the FE software, we must understand the general stages of modeling by using this software. These stages are shown in Figure(3-1).



Figure(3-1)Finite element analysis stages.

(3-3) Material non linearity in ANSYS mechanical

For engineering design and application it is essential to understand and accurately characterize material behavior .

3-3-1) Plasticity and creep

The situ of plasticity models is comprehensive and covers anisotropic behavior. All elastic-plastic models are in rate form and employ fully implicit integration algorithm .For unconditional stability with respect to strain increments. ANSYS ,Inc. Has also made every effort to obtain consistent material jacobain contributions in order to obtain efficient acceptable convergence rates in nonlinear analysis.

(3-3-2) Viscoelasticity

Viscoelasticity is a nonlinear material behavior having both an elastic (recoverable)part of the deformation as well as a viscous (non-recoverable) part. Viscoelasticity model implemented in ANSYS is a generalized integration form of Maxwell model, in which the relaxation function is represented by a Prony series. ANSYS supports both hypo-viscoelastic and large-strain hyper-viscoelasticity .Viscoplasticity and Creep. ANSYS program has several options for modeling rate-dependent behavior of materials, including creep. Creep options include a variety of creep laws that are suitable for convention creep analyses. Anand's model (Anand, L., "Constitutive Equations for Hot-Working of Metals,"which was originally developed for high temperature metal forming processes such as rolling and deep drawing is also made available. Anand's model uses an internal scalar variable called the deformation resistance to represent the isotropic resistance to the inelastic flow of the material, and is thus able to model both hardening and softening behavior of materials.

(3-3-3)Viscoplasticity and creep

ANSYS program has several options for modeling rate-dependent behavior of materials, including creep. Creep options include a variety of creep laws that are suitable for convention creep analyses .Rate –dependent plasticity option is an over stress model and is recommended for analyzing impact loading problems Anand's model ,which was originally developed for high-temperature metal forming processes such as rolling and deep drawing is also made available . Anand's model uses an internal scalar variable called the deformation resistance to represent the isotropic resistance to the inelastic flow materials .The constitutive model has been widely used for other application ,such as analyses of solder joints in electronics packaging .

(3-4)Current study(Models constitute)

Developed mathematical model for biaxial creep behavior of pure low density polyethylene by ANSYS (10)code.

For predicting biaxial creep behavior must be knowledge the tensile behavior of matrix(low density polyethylene) experimentally for getting on tensile properties such as Young's modulus.

Numerical finite element models for pure low density polyethylene materials geometries have been created and executed. Both geometric (large deformation)and material nonlinearities (plasticity) were included in the models. Selected results have been presented including those for the two direction tension loading geometries.

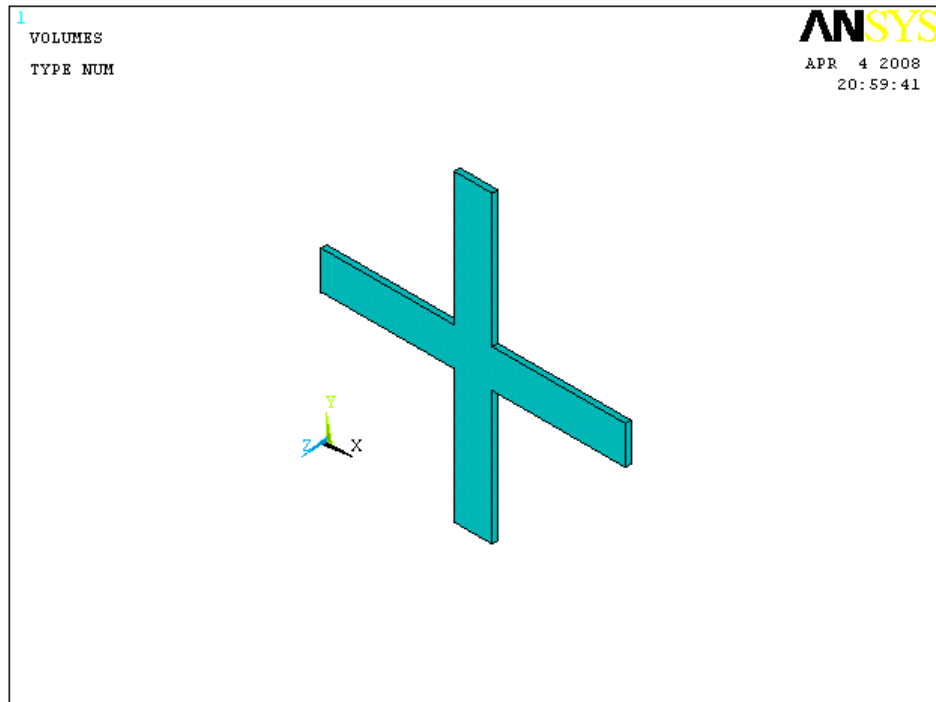
(3-5) Assumption

To simplify of the numerical simulation solution of the investigate biaxial creep of Pure low density polyethylene ,several assumption are used in this case in all steps that described above :

- 1- The clamping system is equal in all directions.
- 2-The load is apply by weight.
- 3- The friction cross the clamp and rolls is neglected.
- 4-The creep condition test at room temperature.
- 5- Coupling aging is not found at the same time the coupling aging is found in experimental process.
- 6-The load is distribution along line.
- 7- Applied strain is not found at z direction .
- 8-The model assume that the movement across the fix clamp is zero.

(3-6)Geometry sub -model

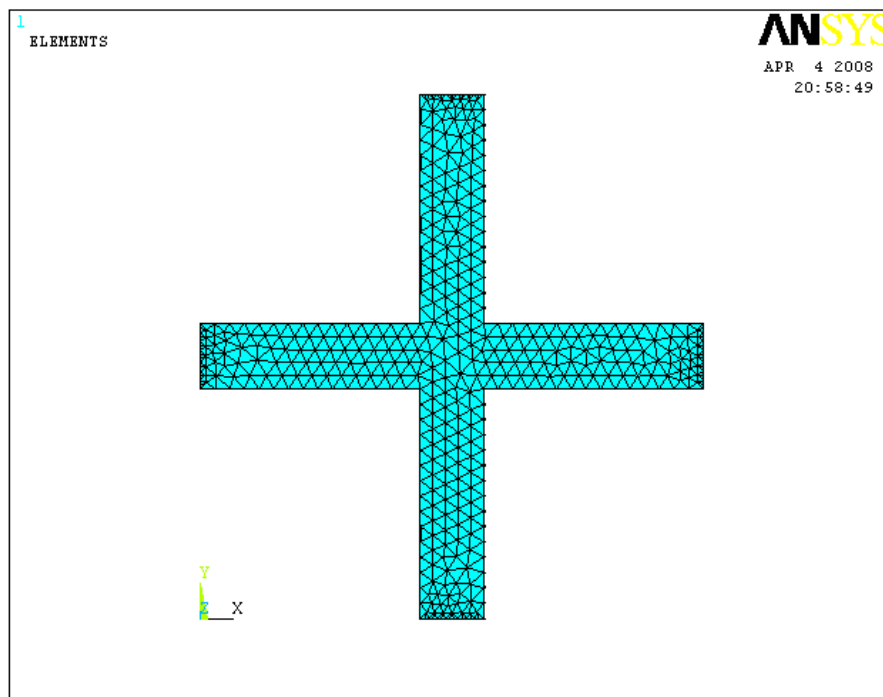
Three dimensional models were built by ANSYS (10)code as shown in Figure(3-2).



Figure(3-2) The geometry sub model of biaxial creep sample .

(3-7) Mesh generation

The models are meshed by using automatic mesh generation process and the element configuration and size are shown in Figure(3-3) to obtain the best result of the modeling process and the models to become more active to describe the real case of the analysis. Node structural solid element SOLID-Triangle 6 node are used in the modeling process. The element is defined by 2 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. Tension is applied on the loading area of the specimen along two perpendicular directions.



Figure(3-3) The FEM model of biaxial creep sample.

(3-8) Boundary conditions of applied load

The symmetry boundary conditions about X, Y, and Z-axes are imposed in the finite element model as shown in Figure (3-4). The dead weight applies loads as drawing force, on all test levels the loads are equal.

to 450N in each direction(X and y). A zero-displacement boundary condition was imposed at the clamp .

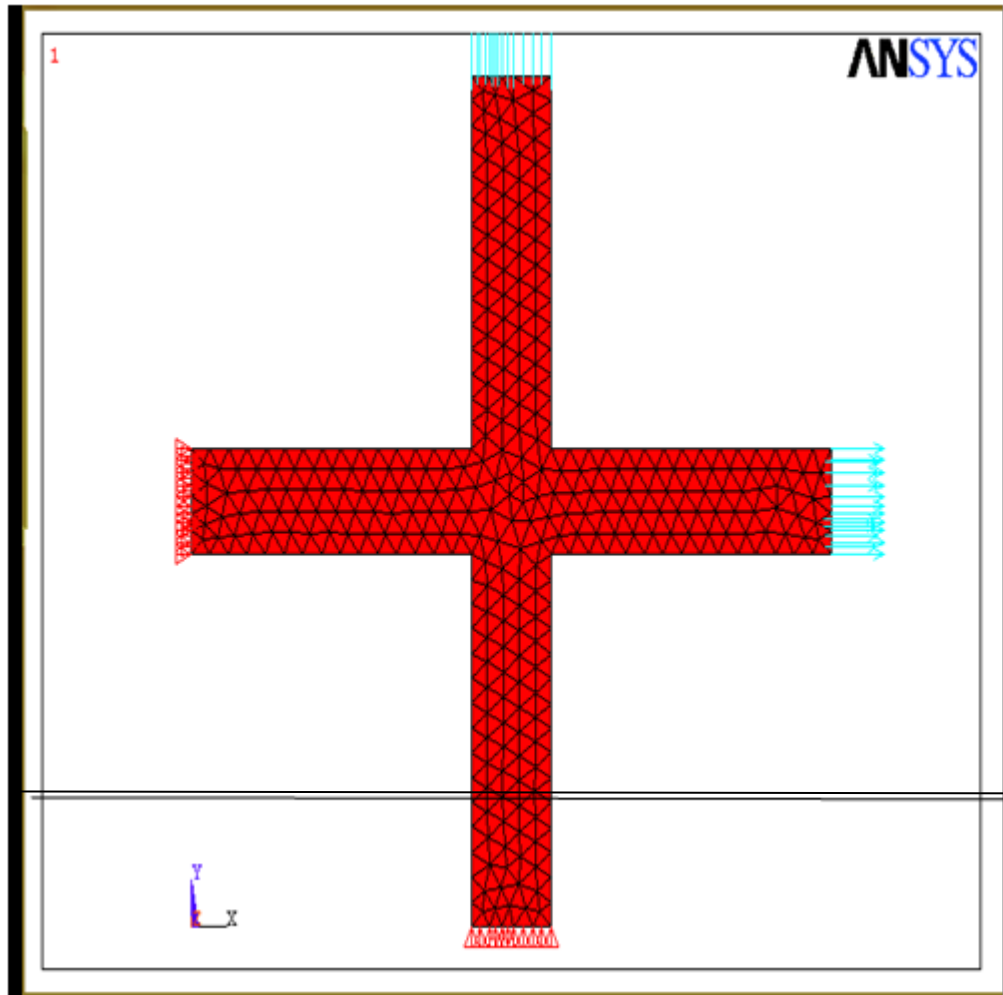


Figure (3-4) The Boundary conditions of applied load.

(3-9) Result output

The result is recorded for the strain with time for matrix(Pure low density polyethylene) and techniques as contour and curves at any point .As example contour result as shown in Figure (3-5).

