
**ADDIS ABABA UNIVERSITY**

**ADDIS ABABA INSTITUTE OF TECHNOLOGY**

**SCHOOL OF GRADUATE STUDIES**

# Experimental Fatigue Behaviour Investigation of Sisal Reinforced Epoxy Composite

**A Thesis submitted to Graduate School of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Master of Science**

**Mechanical and Industrial Engineering (Mechanical Design)**

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**Addis Ababa University**

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**School of Mechanical and Industrial Engineering**

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# Declaration

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This is to certify that the thesis prepared by Sitotaw Mengistie, entitled: “Experimental Fatigue Behavior Investigation of Sisal Reinforced Epoxy Composite” and submitted in partial fulfillment of the requirements for the degree of Master of Science (Mechanical and Industrial Engineering) complies with the regulation of the university and meets the accepted standards with respect to originality and quality.

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## List of Abbreviations and Acronyms

| | |
|---|---|
| m | meter |
| cm | centimeter |
| mm | millimeter |
| GPM | Gallon Per Minute |
| N | newton |
| cN | centi-Newton |
| mN | milli-Newton |
| LED | Light-Emitting Diode |
| NaOH | Sodium Hydroxide |
| SEM | Scanning Electron Microscope |
| PTFE | Polytetrafluoroethylene |
| SFRP | Short Fiber Reinforced Polymers |
| WWFE | World-Wide Failure Exercise |
| Hr. | Hour |
| min | Minute |
| ASTM | American Society of Testing Materials |
| LCD | Liquid Crystal Displays |
| MMC | Materials Mechanics Center |
| FTIR | Fourier transform infrared |

## Abstract

Due to their environment friendliness, natural abundance of the fibers, lower weight and cheap production cost, natural fiber reinforced composites are being used in different application areas. Properties of this material depend on many factors such as fiber reinforcement structure, loading condition, and fiber orientation and so on. In this paper, the effect of fiber orientation on the fatigue reaction of sisal reinforced epoxy composite is investigated. Sisal fiber is manually extracted and prepared. The fiber-matrix weight composition can be taken in different ways. But, due to its better mechanical property result and excellent performance, the weight ratio of sisal fiber to epoxy resin is taken to be 30/70. With a hand-lay-up method, sisal reinforced epoxy composite is produced in $[0^0,90^0]_2$, $[0^0,45^0]_2$ and [Random] fiber orientation and comparisons are made on their static and fatigue reaction. Several specimens, from each group are subjected to static and cyclic loading using Instron machine (Model 4483) with three-point bending test system. From the result, it is found that the $[0^0,45^0]_2$ fiber orientation resulted in a better flexural property such as transversal load capacity, flexural strength and modulus of elasticity. And $[0^0,90^0]_2$ fiber orientation exhibits better fatigue life with the $[0^0,45^0]_2$ orientation scoring the lowest life at about 2/3 of the life of the former. The randomly oriented specimens have the lowest flexural property but better fatigue reaction than that of $[0^0,45^0]_2$ specimens.

**Keywords:** Sisal Fiber, Fiber Orientation, Fatigue, Flexure, Sisal reinforced epoxy composite, Composite Materials, Three-Point Bending Test

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# Chapter One

# 1 Introduction

## 1.1 Background

Now a days Fiber reinforced composites are becoming very important in final product use and the areas of research and development. These composites have characteristics of the soft, elastic polymer matrix and the stiff, strong fibrous reinforcement. Usage of Fiber reinforced composites in almost every type of applications in our day to day activities is growing at an increasing rate [1].

Replacing synthetic fibers, such as glass fibers and carbon fibers, with plant-based fibers (natural fibers,) can be an effective way to realize carbon neutral materials because plants absorb a huge amount of Carbon Dioxide during their growth. This will partially reduce a very sensitive issue in the contemporary world, pollution. Natural fibers are also known to have mechanical properties comparable to glass fibers [2]. Therefore, many research works related to natural fibers and natural fiber-based composites have been performed to clarify the mechanism behind the material characteristics, and to maximize the material performance. However, recent industrial use of natural fiber-based composites is mostly limited to non-structural components such as body panels of automobile from non-woven random material of natural fibers. One of the reasons why industrial applications have been limited so far is the lack of knowledge related to their long-term reliability [3]. Especially, fatigue mechanisms should be clarified to expand the application to load-bearing structural components.

It is now well established that fiber composites, like metals, exhibit a form of degradation in service that can be described as ‘fatigue’. A simplistic description of the phenomenon is that under cyclic loading conditions, the load-bearing capacity of the material falls with time and this results in failures at stress levels which are often well below the ordinary (monotonic) engineering strength. The mechanisms by which this deterioration occurs in composites are quite different from, and much more complicated than, those which are responsible for fatigue phenomena in metals, but the problems facing the designer are similar [4]. From the engineer’s point of view, the challenge is to choose materials and use them in such a way as to avoid failures within the design life of a component or structure. In order to achieve this, it is necessary to understand the mechanisms of degradation in service and to be able to predict the life of a given composite under a certain design condition. In principle, achievement of the first of these should lead with confidence to the second, but at the

present time our progress towards a state of understanding where one follows from the other is less than perfect.

Composites reinforced with natural fibers such as Sisal, received increasing interest from industries in a wide field of application such as automobile, construction, aerospace and packing [5]. The main drawback of using natural fiber is their high level of moisture absorption, insufficient adhesion between untreated fibers and the polymer matrix which can lead to deboning with age [6]. Proper design of a composite system subjected to high loading rates can be accomplished only if the strain rate sensitivity of the material has been measured and the modes of failure and energy absorption are well characterized [7]. This involves choosing and preparing the material for proper loading condition and analyzing it in different scenarios.

As a natural fiber composite Sisal Reinforced Epoxy composite mainly consists of two materials, i.e., Sisal fiber which is stiff and strong fibrous reinforcement and Epoxy which is soft and elastic polymer matrix.

### 1.1.1 Sisal Fiber

Sisal fiber, a member of the Agavaceae family is a biodegradable and environmentally friendly plant. It is a strong, durable, stable and versatile material and it has been recognized as an important source of fiber for composites. With good growing conditions sisal plant forms an inflorescence after 6 - 9 years after having produced 250 - 300 leaves, and then dies. Leaves are around 1.2 m in length and are arranged spirally around the thick stem. The root system is shallow but extends up to 3.5 m from the stem. The leaves have a thorn at the tip and grow up to a height of 0.9 – 1.25 m and yield valuable fiber. More usually plants are harvested after 24-36 months. About 50 leaves, each weighing up to 1 kg may be cut per plant per year. The ripest lower leaves are cut first and this continues periodically over the next four years. On an average, over the first four years, two cuttings are made annually. In following years only one cut is made per year, until the flower stalks begin to develop. A total of about 300 leaves may be harvested during the economic life of each plant [8].

#### 1.1.1.1 Extraction of sisal fiber

Mature sisal plant leaves are harvested from the field for fiber extraction. All lower leaves are cut away from the plant by means of a sharp cutting tool. After harvesting, the leaves are transported to a factory for fiber extraction. There are three major fiber extraction methods: mechanical extraction,

chemical extraction and retting process. After extraction of fibers by any of these methods, all extracted leaves are washed away before drying. Proper drying is important as the moisture content in fiber affects fiber quality. Artificial drying is used in higher grade fibers than sun drying [9].
The fibers were dried under a shade to avoid bleaching by direct sunlight. Dry fibers are then combed, sorted into different grades and packed into bales.

#### 1.1.1.1.1 Mechanical Method

Historically, hand decortication was done by rural people whereby the leaves were pounded and the pulp was scraped away with a knife [10]-[14]. Hand decortication is time consuming and needs a lot of manpower. Nowadays, decortication can be done efficiently by using mechanical decorticator. In the mechanical decoration process, leaves are crushed and beaten by a rotating wheel set with blunt knives, so that only fibers remain [10], [11]. Some decorticators are fed by hand and the pulp is first scraped from half of a leaf, the leaf is withdrawn, and then the opposite half is inserted for scraping. In some machines, the whole leaf is decorticated in single insert [12].

Figure 1 gives a sectional view of the most important parts of fiber stripper/decorticator. Sisal plant leaf is fed through the mouthpiece, then it passes through the fluted feed rollers, which hold the leaves as they are fed in against a stationary bar, while the stripping drum is beating out the vegetable matter as the leaf passes between it and the beater bar. The stripping drum diameter, width and speed vary according to different makes. The drum, scraping against the leaf, held in position by the beating bar and feed rollers beats off the bulk of the vegetable matter and leaves the fibers somewhat roughened and with a residue of vegetable matter remaining upon it [15].
After completion of decortication and washing, the fibers are dried either with mechanical driers or in the sun. The operations of fiber removal, washing and drying must be done promptly after the leaves are cut, otherwise the gums in the leaves harden, causing the pulp to adhere with the fibers and making it difficult to clean the fibers properly [13]-[15]. In this research work, all the fiber is extracted using mechanical method as we only need a small quantity for sample preparation.