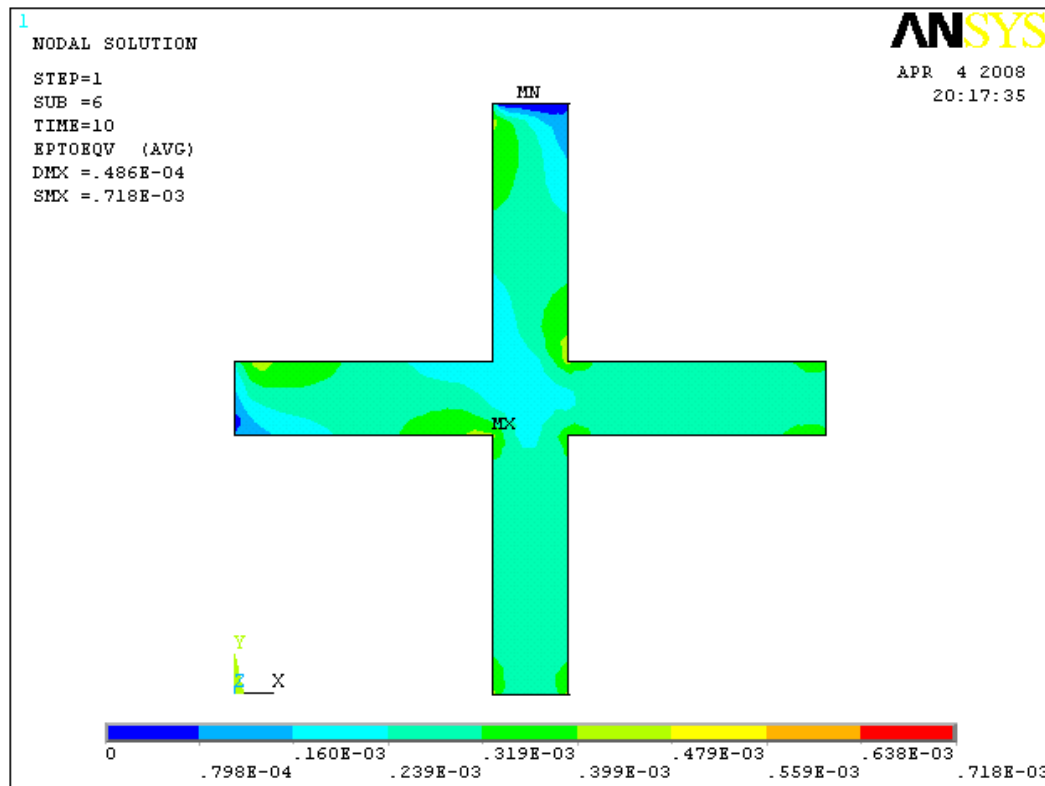


Figure (3-5) Contour result of pure low density polyethylene

(3-10) Experimental work

Planar biaxial mechanical testing is becoming an increasingly utilized technique to characterize the mechanical properties of native and engineered soft tissues. In spite of its growing use, biaxial testing methods have not been standardized and methodologies vary widely. Due to the complex mechanical behavior of soft tissues and the general difficulty in performing biaxial tests, experimental artifacts can easily be introduced. Critical factors affecting biaxial mechanical behavior are the boundary conditions used in testing, such as the uniformity of the loading along the specimen edge and the method of attachment (e.g. grip, sutures). Moreover, the choice of attachment method may depend on the anticipated degree of mechanical anisotropy and compliance. As it is not possible to directly evaluate the effects of different boundary conditions on specimen internal stress distributions. One technique for investigating material behavior under

complex stress states is to use in-plane biaxial loading. Using this approach, cruciform specimens fabricated from plate material. Thus, the technique has the advantage that the loading arrangement is relatively straightforward and uses NASA/TM—2003-2120902 equipment which has seen extensive development over the past thirty years. Also, the test method allows a wide range of biaxial stress states to be investigated with minimum complication from the load application viewpoint. For these reasons, the test method has been used to generate a sizable body of biaxial test data for both monolithic and composite materials. One difficulty facing these investigations has been the selection and/or development of the most suitable specimen design for the particular program. A major complication here is that use of the cruciform specimen configuration and associated gripping fixtures results in “coupling” between the two loading directions.

An experimental method for precisely measuring the strain-time and predicting the material anisotropic behavior under certain specialized service conditions has been developed using in-plane biaxial testing. The basic requirement for an ideal biaxial testing is that the stress and strain distribution in the gage area of the specimen (region of uniform thickness) should be homogeneous; it should be possible to determine properly the developed stress state i.e. the values of the stresses and the orientation of the principal stress directions; and the initial yielding should occur in the central gage area of the specimen.

It is observed in literature that all proposed specimen have been obtained empirically, by means of photo elastic tests . In the present study analysis is carried out on cruciform specimen by using the finite element technique and experimental practical analysis by using the biaxial creep test. Many trails have been carried out by changing the size, thickness of the gage area to get the optimum dimensions of the cruciform specimen.

(3-11) Current Study

(3-11-1)Bi-axial hybrid woven fabrics properties

Biaxial hybrid woven fabrics exhibit significant stiffness and strength in two orthogonal directions. In these materials. Anisotropic biaxial hybrid woven fabrics exhibit dissimilar stiffnesses in the two principal directions. They are used in anisotropic loading conditions, i.e. where there is a primary

and a secondary degree of loading/strain. while Isotropic biaxial woven fabrics exhibit very similar stiffnesses and strengths in the two orthogonal directions. They are used in isotropic loading conditions, i.e. where there is almost an equal degree of loading/strain in two orthogonal directions.

(3-11-2) Overview of biaxial test

(3-11-2-1) Biaxial testing machine

A biaxial stress system can be produced by a variety of methods ;the use of cruciform type specimens ,thin - walled tubes with applied torsion and axial load ,or thin walled tubes under internal or external pressure and axial load .The cruciform method has the disadvantages that the stresses are not known in the centre dished section though the strains can be measured. Buckling can be a problem with the other methods ,especially at high strains. The nearest practical case appears to be internal pressure plus axial load (tensile and compressive)to achieve the desired stress ratios and the servo - controlled rig was therefore designed on this basis .

(3-11-3) Method for biaxial tensile testing of woven fabrics composite materials

Biaxial tensile of coated and uncoated woven fabrics has been undertaken on airship materials, sails and fabric structures .However ,the majority of biaxial testing has been performed on other materials , particularly metals and engineering composites .Consequently , most commercial biaxial testers have been developed for this area .Small , low-load biaxial testing is not met by commercial machines or those available in research institutions. In conservation department , even access to uniaxial testing equipment is limited . Uniaxial rigs can be adapted for biaxial testing, offering a cost - effective way of using standard equipment .There is , however , a restriction on the loading conditions that can be applied . In many cases it is better to design a simpler , smaller instrument for the particular application. Existing biaxial testers most relevant to painting conservation research are those designed for tensile testing thin plates or sheet samples . The basic elements of a biaxial tensile tester are a system for inducing strain in two (usually orthogonal) axes , methods of measuring the

strains and the change in the loads in those axes , and a system for gripping the sample . Complex loading cycles are achieved by feeding the measured parameters routine (feed back control) .The systems used to induce biaxial in plane strains . And hence loads , fall into three main categories:

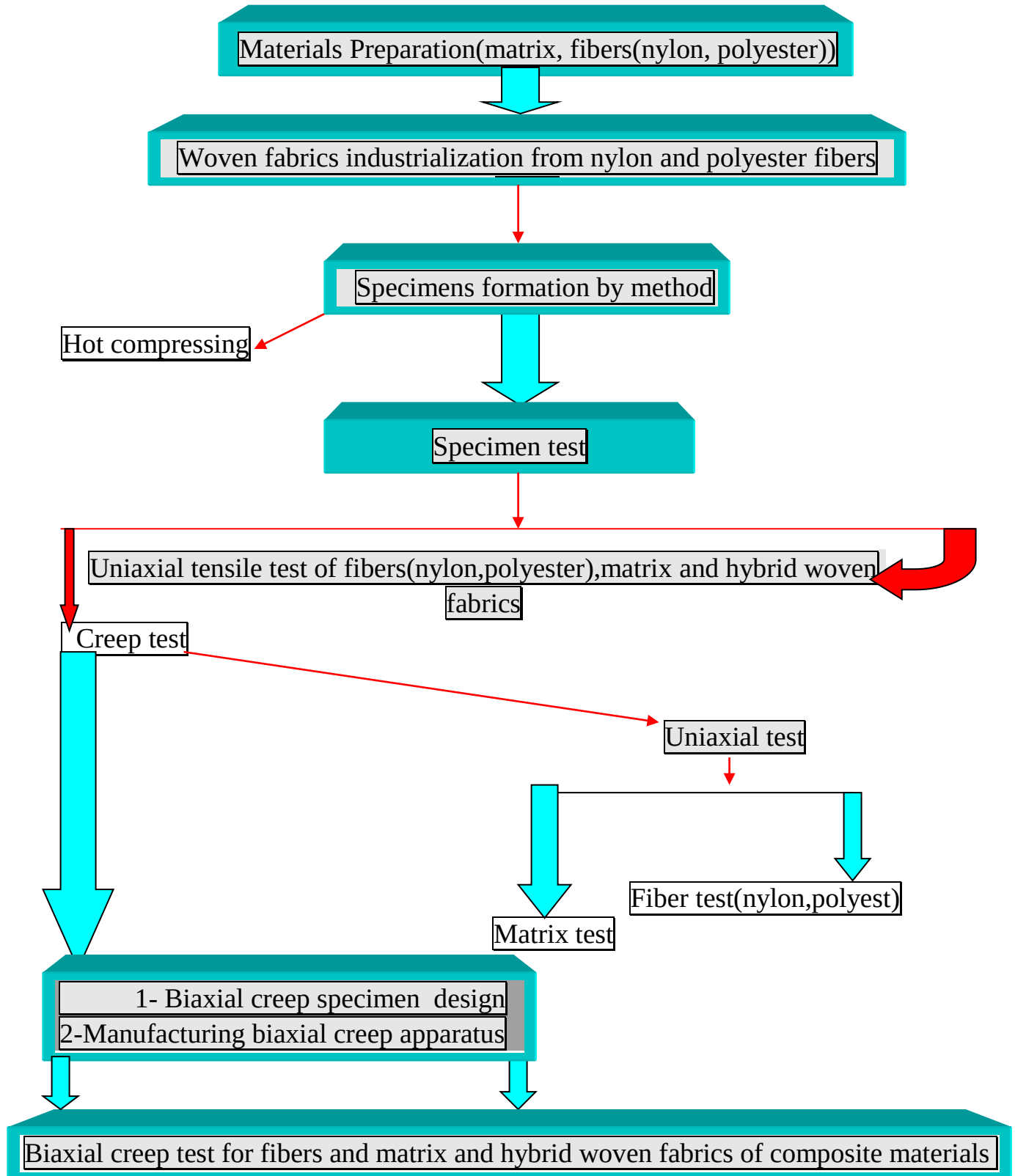
1- Dead weight system : In a dead weight configuration , affixed weight produces the load . Hayhurst developed such a system where the load is applied via wire ropes over pulleys to the clamping mechanism .Simple pulley designs suffer from friction in the bearings of the tension linkage. The use of a knife - edge lever system overcomes this problem ;it has the advantage of self - centering the sample . dead weight systems work well where a uniform load is applied over a long period of time , for example in creep tests , but it hard to implement feedback control .

2- Hydraulic system : These systems produce displacement of the grips via an hydraulic actuator (a piston moved by oil pressure) . To achieve displacement control ,they are fitted with feedback loops between the position and load sensors and the actuators . They are commonly used for testing at loads in the order of 200KN . Hence , the typical loads and order physical size of such testers are too large for application to conservation.

3- Screw driven systems :Screw driven systems produce displacement by either a manual or motor driven screw thread to which the grips are attached. These systems are most suited to low - speed loading conditions below 200KN and are easy to implement with feedback control.

Flow chart for investigation steps

The work stages for this research can be described as flow chart as shown hereinbelow:



(3-12) The used materials in current

for investigation steps.

Figure (3-6)
Describe
flow chart

The following input components were used in the current experiments:

(3-12-1)Nylon fibers

This textile is obtained from Babylon Tyre Company. The woven fabrics of this fiber are used as reinforced material in rubber industry , Table (3-1) describes the properties of these fibers .

Table(3-1) Nylon fiber properties.

Min=137	tension force
(8.2- 902)	At(45N)the extension
(0.204-0.216) gram/m	The weight to one meter
(0.51-0.57) mm	Diameter(D)
max 5%	exothermal shrinkage(150c°)
Max (4N)	exothermal shrinkage force(150)
(4-6)%	Dip pick up
min(80N)	Adhesion
Max(3%)	Humidity
(440-470)	Twist force

(3-12-2)Polyester fibers

This textile is obtained from Babylon Tyre Company.The woven fabrics of this fiber used as reinforcing material in rubber industry , Table (3-2) describes the properties of these fibers .

Table (3-2) Polyester fibers properties.

(290-330)	twist
Min (185N)	Cutting force
(3.5-5.5)%	Extension at (67N) is
(0.65)mm	Diameter average (D)
Max (3.5)%	exothermal shrinkage(177c°)
Weight upside	(N) diameter upside
(4.5-7.5)%	chemical treatment
(140)N	Adhesion

(3-12-3) Low density polyethylene sheet as matrix

Low density polyethylene sheet with specification (sepilene 22004 NA 463,P-0.922) was used as a matrix phase. The tensile test is carried out to determine its properties. The dog – bone specimen type was used in this test according to ASTM D30339. The properties are described in Table (3-3).

Table(3-3) properties of pure low density polyethylene.

Tem.- °C	E _m (MPa)	v _m	V _m %	Matrix Volume(mm) ³
23	68	0.4	90	337.5
75	11	0.45	90	337.5
110	0.68	0.49	90	337.5

(3-13) Specimen design and preparation

(3-13-1) Hybrid Woven fabrics preparation

Two methods used for hybrid woven fabrics preparation:

(3-13-1-1) Conventional weaving method

Woven fabrics are applied by a loom or weaving machine as described in Figure (3-7). The basic functions of a loom is (shedding, filling insertion, beat-up and warp-control (let-off, take-up)). Shedding is a function of weaving involving the lifting of harnesses containing warp ends in order to provide a shed opening for filling insertion and to control design. As described in Figure (3-9). There are three types of shedding as the following:

1-Cam Shedding

- Employs circular profiled cams to lift the harnesses
- Usually 6 - 8 harnesses
- High loom speeds
- Lifting plan relatively easy to change
- . - Plain, simple twill and satin weaves

2- Dobby Shedding

- Employs a chain of wooden bars with pegs inserted or plastic paper with holes inserted or computer controls
- Usually 8 - 24 harnesses
- More complex twill and satin weaves
- Small geometric figures and spot weaves
- Pattern stripes
- Slower loom speeds than cam shedding
- Lifting plan more difficult to change

3- Jacquard Shedding

- Employs cardboard cards with holes inserted, plastic paper with holes, or computer controls

- Individual warp ends or groups of warp ends are lifted without the use of harnesses
- Design capability is virtually unlimited
- Can produce very large design repeats
- Slowest loom speeds
- More expensive fabrics



Figure(3-7) The weaving machine .