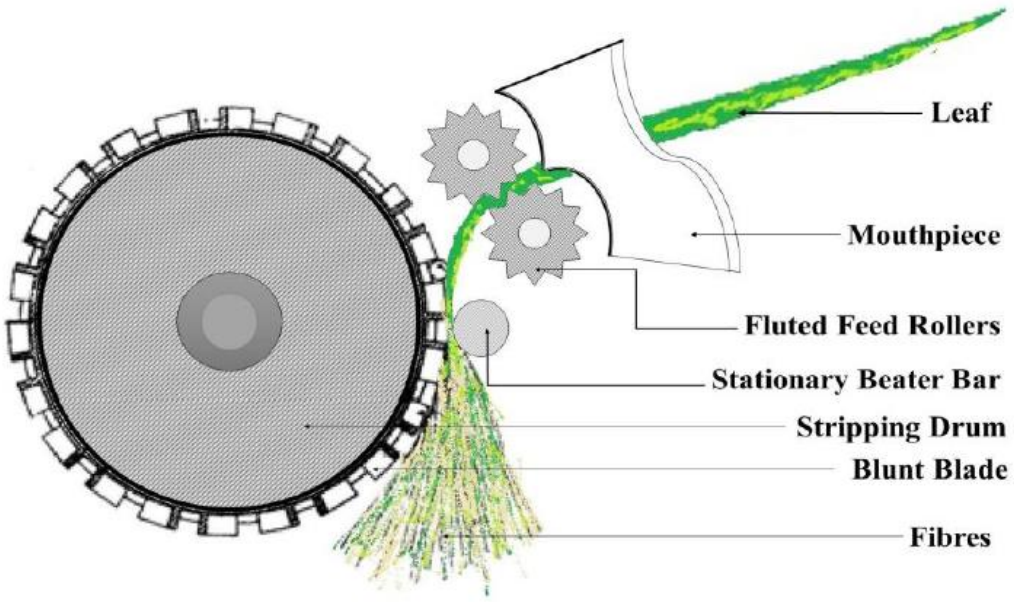


Figure 1: Sketch of simple fiber Decorticator

#### 1.1.1.1.2 Chemical Method

Chemical fiber extraction involves the use of acids, alkali and enzymes. The use of acids in cellulosic fiber extraction hydrolyses lignin and hemicellulose into shorter chain pentose molecules. Acid treatment results in the formation of reactive groups and causes fibers to fibrillate, revealing a higher degree of crystallinity of fibrils. Alkali used in fiber extraction dissolves the lignocellulosic material between fibers and separates structural linkages between lignin and cellulose, which leads to increased surface area as well as a degree of polymerization and lowers the breaking strength of fibers. In enzymatic process of fiber extraction, there is degradation of lignocellulosic component in fibers by enzymes resulting increased fiber swelling and lowers the degree of polymerization.

#### 1.1.1.1.3 Retting Method

Retting is a well studies method of extraction of fibers by a natural microbial process. Retting involves the degradation of non-fibrous matter which acts as glue between the fibers in woody plant parts and fibers without damaging the fiber cellulose.

This process allows easy separation of individual fiber strands and the woody core. Since retting is a biological process, it requires both moisture and a warm temperature for microbial action to occur.

## Natural Retting

It is a preferential rotting process to separate the fiber from lignocellulosic biomass without damaging the fiber cellulose. Retting is the microbial freeing of plant fibers from their surroundings. The process takes up to three weeks. Retting microbes consume the non-fibrous cementing materials mainly pectin and hemicellulose. This gradually softens the leaves by the destruction of the less resisting intercellular adhesive substances. When fermentation has reached the appropriate stage, the fibers can be separated quite easily from the leaves. If retting process is allowed beyond this point, fibers decline in quality. Under-retting causes incomplete removal of gummy materials such as pectin substances, and extraction of fiber becomes difficult. Hence, the progress of retting must be observed carefully at intervals to avoid fiber damage. Though the natural retting takes more time, the process is economical.

There are two traditional types of retting include water retting and field or dew retting. In water retting, plant leaves are immersed in water (river, pond or tanks). In field or dew retting, the crop is spread in the field where rain or dew provide moisture for retting.

## Enzymatic Retting

Enzymatic retting is the process in which the pectin materials surrounding the fiber bundles are degraded by industrially produced enzymes. Enzymatic retting is faster than natural fermentation retting and results into softer fibers. It has the potential to simplify and reduce fiber extraction costs. Enzymatic retting is expected to offer greater process control, increased fiber yield and shorter processing time. Enzyme solution used in retting can be recycled several times, which makes the process eco-friendly and cost effective.

Pectinases and xylanases are the enzymes which can be used for retting plant portions for fiber release. The enzyme can be used at higher concentrations to speed up the retting process. For example: 1.5 GPM of water or 3.0 GPM of water or 5.0 GPM of water can be used. The enzyme cellulase should be avoided in any enzymatic retting process of cellulosic fibers, since this will reduce the strength of the fibers.

### 1.1.1.2 Mechanical Behavior

Tenacity of sisal fiber is in the range of 30–40 cN/tex. The elongation of fiber at rupture is in the range of 2%–3%. This implies that sisal fiber can perform well when instantaneous forces act on the fibers during the use of the end product. Higher values of tensile properties of these fibers indicated that it is strong enough to be a textile fiber. It is thought that its strength is due to high degree of cellulose polymerization and crystallization processes that may be due to many years of growth. This tensile strength implies that sisal fiber can function well for furnishing fabrics, carpets, floor mats, rugs, upholstery fabrics as well as in nonwovens and fiber reinforced composites [12].