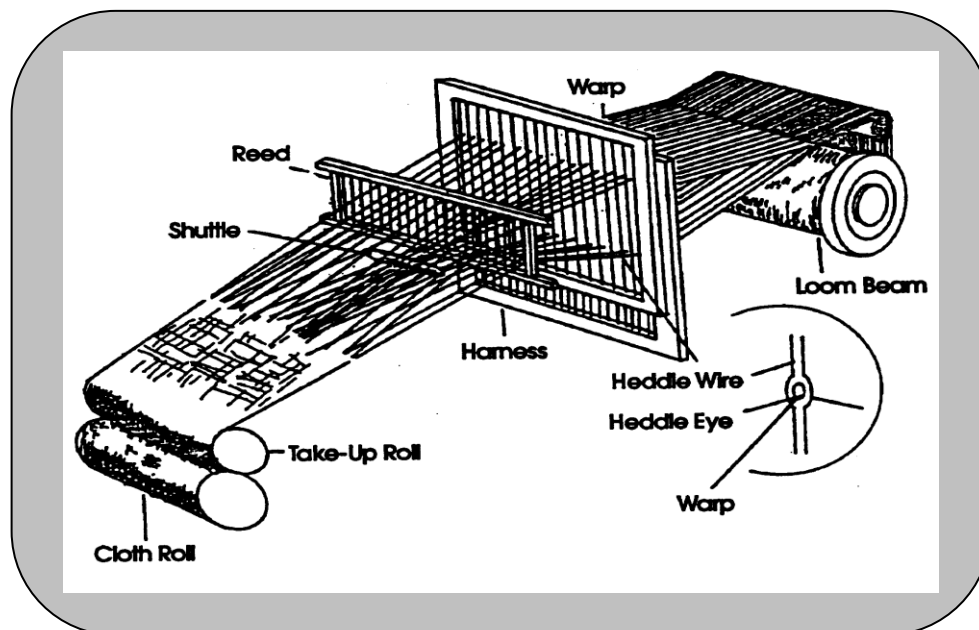
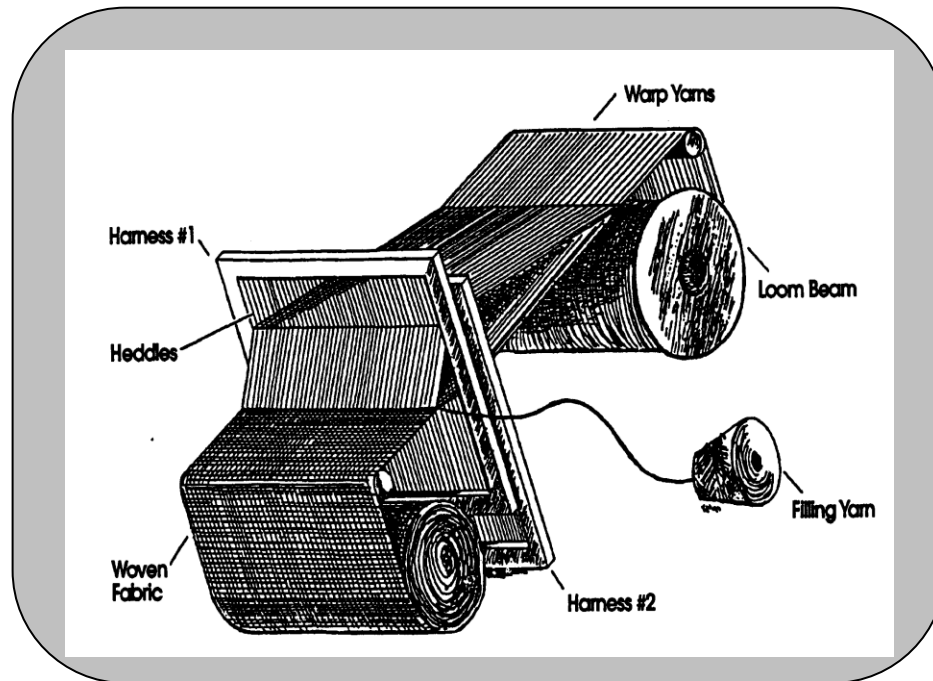


Figure (3-8). The front view of the prototype hybrid machine prior to the start of this project.



Figure(3-9) Describe the Shedding formation.

(3-13-1-2) Manual method

Wood frame is used for preparation plain weave hybrid woven fabrics from nylon and polyester fibers .This required a wood frame which was made in square shape and fixed on the outside dimensions of dies as shown in Figure (3-10);the nails were fixed on the wood frame in equal space to fix the fibers .

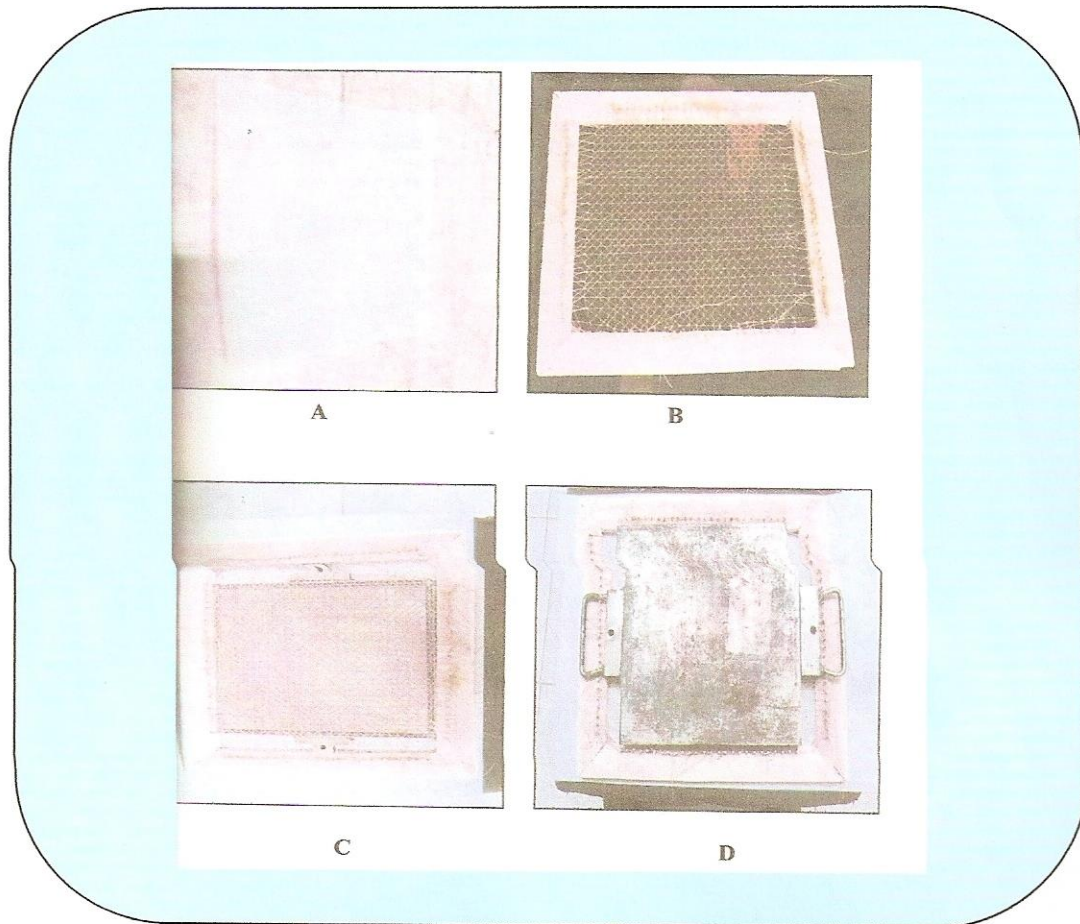
(3-14) Manufacturing Hybrid woven fabrics composite materials

Used materials:

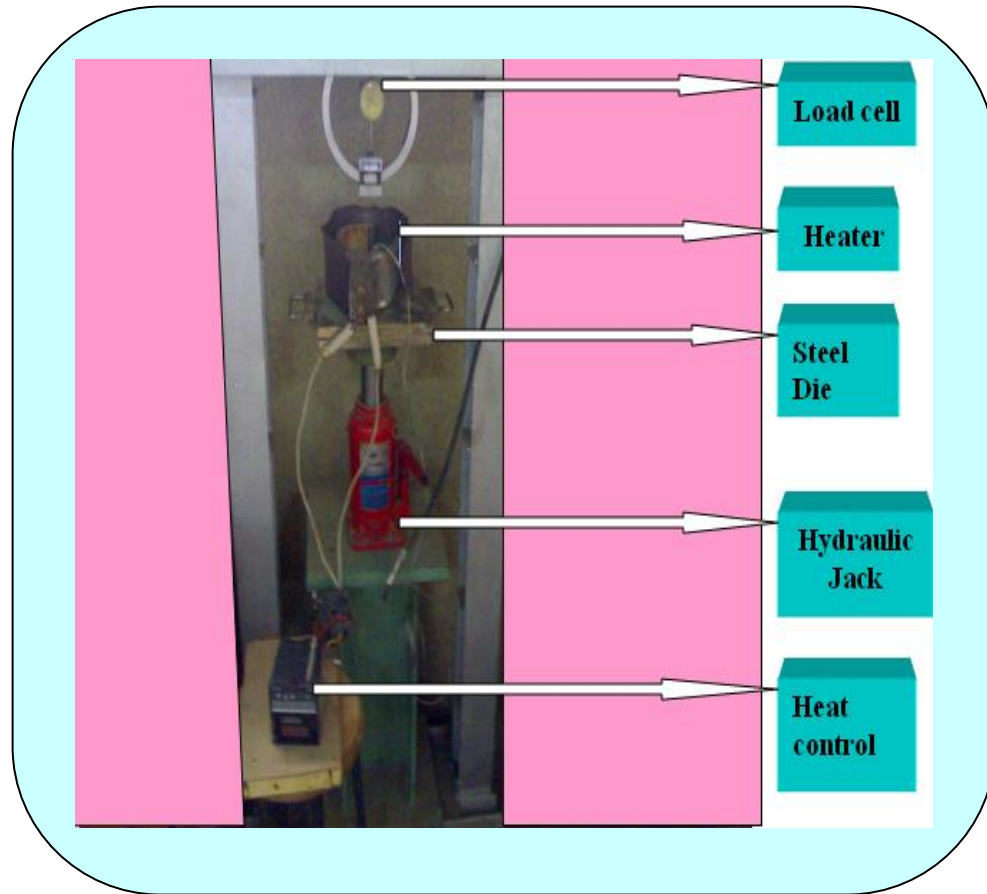
1-Low density polyethylene.

2-Hybrid Woven fabrics type (1) weave as plain from nylon and polyester fibers

The specimens Formation from the hereinbefore materials achieved by put the hybrid woven fabrics between two sheet from polyethylene and put them in die from carbon steel after that and in the same time the mold is heating to temperature (180°C).The closed die remained inside the heater for (1 hours)under pressure value equals (0.5)MPa .After cooled the die with water the die was opened and then the composite sheet was removed. The Figures(3-10)and (3-11) describe the Hot – compression molding method.



Figure(3-10)
describe the :A-Pure low density polyethylene.
B-Wood frame.
C-Wood frame fixed on steel dies.
D-Closed die.



Figure(3-11) The press .

(3-15)Tensile test

Sheet from hybrid woven fabrics of composite materials is manufactured to uniaxial tensile test . Uniaxial tensile test is used for getting hybrid woven fabrics properties in (x,y) directions. Specimen is cut in warp direction and cut another specimen in fill direction. The testing procedure and the specifications were selected according to ASTM

standard(D412-88).The apparatus is specifications of the tensile testing were; initial speed =5 mm/minute with stress range 50 MPa and strain range 100% , secondary speed = 10 mm/minute, and strain range 100% .