The tensile properties of sisal fiber are not uniform. This can be explained by the fact that it is a natural fiber and natural fibers are subject to growth irregularities to the extent that fibers from the same plant are not uniform in size and properties. The outer leaf sheaths produce the strongest fibers while the inner sheaths produce the weakest fibers. The innermost fibers have a high fracture strain while the peripheral fibers have lower tensile strength [12,16].

The outermost fibers have more elongation before breaking than inner fibers. The fibers are difficult to extend. This means sisal fiber is rigid and has low elongation. The fiber is having lower elongation at break values. Therefore, the product manufactured using this fiber will be rigid one. The wet strength of this fiber is lower than that of dry fiber. However, elongation of the break is higher when the fiber is in wet conditions [12,14]. Table 1 and 2 exhibits mechanical property of Sisal fiber and its comparison of mechanical properties with other fibers.

Table 1: Mechanical property of chemically treated sisal fiber

| **Total Evaluation** | **Mean Value** |
|---|---|
| Elongation | 1.69 % |
| Maximum Force | 6.57 N |
| Work to break | 3.61 Ncm |
| Tenacity | 37.84 cN/tex |
| Linear Density | 34 Ne |
| Modulus of Elasticity | 2179.30 cN/tex |

Note: Tensile test is conducted in the laboratory of Ethiopian textile factory.

Table 2: Comparison of mechanical properties between textile fibers [17]

| Fibers | Tenacity (cN/tex) | Elongation (%) | Modulus of Elasticity (N/tex) | Work to break (mN/tex) |
|---|---|---|---|---|
| Sisal | 30–40 | 2–3 | 20–25 | - |
| Flax | 25–26 | 2.7–3.3 | 18 | 8 |
| Jute | 29–56 | 1.2–1.9 | 17.2 | 2.7 |
| Cotton | 28–48 | 3–10 | 5 | 10.7 |
| E Glass | 82 | 2.5 | 29.4 | 9.8 |
| Polyester (HT) | 61 | 7 | 13.2 | 22 |

### 1.1.2 Epoxy

Epoxy is either any of the basic components or the cured end products of epoxy resins, as well as a colloquial name for the epoxide functional group. Epoxy resins, also known as polyoxides, are a class of reactive prepolymers and polymers which contain epoxide groups. Epoxy resins may be reacted either with themselves through catalytic homopolymerisation, or with a wide range of co-reactants including polyfunctional amines, acids, phenols, alcohols and thiols. These co-reactants are often referred to as hardeners or curatives, and the cross-linking reaction is commonly referred to as curing. Reaction of polyoxides with themselves or with polyfunctional hardeners forms a thermosetting polymer, often with high mechanical properties, temperature and chemical resistance. Epoxy has a wide range of applications, including metal coatings, use in electronics / electrical components / LED, high tension electrical insulators, paint brush manufacturing, fiber-reinforced plastic materials and structural adhesives. In general, epoxies are known for their excellent adhesion, chemical and heat resistance, good-to-excellent mechanical properties and very good electrical insulating properties.

## 1.2 Possible Application areas

Due to superior mechanical properties and recyclable nature, sisal fiber can be used as a potential input material to make composites for different application such as in buildings, automobiles, railways, geo-textiles, marine, renewable energy, and packaging industries, etc. Sisal fiber reinforced composite building materials like; wood substitute products, panels, doors, corrugated roofing sheets and instant houses suitable for disaster-affected areas would be made with attract prospective entrepreneurs and stakeholders due to its durability and cost-effectiveness [18].

The present scenario indicates that the use of plant fiber such as sisal-based automobile parts like trim parts, various panels, seat backs, shelves, brake shoes, etc., are picking up momentum worldwide. Reduction in weight, consumption of less energy for production and decreased cost of the components as experienced elsewhere, could attract the automobile industry to employ sisal fiber composite parts [19]. Through further investigation, parts such as bumpers, fascia, and braking system of bicycles could be made using sisal fiber reinforced epoxy composite. Packaging materials for bags, boxes, crates, containers, which is now made up of wood, may also be replaced by cost-effective sisal reinforced composites. Boats could be made by replacing the conventional polymer composite fibers with sisal as reinforcement. Sisal reinforced epoxy can also be used to produce surfing board if highly treated to withstand the failure due to its moisture content.

## 1.3 Basic research questions

- Which type of fiber orientation will provide better fatigue reaction of sisal reinforced epoxy composite?

## 1.4 Problem statement

Although there are only few studies related to fatigue in natural fiber composites, a common observation is stiffness increasing during fatigue life of natural fiber composites [20,21], while composites based on artificial fibers such as carbon fibers and glass fibers are known to show stiffness decreasing due to damage progression [22,23]. Liang [20] indicated that a natural fiber composites from a bi-axial flax fabric with yarns in 0° direction showed continuous increase of stiffness during almost all the fatigue life while a glass fiber-based composite with an identical fiber configuration exhibited significant decrease of stiffness. It is generally accepted that the mechanical properties of fiber reinforced polymer composites are controlled by factors such as nature of matrix, fiber-matrix interface, fiber volume or weight fraction, fiber aspect ratio, fiber orientation etc. [24]. Nevertheless, it remains unclear to what extent the fiber orientation affects the mechanical properties, especially, fatigue resistance of the composites. The answer to this question is very important to the fatigue design of products from natural fiber composites and their structural health monitoring.

The fatigue result due to fiber orientation in natural fiber composites should be understood in order to know and control the damage accumulation during the long-term use of natural fiber composites. Sisal fiber as one of those inputs to make composites which can be used in different industries, needs a proper examination in terms of its durability (fatigue life). Therefore, in this paper, fatigue of sisal fiber reinforced epoxy composite will be evaluated by changing the fiber orientation to show its effect. Initially, the sisal fiber is prepared manually by hand as a sufficiently small amount of fiber is required for the test.

## 1.5 Objective

### 1.5.1 General objective

The general objective of this study is to investigate fatigue reaction of sisal reinforced epoxy composite.

### 1.5.2 Specific objective

The specific objective of this study is to carry out the fatigue test on the specimens and discuss the experimental results.

## 1.6 Significance of the study

This study will have a contribution in increasing the acceptance and utilization of natural fibers such as sisal fiber in a composite form for different applications. This study will also help in advancing the technology involving natural fiber-based composites. It can encourage others in doing research for further innovation in the area. It enables us to understand how we can make use of natural fibers, i.e., in what kind of loading condition and manufacturing for long term service.

## 1.7 Scope and Limitation

This study goes through the manufacturing and preparation of sisal fiber reinforced epoxy composite specimens and performing fatigue test using a fatigue testing device. But there is no ready-to-use and highly competitive laboratory equipment to manufacture and test the sample composite. There is also lack of other devices to measure some of the sisal fiber properties, which could be used as an input during modelling and simulation of the composite using finite element analysis software.

# Chapter Two

# 2 Related Research Works

## 2.1 Literature Review

Research into the fatigue response of fiber composites has been carried out since the materials themselves first began to be a subject of serious study. Some of the first papers on the fatigue behavior of glass-reinforced plastics, for example, were published in the USA by Boller [25] – [29] in the 1950s and 60s, and shortly after this Owen [30] and his collaborators at Nottingham University in the UK were reporting the results of work on early carbon-fiber reinforced plastics. Simultaneously, Baker and co-workers at Rolls Royce, also in the UK, were laying the foundations for an understanding of the fatigue behavior of metal matrix composites. While much of this early work on fatigue involved phenomenological studies, it quickly became apparent that an understanding of the microstructural damage mechanisms responsible for failure under cyclic loading was a prerequisite for the development of new fatigue-resistant materials and, in the longer term, for the prediction of fatigue life, and the names of Reifsnider[31] in the USA and Talreja[32] in Denmark began to be associated with key developments in the emerging field of damage mechanics. And since the build-up of fatigue damage is essentially a stochastic process, vital statistical interpretations of fatigue behavior, again with life prediction as the objective, were made, among others, by Hahn, Talreja, Whitney, and Yang [32]-[34].

Initially, research into the fatigue behavior of fiber-reinforced plastics was driven largely by the aerospace industry, and much of the work was funded by that industry and by government. In the half-century or so since fiber-reinforced plastics were first developed, the picture, as far as applications are concerned, has changed substantially and aerospace is now only one of several fields where designers are seeking (and using) the latest of these materials which offer them the desirable benefits of high strength and stiffness combined with low density. It is perhaps for this reason more than any other that it seems an appropriate time to produce a new study of our current level of knowledge of the fatigue behavior of composites – and extend it to deal with the wider range of problems met with by designers in automotive, marine, and structural engineering.

Zhao Qian Li et al [35] showed that surface-treated sisal fiber reinforced composite offered superior mechanical properties compared to untreated fiber reinforced polylactide composite, which indicated that better adhesion between sisal fiber and Polymer matrix was achieved. Thus, the fiber will be treated with NaOH solution for enhancing the bonding strength between fiber and resin by removing moisture contents.

M K Gupta & R K Srivastava [36] reported that addition of sisal fiber in epoxy matrix up to 30 wt. % increases the mechanical, thermal and water absorption properties of the composite. Regardless of the fiber orientation, the weight ratio of sisal fiber to epoxy resin will be 30:70 for better mechanical property and performance. The sisal epoxy composite is manufactured using hand layup technique, which is the most common and least expensive open molding method, followed by static compression, as it requires least amount of equipment to produce the composite sample.

Arnold N. Towo [37] discussed the effect of chemical treatment on fatigue life of sisal reinforced polymer composites. The composites were prepared using a hot press technique from untreated and 0.06M NaOH treated sisal fiber with polyester and epoxy matrices. Evaluating the fatigue at different loading levels and at a stress ratio R of 0.1, He found out that the effect of chemical treatment on fatigue life is significantly positive for polyester matrix composites but has much less influence on the fatigue life of epoxy matrix composites.