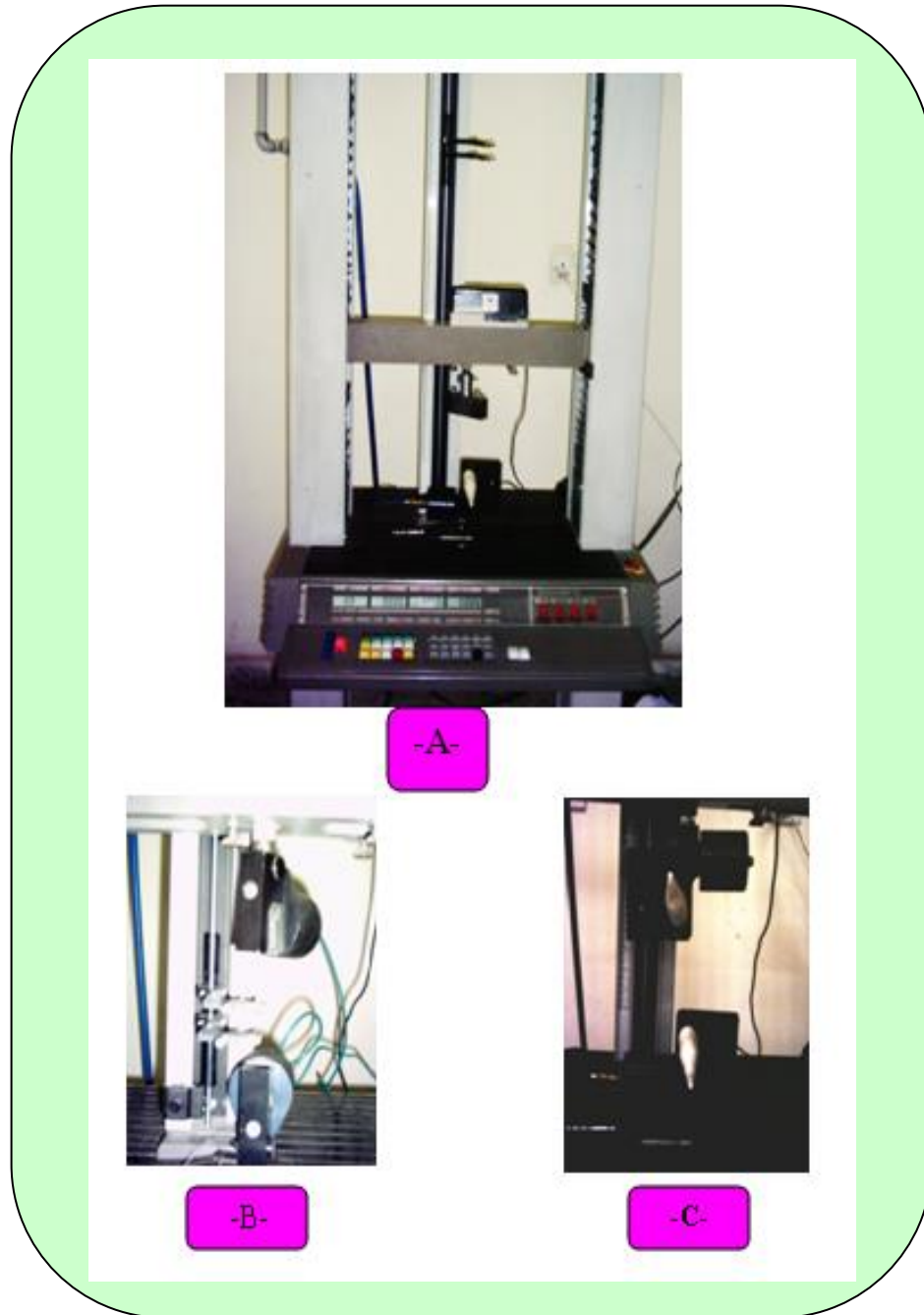


Figure (3-12): (A)- Tensometer(B)-Jaw for tensile(C)- Jaw for force textile

(3-16) Biaxial Specimen Design

The first step in the design process was to select overall specimen dimensions. Consideration was given here to a number of test system features and characteristics including:

- 1-Load capacity of specimen grips, load cells, and load frame.
- 2- Size envelope available within the load frame for specimen installation and gripping.
- 3- Gripping arrangement.
- 4-Specimen gage area needed to meet strain measurement and other instrumentation needs.

(3-17) Optimization Method

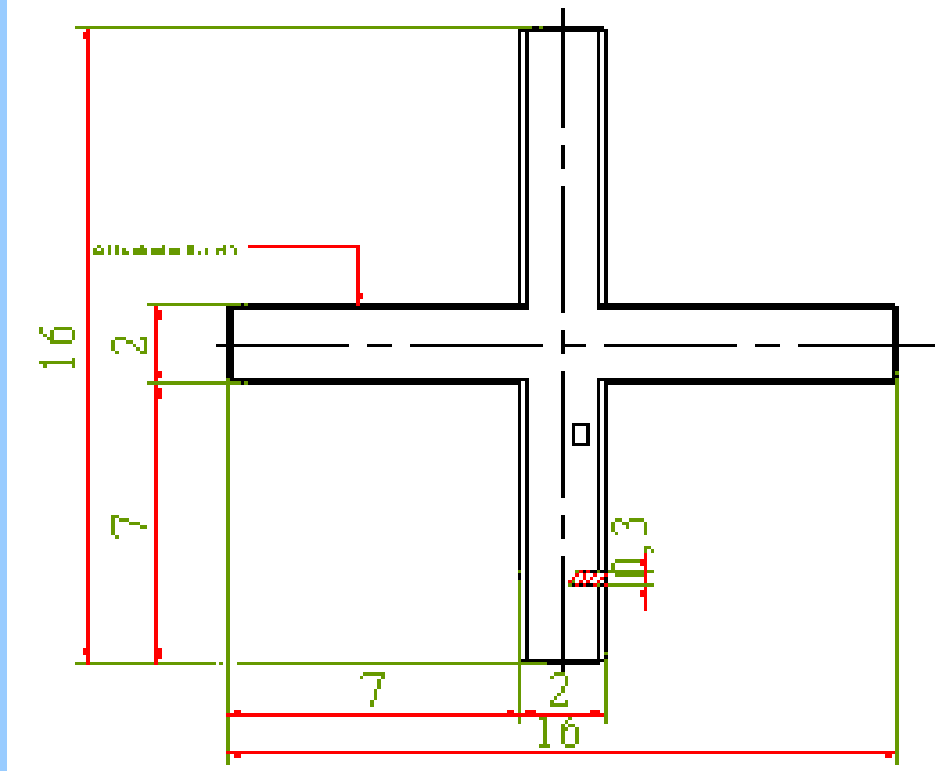
The optimization method used in achieving these goals focused on The distribution of stress within the gage area should be relatively uniform, the optimization process simply involved making systematic changes to the specimen design and repeating stress analysis as necessary until the design requirements had been met.

(3-18) Specimen Sizes

Cruciform shaped test specimens, similar to those employed in other disciplines were used in order to avoid problems reported in earlier work with square or rectangular specimens. The cruciform shape prevents the distortion of the test specimen at higher strain levels and avoids the problem associated with on-uniform stress conditions.

The central biaxial test specimen size was(20*20mm) square, with an overall cruciform specimen dimensions of some 160×160 mm, . The sizes of the biaxial woven fabrics test specimens were chosen in order to be

representative of the macro-structure of the woven fabrics . Similar considerations to those adopted for the choice of uniaxial test specimens were chosen. Thus for the woven fabrics tested. This resulted in overall cruciform test specimen dimensions of some 160 * 160 mm, with central areas of 20*20 mm square and thickness 3mm, as shown in Figure (3-13).



Note: all dimensions of cm except the thickness of mm

Figure (3-13) Test Specimen Shape and Size.

(3-19) Experimental Set-up

The results presented in this study were obtained by tests performed at different levels of structure, from single fibers to the specimen of woven fabrics of composites materials .

(3-19-1) Uniaxial creep behavior of polyester and nylon fibers

The fibers studied here are polyester and nylon 66 of specification as Tabled in Table(3-1, 3-2) . The fibers were clamped in special grips and loaded on a standard uniaxial creep test machine as shown in Figure (3-14) to obtain strain-time plots. The creep test perform at room temperature and at different dead weight (5-15-45) Kg.



Figure(3-14) Uniaxial creep apparatus.

(3-19-2) Biaxial Testing Apparatus

The biaxial tester apparatus manufactured and designed depending on the literature survey from different sides initiating from biaxial specimens dimensions and the applied load to reach comprehensive knowing for study requirements creep phenomena .

This biaxial tester as described in the Figure (3-15) is a tensile machine equipped with four grips for clamping the cruciform specimen, The clamping system consisting of the two grips which are freely moveable through constant pathway on each axis(x and y)and the others are constants . The gripping area provided for each specimen grip was (8*2.5*2.5)cm. which meets the size requirements and load transfer requirements of the hydraulic grips available for this work. After installation, cruciform specimen of hybrid woven fabrics composite materials are stretched by four wires cross two pulleys in both lengthwise and width wise directions simultaneously over time periods. The sustained loads in the two orthogonal directions, were applied in an isotropic manner, i.e. the loads in both directions were equal. This is not a requirement of the test procedure, anisotropic loads may be applied. However, no matter what loads are applied they must be applied in both directions at the same time. The sustained loads were thus applied simultaneously at the beginning of the test. Subsequently they were removed at the end of the test.

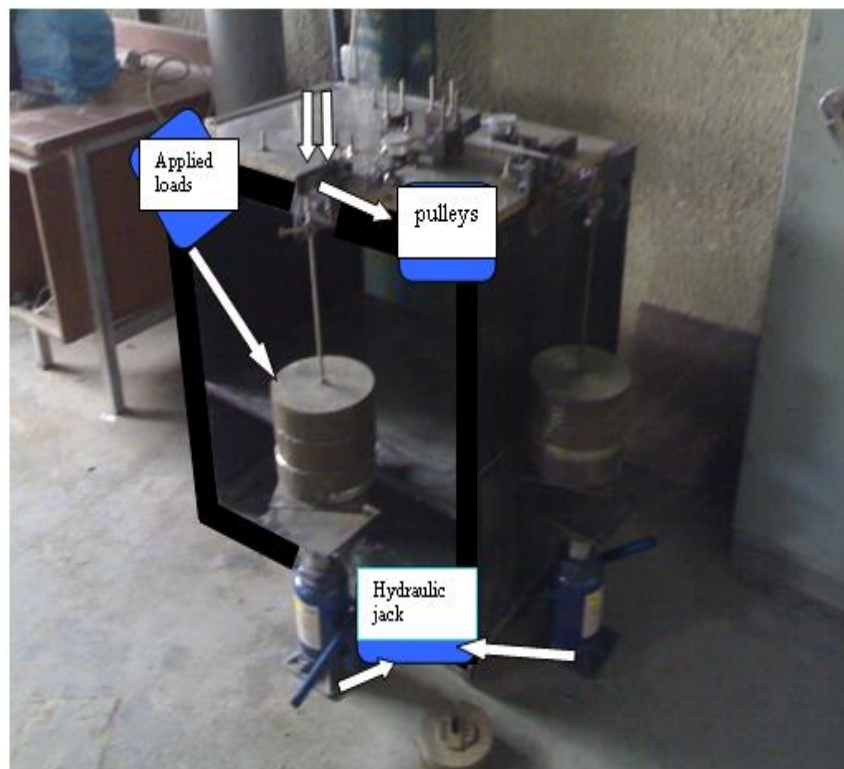
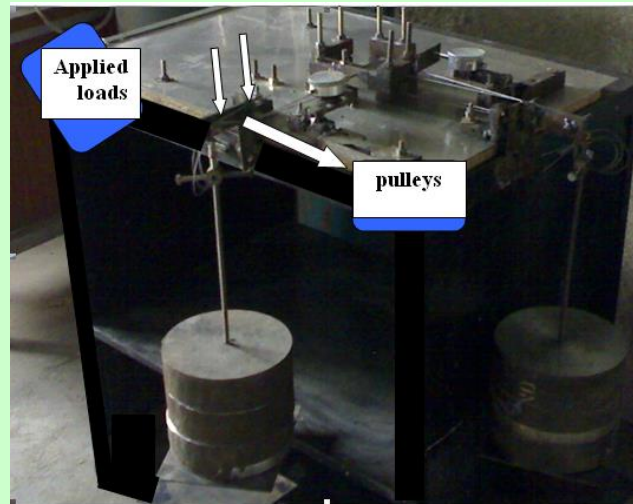
Therefore in this research, it was desirable to use a biaxial testing apparatus that would be able to stretch a sample in both directions and hold the sample stretched for a period of time. For this purpose, a biaxial tester, designed for testing the biaxial creep of woven fabric composite materials samples, was borrowed from Fabrics and Fibers. The biaxial tester, shown in Figure (3-15),. All four corners of the sample are slit diagonally one inch toward the center in order to alleviate any diagonal bias during the test.

The biaxial tester of cruciform specimens uses two load cells (A and B) to measure the load values in the warp (A) and fill (B) directions and two dial displacement gauges with accuracy 0.01 (mm) to measure the

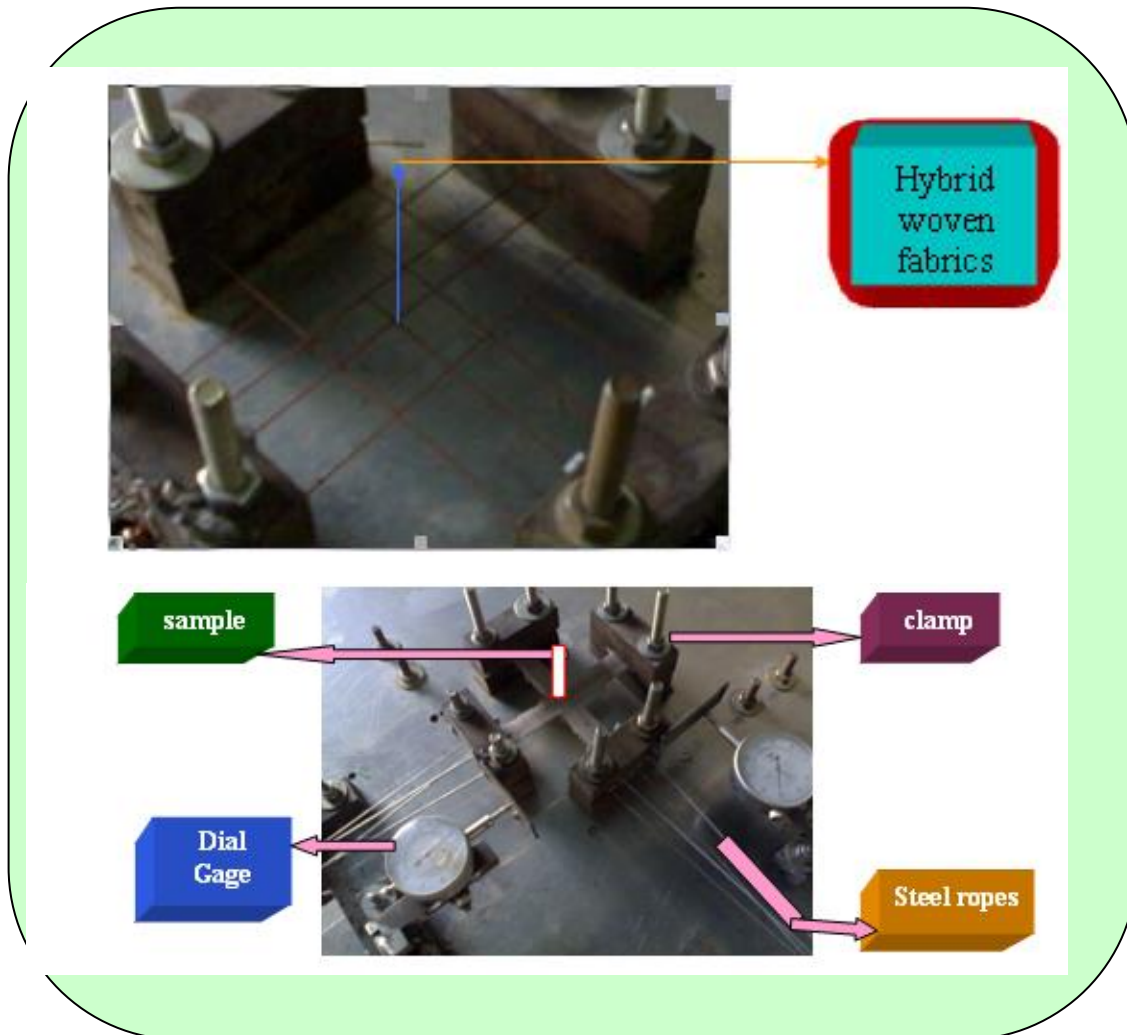
elongation along specimen in orthogonal directions. Gauge area only is mannequin to biaxial stress state. Method is used in this study to measure the elongation in gauge area approximately by division the total elongation on the eight areas each area equal to the gauge area by assume the cruciform specimen similar to the rectangular specimen and stresses distribution is uniform .The load is applied via wire ropes over pulleys to the clamping mechanism. Since this tester was designed specifically for biaxial creep testing which requires the sample to be held at a constant elongation for a period of time, the dial displacement gauges are simple and the deformation or stretching of the sample can be done manually. In order to collect the greatest amount of information during testing, the biaxial creep behavior of materials described by graph the strain in both axes (X,Y) versus time .

The apparatus can be used to investigate the constitutive behaviour, anisotropy and limits of deformation of the material.

Rigid clamping of the samples is of the first importance for the test. It can be ensured by making epoxy tabs , impregnating the fabric in the gripping sites.



Figure(3-15) Biaxial creep apparatus.



Figure(3-16) Clamped system .

the fabric behaviour in biaxial tester is determined by a linkage between the yarns or fibres. The theory of the test is well-developed for woven fabrics, where interference between warp and weft is determined by the crimp of the yarns .

The strong influence of boundary conditions in biaxial tests were recently underscored by waldman,et.al where in substantially different experimental results were obtained using different sample gripping methods

on the same specimens for this cause the biaxial creep apparatus parts details are describing in the appendix .

Chapter Four

Results and Discussion

(4-1) Introduction

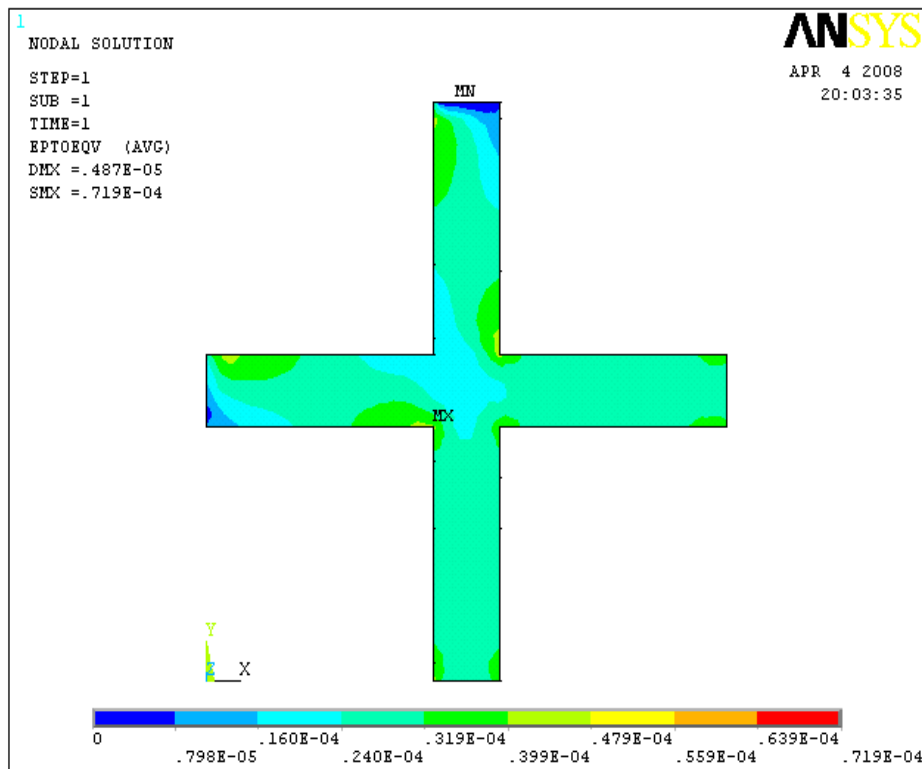
This chapter includes the experimental results and discussion of the effect of hybrid fibers in composite materials on creep behavior in different direction and it also discusses experimental and numerical results of biaxial creep of pure low density polyethylene as matrix at isotropic conditions from loading, temperature and geometry .

(4-2) Results and discussion of numerical analysis

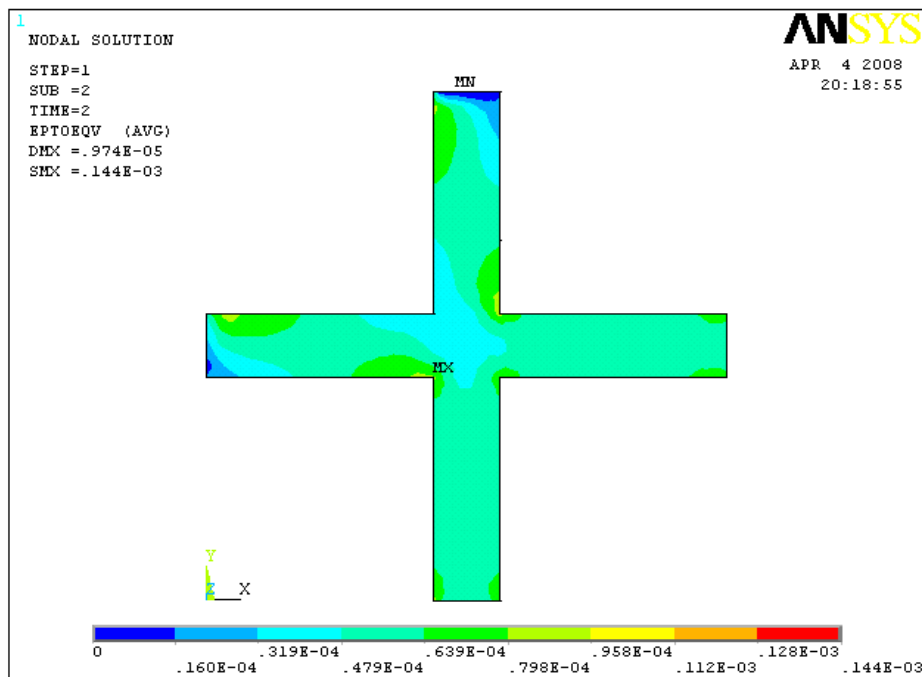
From observing the numerical result of biaxial creep analysis which is carried out by ANSYS (10)code for pure low density polyethylene in Figures (4-1,4-2,4-3,4-4,4-5,4-6) respectively notice that these results represent the contour result of creep behavior in (x,y)direction under applied load (450 N) at room temperature. From observation of the result, it can be concluded that the strain with time behavior in (x)direction symmetry with the (y)direction for creep , and increase from beginning of the creep test to the (10)hours periods as shown in contours Figures(4-1 to 4-6)respectively. The FEA of stress distribution in the biaxial specimen for of pure low density Polyethylene is described in Figures(4-9,4-10).

The symmetry of the results in (x,y)directions is due to the isotropic behavior properties of pure low density polyethylene . These results show that the model is useful to predict the change in the creep behavior with direction, These results are compared with the experimental results for pure low density polyethylene as shown in Figure (4-11,4-12)also these results are examined by the values of the strain

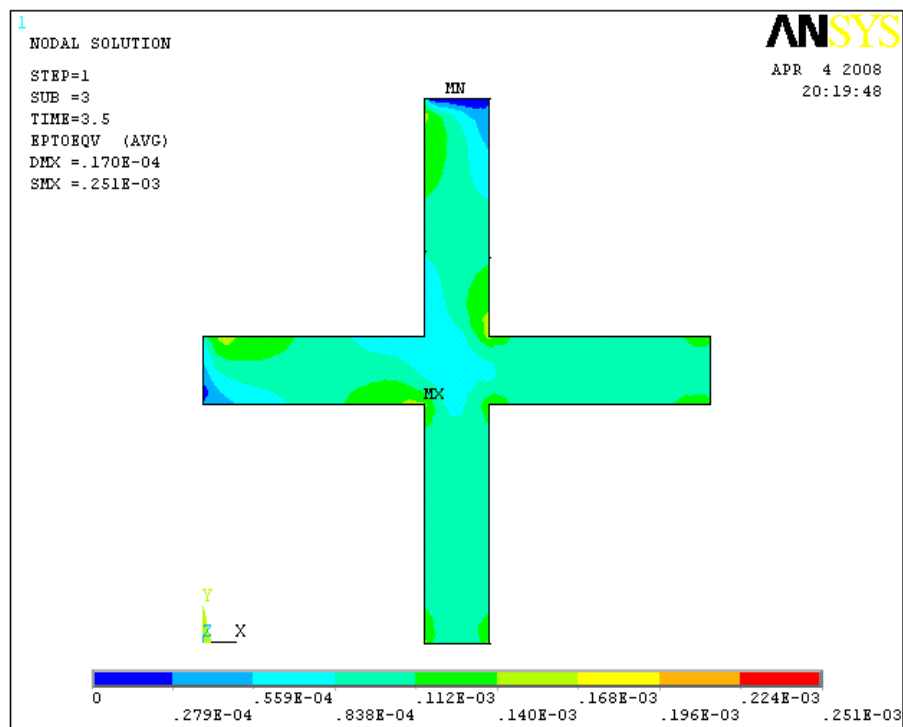
deformation in (x,y)directions as shown in Figure(4-11,4-12).