Bisanda and Ansell [38] reported on the effect of silane treatment and alkali treatment on mechanical and physical properties of sisal-epoxy composites. They have reported that incorporation of sisal fibers in an epoxy resin produces stiff and strong composite materials. The treatment of the sisal fibers with silane, preceded by mercerization, provides improved wettability, mechanical properties and water resistance.

Paulo R. et al [39] discussed about the characterization and treatment of sisal fiber residues for cement-based composite application. In the study, they used sisal agricultural residues called field bush and refugo. These residues were treated with wet-dry cycles and evaluated using tensile testing of fibers, scanning electron microscopy (SEM) and Fourier transform infrared (FTIR) spectroscopy. Compatibility with the cement-based matrix was evaluated through the fiber pull-out test and flexural test in composites reinforced with 2 % of sisal residues. The results indicate that the use of treated

residue allows the production of composites with good mechanical properties that are superior to the traditional composites reinforced with natural sisal fibers.

Yosuke Ueki et al [40] have described the fatigue behavior of unidirectional flax fiber reinforced epoxy composite. During fatigue testing, the composite showed an increase of stiffness, a typical observation for natural fibre-reinforced composites, and this was found to be accompanied by accumulation of residual strain. A clear linear relationship was found between the stiffening effect and the residual strain. In addition, it was revealed that the fatigue behavior was clearly influenced by the frequency of cyclic loading. Lower frequencies induced more significant stiffening and shorter fatigue life. These results suggest that fatigue damaging is progressing simultaneously with the stiffening effect in natural fibre-reinforced composites, and it is therefore important to involve creep damaging to the failure criteria for these composites.

Nenad Stojkovic et al [41] provided a mathematical model for the prediction of strength degradation of composites subjected to constant amplitude fatigue. The mathematical model uses a single set of parameter values to predict the strength degradation of the elements subjected to different load levels, and thus, to reduce the required experimental effort for the determination of model parameters for each load level separately. They developed a new two-parameter model based on normalization of the difference between the residual strength and maximal applied load in the constant amplitude cyclic loading, herein referred to as the strength reserve, with respect to initial conditions.

Shao-Yun Fu & Bernd Lauke [42] have showed the effects of fiber length and fiber orientation distributions on the tensile strength of short-fiber-reinforced polymers. They presented an analytical method considering the effects of fiber length and fiber orientation distributions for predicting the tensile strength of short-fiber-reinforced polymers. Two probability density functions are used for modelling the distributions of fiber length and fiber orientation. The strength of SFRP is derived as a function of fiber length and fiber orientation distribution considering the dependences of the ultimate fiber strength and the critical fiber length on the inclination angle and the effect of inclination angle on the bridging stress of oblique fibers. The effects of the mean fiber length, the most probable length (mode length), the critical fiber length, the mean fiber orientation, the most probable fiber orientation and the fiber orientation coefficient on the tensile strength of SFRP have also been studied in detail. The results show that the strength of SFRP increases rapidly with the

increase of the mean fiber length at small mean fiber lengths (in the vicinity of the critical fiber length) and approaches a plateau level as the mean fiber length increases for the cases of large mean fiber lengths. And the composite strength increases with the decrease of critical fiber length and hence with the increase of interfacial adhesion strength and slightly with the decrease of the mode fiber length. In general, the strength of composites increases with the increase of fiber orientation coefficient and the decrease of mean fiber orientation angle; however, when the fiber orientation coefficients are the same, the strength of composites increases with the increase of mean fiber orientation angle and with the decrease of mean fiber length.

E. Laranjeira et al [43] explained about the influence of fiber orientation on the mechanical properties of Polyester/Jute composites. They investigated the tensile and impact properties of compression molded unsaturated polyester/jute composites as a function of fiber content and orientation. Unidirectional composites were tested along and transversally to the fiber axis. Higher values for all mechanical properties were obtained when long-fiber oriented composites were tested along the fiber axis, even at low fiber content. The tensile properties of the composites tested perpendicular to the fiber were dominated by the strain at the fiber–matrix interface. Properties for randomly distributed short-fiber composites were found to be intermediate between those obtained with long-fiber oriented composites with the same fiber load tested along and across the fiber direction.

Nak-Ho Sung and Nam P. Suh [44] discussed the effect of fiber orientation on friction and wear of fiber reinforced polymeric composites. Taking uniaxially oriented graphite fiber-epoxy, Kevlar fiber-epoxy and biaxially oriented glass fiber- MoSs polytetrafluoroethylene (PTFE), they performed wear and friction examinations as a function of varying fiber orientations with respect to the sliding direction. In graphite fiber-epoxy composites, both wear and friction coefficients were minimum when the orientation of the fibers was normal to the sliding surface. In Kevlar-epoxy composites when the fibers were oriented normal to the surface and the sliding direction, the wear rate was also minimum but the friction coefficient was the highest. In glass fiber-Moss-PTFE composites, wear was minimum when the largest fraction of fibers was oriented normal to the sliding surface.