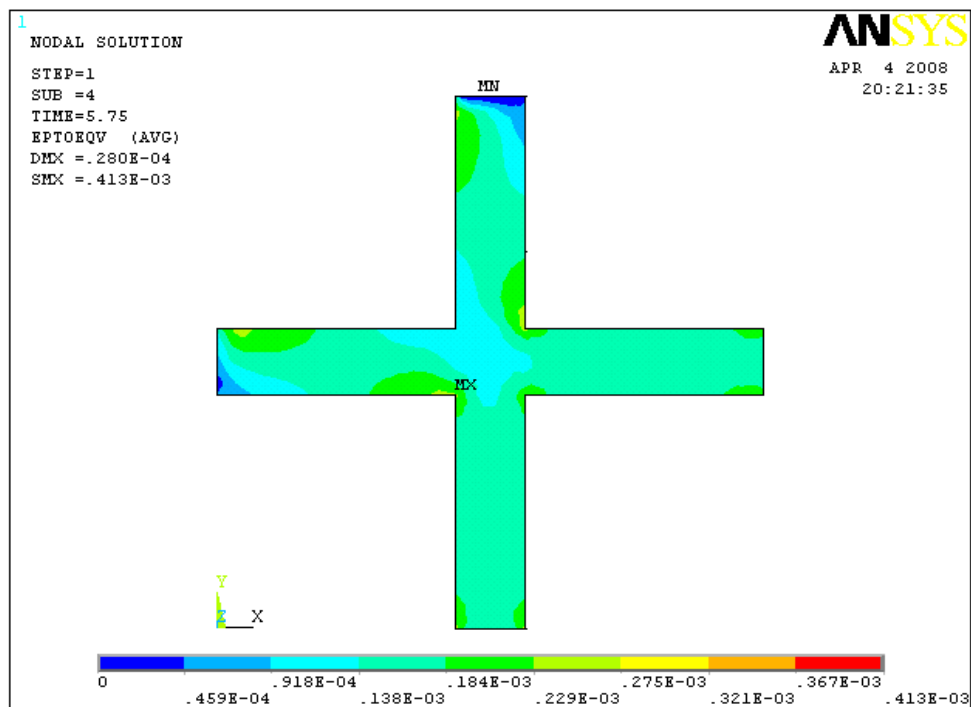
Figure(4-1) Numerical results for biaxial creep of pure low density polyethylene.



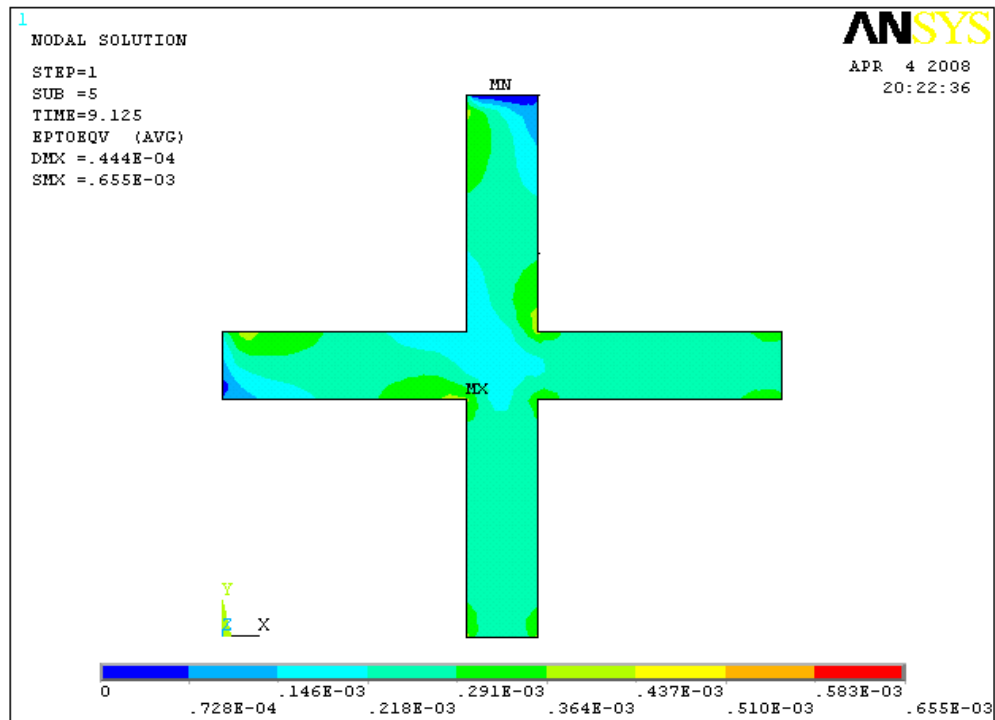
Figure(4-2) Numerical results for biaxial creep of pure low density polyethylene.



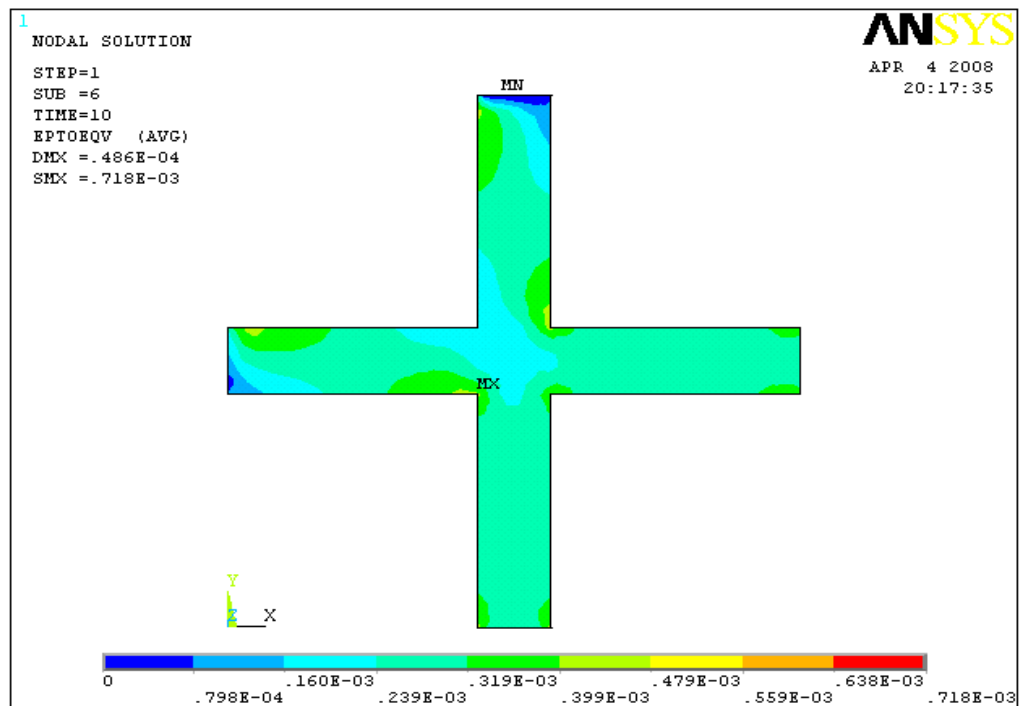
Figure(4-3) Numerical results for biaxial creep of pure low density polyethylene.



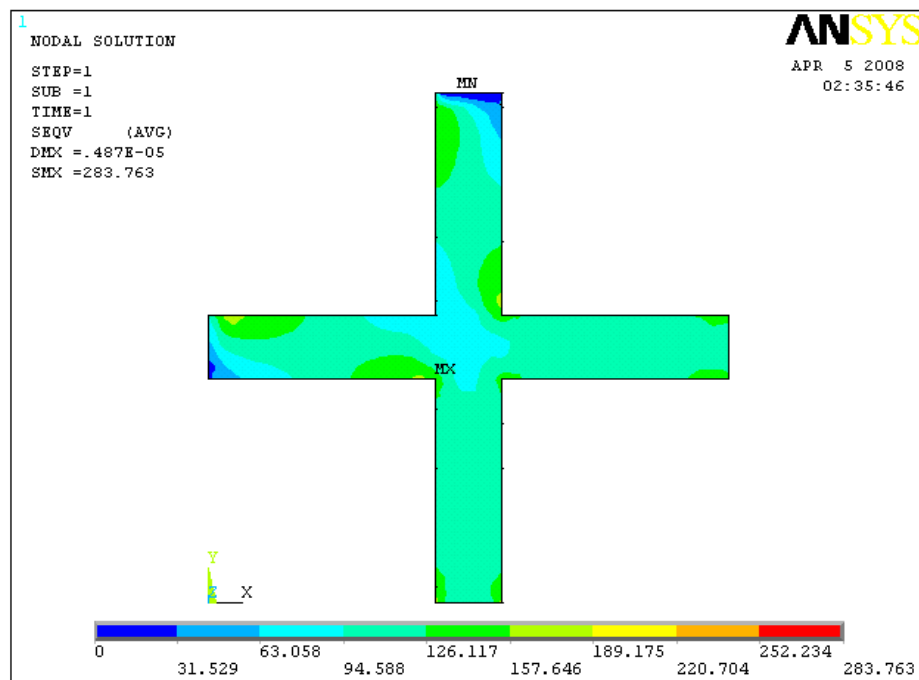
Figure(4-4) Numerical results for biaxial creep of pure low density polyethylene.



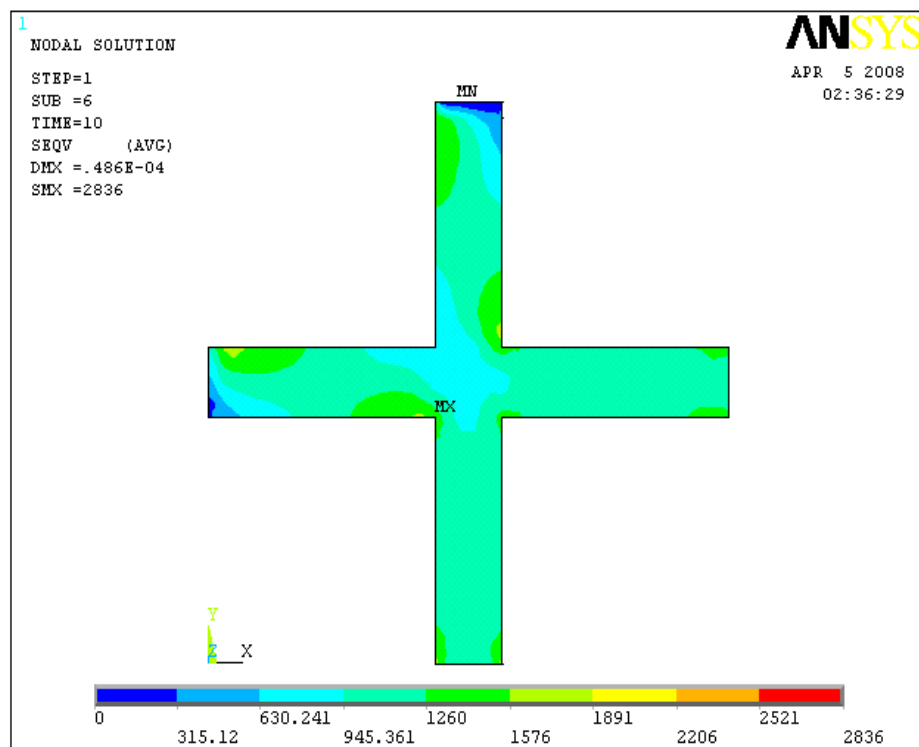
Figure(4-5) Numerical results for biaxial creep of pure low density polyethylene.



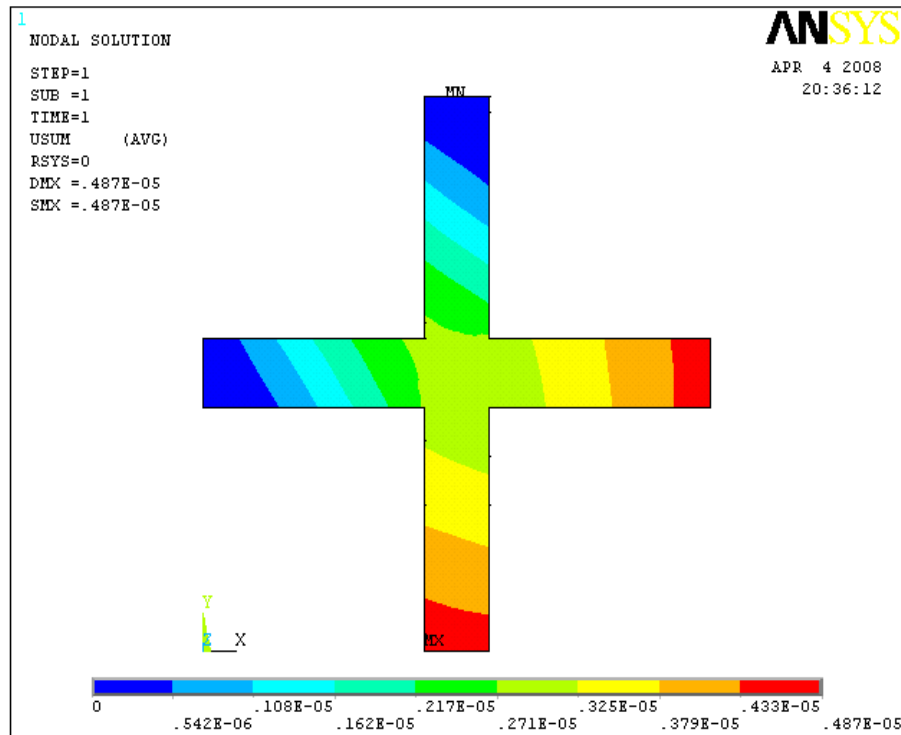
Figure(4-6) Numerical results for biaxial creep of pure low density polyethylene.



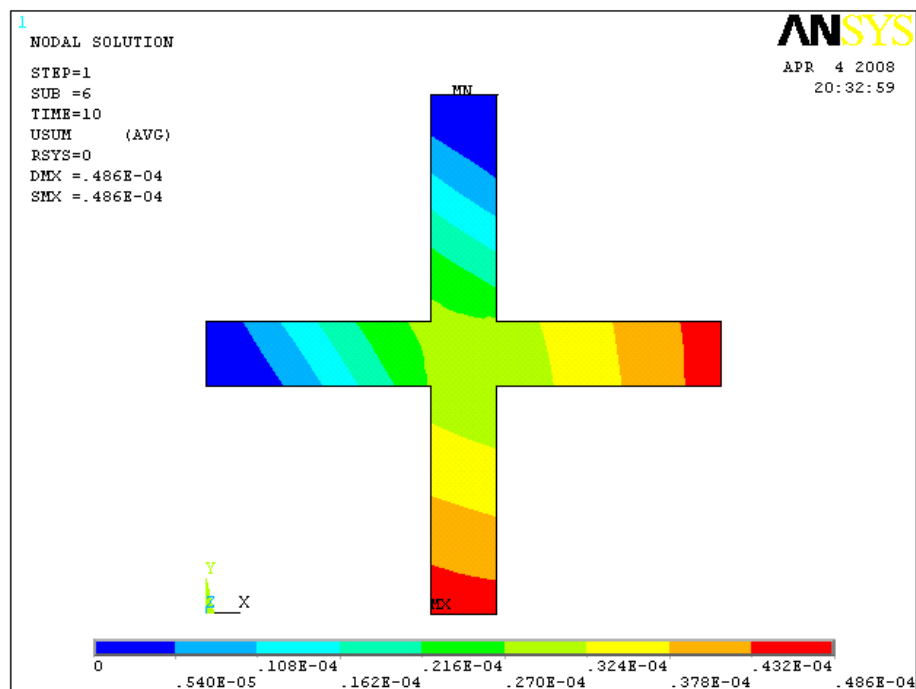
Figure(4-7) Numerical result for biaxial displacement of pure low density polyethylene.



Figure(4-8) Numerical result for biaxial displacement of pure low density Polyethylene.



Figure(4-9) FEA of stress distribution in the biaxial specimen of pure low density Polyethylene.



Figure(4-10) FEA of stress distribution in the biaxial specimen of pure low density Polyethylene.

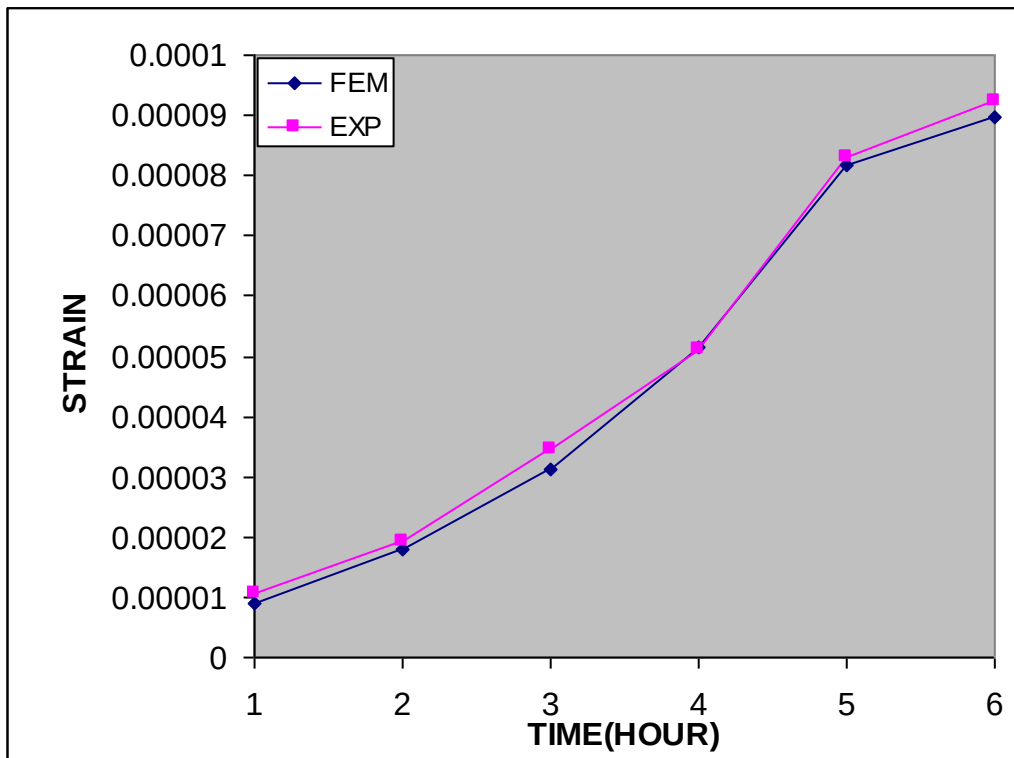


Figure (4-11)Biaxial creep (in Y direction) of pure polyethylene low density.

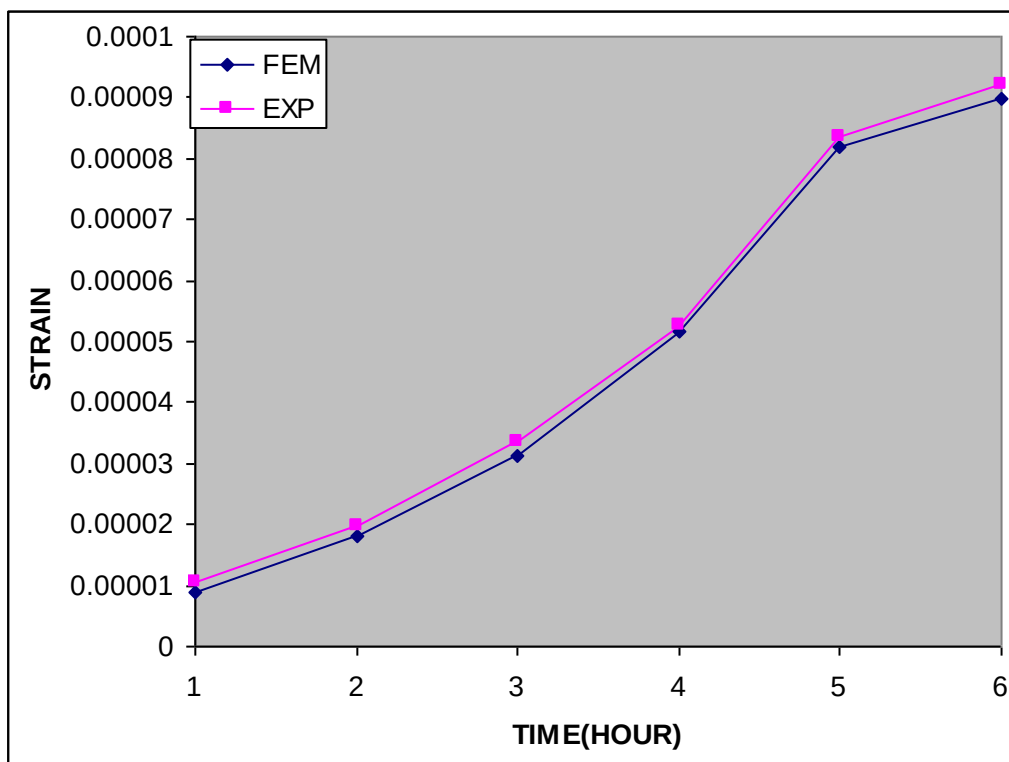


Figure (4-12) Biaxial creep(in X direction) curves of pure low density polyethylene.

(4-3) Results and discussion of experimental results

(4-3-1) Results and discussion of biaxial creep pure low density polyethylene

From the results observed in the experimental creep result of pure low density polyethylene samples which are conducted under load value (450N) in(x,y)direction and for ten hours note increasing of creep strain with increasing time in the same behavior and the same value is due to equal of properties with direction because of isotropic of these materials. This test is carried out to study the behavior of creep in isotropic materials .Pure low density polyethylene represents the matrix materials. Also this test considers a verification method to a certain the accuracy of the creep test in two directions.

The knowledge of the strain values in two directions of pure low density polyethylene is also an important criteria to evaluate the effect of woven fabrics strengthening on the creep behavior in woven fabric composite materials specially in current case where different types of fiber are used in woven fabric .

(4-3-2) Results and discussion of uniaxial tensile of fiber and composite materials

The tensile test is one of the important test to measure the ultimate tensile strength of polyester and nylon fiber to predict the effect of the yield strength of every type of these fibers on the creep because behavior of the increasing of the failure strength leads to the increasing of the creep resistance.

These tests are repeated on the samples woven fabrics composites to evaluate the tensile strength of the composite materials with the direction of fiber and this result is shown in Figure(4-13).

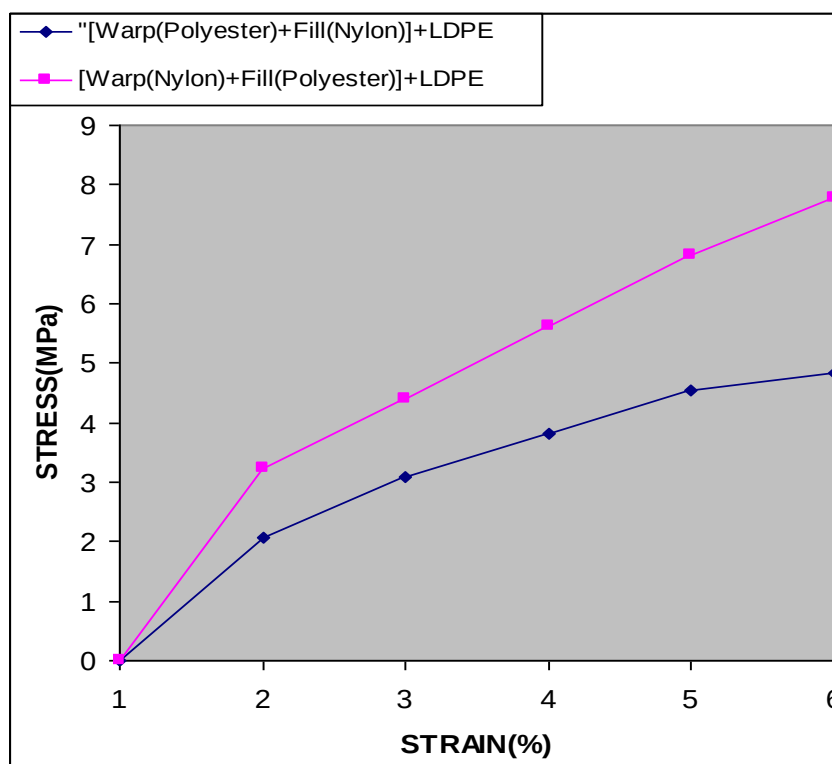


Figure (4-13) Tensile strength of composite material from(Hybrid woven fabrics (Nylon, Polyester) fibers and pure low density polyethylene(LDPE).

From observing the results of the stress-strain curve of these sample with warp(Nylon)+fill(Polyester),with warp(Polyester)+fill(Nylon) it can be noted that the increasing of the stress with increasing strain and observe difference in the value of the stress of polyester fiber compared with nylon fiber and that is because of increasing of polyester strength .

(4-4) Result and discussion of uniaxial and biaxial creep test of fibers and composite materials

From Figures (4-14,4-15,4-16,4-17)which represent experimental results under different loads and for the different time periods, note the increasing of the creep strain with time for every types of fibers (polyester and nylon)because of undulation of fiber yarns in the fabric as first stage with increasing time the fibers begin of breakage in the fabric that lead to increase of strain with time ,But we observe the difference in

the value of the strain for every each one of fiber where seem the polyester strain value is lower than from nylon fiber strain and that belongs that to rising the polyester strength also that difference is caused by the morphology structure and method of manufacture. Generally, as the degree of stretch is increased, which yields higher crystallinity and greater molecular orientation, so are the properties, e.g., tensile strength and initial Young's modulus. At the same time elongation normally decreases.

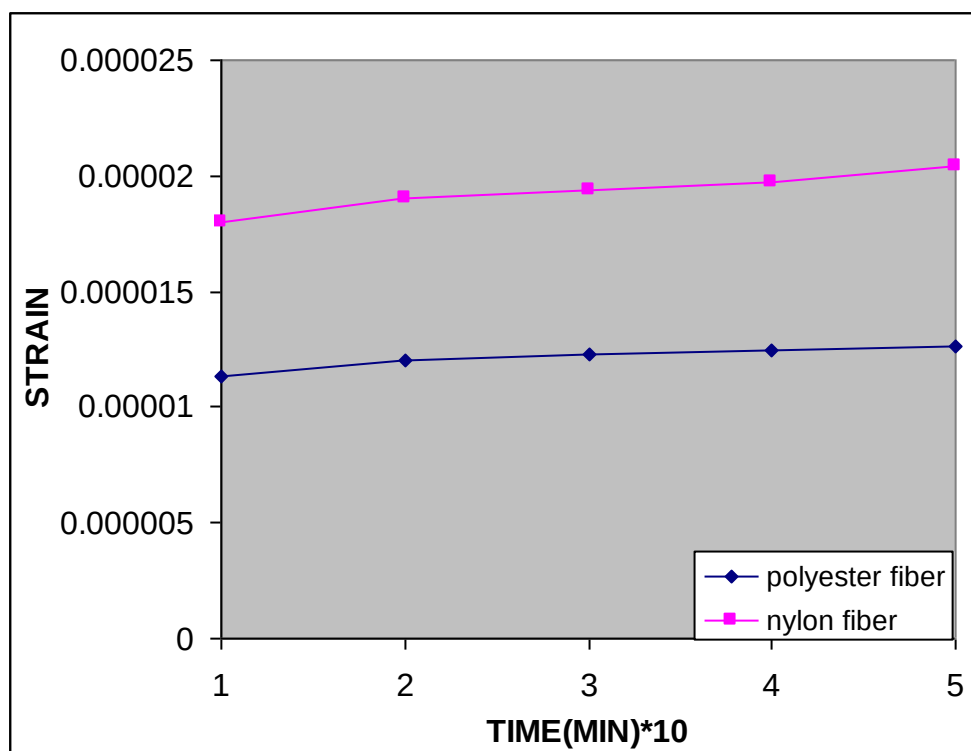


Figure (4-14) Uniaxial creep curve of fibers under (50N).