H.W. Wang et al [45] analyzed the effect of fiber orientation on Young's modulus for unidirectional fiber reinforced composites. They investigated the Young's modulus of unidirectional glass fiber reinforced polymer composites using analytical, numerical and experimental methods. Results

indicate that Young's modulus of the composites strongly depends on the fiber orientation angles. A U-shaped dependency of the Young's modulus of composites on the inclined angle of fiber is found, which agree well with the experimental results. The shear modulus is found to have significant effect on the composites' Young's modulus, too.

M. Ramesh et al [46] have worked on Mechanical property evaluation such as tensile strength, impact strength and flexural strength of sisal–jute–glass fiber reinforced polyester composites. He also evaluated the interfacial properties, internal cracks and internal structure of the fractured surfaces using a SEM device. The result showed that the glass-jute-sisal mixture composite sample can have maximum flexural strength and the maximum impact strength is obtained for the glass and sisal fiber Composite. The research result also indicated the incorporation of natural fibers with artificial fiber such as glass fiber, can improve the property and be used as an alternative material for glass reinforced polymer composites.

Kumar Esan. M. et al [47] have carried out experimental study to determine the effect of fiber orientation such as $0^0$,$90^0$ and $45^0$ on the mechanical property of epoxy composite. In their work sisal fiber is used as reinforcement which treated with NaOH solution for enhancing the bonding strength between fiber and resin by removing moisture contents. Samples of different orientations of sisal fiber reinforced composites were fabricated by compression molding and investigated their mechanical properties like tensile strength and flexural strength. The results of this study indicate the orientation $[90^0]_2$ shows better mechanical properties compared to $[0^0/90^0]_2$ and $[45^0]_2$. But it does not describe any fatigue effect other than tensile, flexural and impact effects. Therefore, in this research work, the fatigue life of sisal fiber reinforced epoxy composite will be investigated by altering the orientation of the fiber.

## 2.2 Fatigue damage modelling

In general fatigue of fibre-reinforced composite materials is a quite complex phenomenon, and a large research effort is being spent on it today. Fibre-reinforced composites have a rather good rating as regards to life time in fatigue. The same does not apply to the number of cycles to initial damage nor to the evolution of damage.

Composite materials are inhomogeneous and anisotropic, and their behavior is more complicated than that of homogeneous and isotropic materials such as metals.

The main reasons for this are the different types of damage that can occur (e.g. fibre fracture, matrix cracking, matrix crazing, fibre buckling, fibre-matrix interface failure, delamination...), their interactions and their different growth rates.

Among the parameters that influence the fatigue performance of composites are:

- Fibre type,
- Matrix type,
- Type of reinforcement structure (unidirectional, mat, fabric, braiding...)
- Laminate stacking sequence,
- Environmental conditions (mainly temperature and moisture absorption),
- Loading conditions (stress ratio R, cycling frequency...) and boundary conditions.

Therefore, the microstructural mechanisms of damage accumulation, of which there are several, occur sometimes independently and sometimes interactively, and the predominance of one or other of them may be strongly affected by both material variables and testing conditions.

There are several differences between the fatigue behavior of metals and fibre-reinforced composites. In metals the stage of gradual and invisible deterioration spans nearly the complete life time. No significant reduction of stiffness is observed during the fatigue process. The final stage of the process starts with the formation of small cracks, which are the only form of macroscopically observable damage. Gradual growth and coalescence of these cracks quickly produce a large crack and final failure of the structural component. As the stiffness of a metal remains quasi unaffected, the linear relation between stress and strain remains valid, and the fatigue process can be simulated in most common cases by a linear elastic analysis and linear fracture mechanics.

In a fibre-reinforced composite damage starts very early and the extent of the damage zones grows steadily, while the damage type in these zones can change (e.g. small matrix cracks leading to large size delamination). The gradual deterioration of a fibre-reinforced composite – with a loss of stiffness in the damaged zones – leads to a continuous redistribution of stress and a reduction

of stress concentrations inside a structural component. Consequently, an appraisal of the actual state or a prediction of the final state (when and where final failure is to be expected) requires the simulation of the complete path of successive damage states.

According to Fong [48] there are two technical reasons why fatigue damage modelling in general is so difficult and expensive. The first reason are the several scales where damage mechanisms are present: from atomic level, through the sub grain, grain and specimen levels, to the component and structural levels. The second reason is the impossibility of producing 'identical' specimens with well-characterized microstructural features.

Fong also draws the attention to some pitfalls of fatigue damage modelling:

- Confusion over scale: information from measurements on different scale levels, is combined improperly and leads to erroneous results
- False generalization: for example, stiffness reduction can often be divided in three regimes: sharp initial reduction, more gradual decrease and final failure [49], [50], but the related models are not always valid in the three stages,
- Oversimplification: curve fitting of experimental data is done by using oversimplified expressions. This last statement was confirmed by Barnard et al [51]. He presented evidence that much of the scatter of the S-N curve drawn from his experimental data was caused by a change in failure mode, generating a discontinuity in the S-N curve.