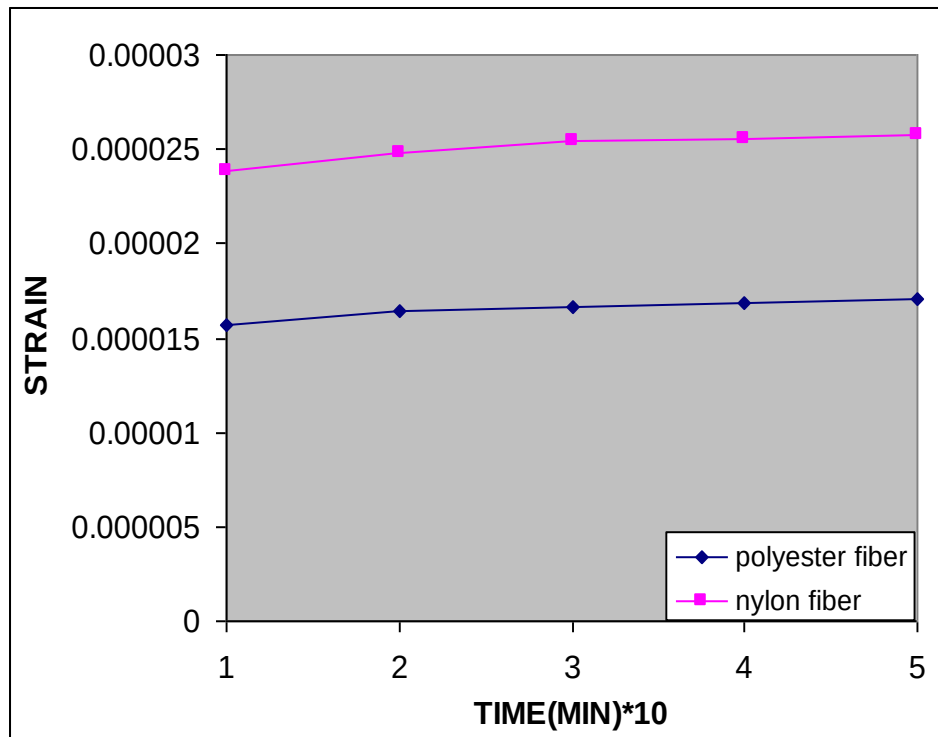


Figure (6-15) Biaxial creep of fibers under (150N).

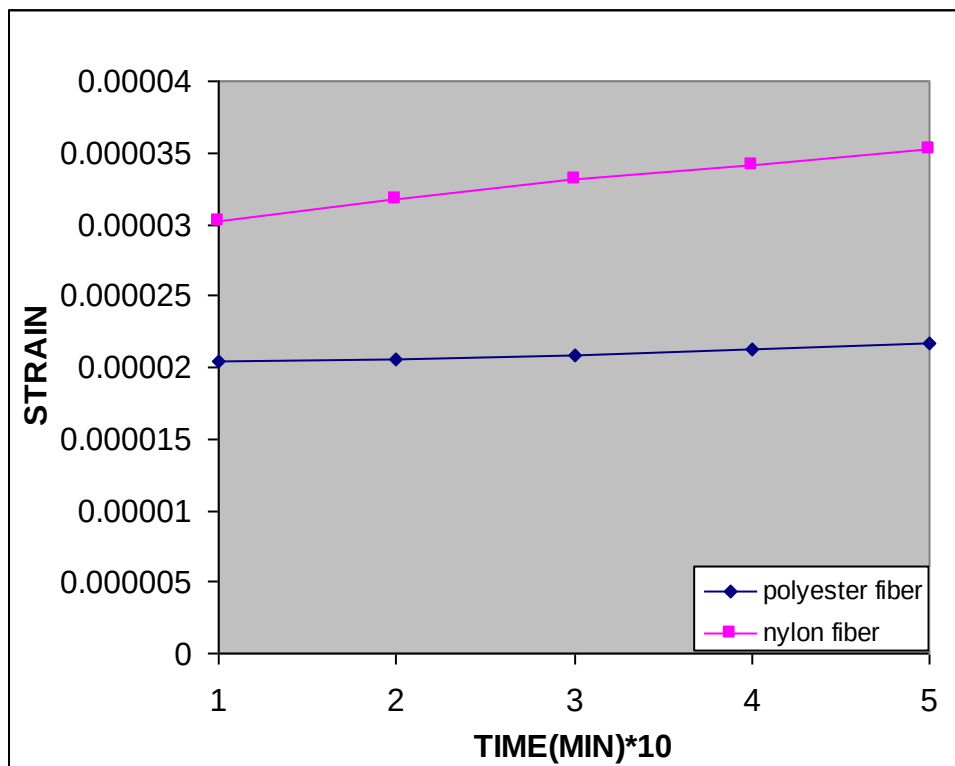


Figure (4-16) Biaxial creep of fibers under load (450).

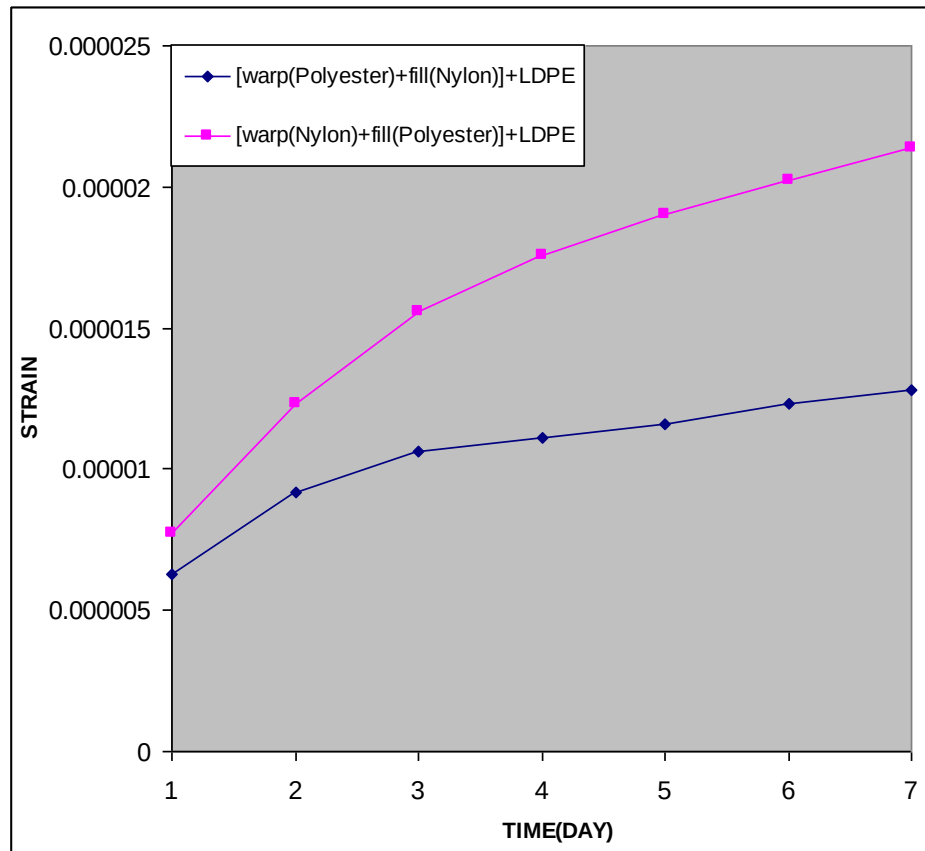


Figure (4-17) Biaxial creep of composite material from hybrid woven fabrics (Nylon with Polyester)fibers and Pure low density polyethylene(LDPE) under (450N).

Chapter five

Conclusions and Recommendations

(5-1) Conclusions

From the results and the discussions of the numerical and experimental study of biaxial creep of pure low density polyethylene and experimental results of biaxial creep of hybrid woven fabrics composite materials we can be conclude.

1- The creep value in the direction of polyester fiber is lower than that for nylon fiber direction.

2-Creep value ,creep strength ,deformation are equal in all directions in pure low density polyethylene in theoretical analysis and experimental and that means the model is active to predict creep behavior in biaxial direction for hybrid woven fabrics of composite materials.

(5-2)Recommendation

As mentioned previously in the thesis, for the past few decades structural composites made of fiber polymers composites have been used in the fields of mechanical, aeronautical and aerospace engineering . Putting this new material in actual use requires careful design practices and appropriate developments based on the understanding of their unique mechanical and physical properties. This investigation represents the important object to predict materials behavior with time at anisotropic conditions . Future research is needed, as extension to this study, to obtain a full understanding about the behavior of hybrid woven fabrics of composite materials. The following points are suggested as a future direction for research to be conducted on hybrid woven fabrics of composite materials.

- 1-The work can be extended in three dimensional (in tri-axial creep).
- 2-The work can be extended to predict biaxial creep behavior to another composite materials.
- 3-The work can be extended in different temperature variation and different loads.
- 4- the work inverse to this work can be used to study stress relaxation phenomena.
- 5-The work can be extended in other analytical and numerical methods such as finite difference or mathematical formulation .
- 6-Study of biaxial creep by micromechanics approach.
- 7-Study biaxial tensile behavior of woven fabrics of composite materials.

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LIST OF SYMBOLS

Grading	Symbols	Definition	Unit
1	A_{ij}	Extensional stiffness	
2	A_s	Cross-sectional areas of the shell element	mm ²
3	A_y	Cross-sectional areas of the yarn	mm ²
4	B_{ij}	coupling stiffness	
5	$\overline{A_{ij}}, \overline{B_{ij}}, \text{ and } \overline{D_{ij}}$	Rigid coefficients	
6	C_{ij}	Stiffness matrix	
7	D_{ij}	Bending stiffness	
8	$\overline{b_{ij}}, \overline{d_{ij}}, \overline{a_{ij}}$	Average coefficients of compliance	
9	$\overline{B_{ij}^s}, \overline{D_{ij}^s}, \overline{A_{ij}^s}$	Stiffness coefficients of the sub-ply laminate	
10	$D(t)$	The creep function	MPa ⁻¹
11	d_f	Yarn packing density	
12	E	Young's modulus	GPa
13	E_f	Young's moduli of the fiber	GPa
14	E_m	Young's moduli of the matrix	GPa
15	e°	Exponential constant	
16	g°	Initial inter-yarn gap between adjacent parallel yarns	
17	h	Thickness of fabric	mm
18	ΔH	The potential energy barrier	J
19	k	The k-th layer.	
20	$\overline{M_i}$	Average moments	N.mm
21	N	Total numbers of ply (or layer)	
22	$\overline{N_i}$	Average stresses	MPa

23	N_{ga}	A unit of length	mm
24	pd	Ratio of the fibers volume to the yarn overall	
25	s	Denotes shell element	
26	S	Shear strength	GPa
27	t	Time	
28	U	Yarn undulation	
29	u	Correspond to unit cell	
30	V_{fp}	Fiber packing fraction in a yarn	
31	w°	Initial yarn width	
32	(X, X')	Longitudinal tensile and compressive strengths	GPa
33	y	Yarn	
34	(Y, Y')	Transverse tensile and compressive strength	GPa
35	z	Position of ply in z-direction	

GREEK SYMBOLS

Grading	Symbol	Definition	Unit
1	σ_{ij}	Stress components	
2	ε_{ij}	Strain components	
3	θ	Angle between the fibers and the loading direction	Degree
4	$\sigma_1, \sigma_2, \sigma_3$	Stress components in the reference coordinate axes	MPa
5	$\sigma_x, \sigma_y, \sigma_z$	Stress components in the material symmetry axes	MPa
6	ε_s	Maximum allowable shear strain in x-y plane	
7	ν	Poisson's ratios	
8	ν_f	Poisson's ratios of fiber	
9	ν_m	Poisson's ratios of matrix	
10	V_o	Exponential factor	
11	ν	Frequency	Hz
12	$\sigma\beta$	A linear shift	
13	β	Activation volume for the molecular event	
14	$\varepsilon(t)$	Increase strain with time	
15	η	Viscosity	$\frac{N \cdot sec}{mm^2}$
16	β_4	Adjustable coefficient is introduced to reflect the effect of yarns normal to the loading direction on the tensile properties	