Next, many models have been established for laminates with a stacking sequence and boundary conditions, under uniaxial cyclic loading with constant amplitude, at a certain frequency, ... The extrapolation to real structures with a stacking sequence varying from point to point, and more complex variations of the loads, is very complicated, if not impossible. Indeed, some serious difficulties must be overcome when fatigue life prediction of composite materials under general loading conditions is pursued:

- The governing damage mechanism is not the same for all stress level states [50], [51]. Failure patterns vary with cyclic stress level and even with number of cycles to failure
- The load history is important. When block loading sequences are applied in low-high order or in high-low order, there can be a considerable difference in damage growth [52].

- Most experiments are performed in uniaxial stress conditions (e.g. uniaxial tension/compression), although these stress states are rather exceptional in real structures
- The residual strength and fatigue life of composite laminates have been observed to decrease more rapidly when the loading sequence is repeatedly changed after only a few loading cycles [53]. This so- called 'cycle-mix effect' shows that laminates that experience small cycle blocks, have reduced average fatigue lives as compared to laminates that are subjected to large cycle blocks, although the total number of cycles they have been subjected to, is the same for both laminates at the end of the experiment,
- The frequency can have a major impact on the fatigue life. Ellyin and Kujawski [54] investigated the frequency effect on the tensile fatigue performance of glass fibre-reinforced $[\pm 45°]_{5S}$ laminates and concluded that there was a considerable influence of test loading frequency. Especially for matrix dominated laminates and loading conditions, frequency becomes important because of the general sensitivity of the matrix to the loading rate and because of the internal heat generation and associated temperature rise.

Clearly a lot of research has still to be done in this domain. However, several attempts have been made to extend models for uniaxial constant amplitude loading to more general loading conditions, such as block-type and spectrum loading and to consider the effect of cycling frequency and multiaxial loads.

Although the fatigue behavior of fibre-reinforced composites is fundamentally different from the behavior exposed by metals, many models have been established which are based on the well-known S-N curves. These models make up the first class of so-called 'fatigue life models'. This approach requires extensive experimental work and does not consider the actual damage mechanisms, such as matrix cracks and fibre fracture.

The second class comprises the phenomenological models for residual stiffness and strength. These models propose an evolution law which describes the (gradual) deterioration of the stiffness or strength of the composite specimen in terms of macroscopically observable properties, as opposed to the third class of progressive damage models, where the evolution law is proposed in direct relation with specific damage. Residual stiffness models account for the degradation of the elastic properties during fatigue. Stiffness can be measured frequently during fatigue experiments and can

be measured without further degrading the material [55]. The model may be deterministic, in which a single-valued stiffness property is predicted, or statistical, in which predictions are for stiffness distributions. The other approach is based on the composite's strength. In many applications of composite materials, it is important to know the residual strength of the composite structure, and consequently the remaining life time during which the structure can bear the external load. Therefore, the so-called 'residual strength' models have been developed, which describe the deterioration of the initial strength during fatigue life. From their early use, strength-based models have generally been statistical in nature. Most commonly, two-parameter Weibull functions are used to describe the residual strength and probability of failure for a set of laminates after an arbitrary number of cycles.

Generally, fatigue models can be generally classified in three categories:

- The fatigue life models;
- The phenomenological models for residual stiffness/strength; and
- The progressive damage models.

One of the important outcomes of all established fatigue models is the life time prediction. Each of the three categories uses its own criterion for determining final failure and consequently for the fatigue life of the composite component.

The fatigue life models use the information from S-N curves or Goodman-type diagrams and introduce a fatigue failure criterion which determines the fatigue life of the composite specimen. Regarding the characterization of the S-N behavior of composite materials, Sendeckyj [56] advises to consider three assumptions:

- The S-N behavior can be described by a deterministic equation,
- The static strengths are uniquely related to the fatigue lives and residual strengths at runout (termination of cyclic testing). An example of such a relationship is the commonly used 'strength-life equal rank assumption [57], [58], which states that for a given specimen its rank in static strength is equal to its rank in fatigue life,
- The static strength data can be described by a two-parameter Weibull distribution.

Residual strength models have in fact an inherent ‘natural failure criterion’: failure occurs when the applied stress equals the residual strength [59], [60]. In the residual stiffness approach, fatigue failure is assumed to occur when the modulus has degraded to a critical level which has been defined by many investigators. Hahn and Kim [61] and O’Brien and Reifsnider [62] state that fatigue failure occurs when the fatigue secant modulus degrades to the secant modulus at the instance of failure in a static test.

According to Hwang and Han [52], fatigue failure occurs when the fatigue resultant strain reaches the static ultimate strain.

Damage accumulation models and life time prediction methodologies are very often inherently related, since the fatigue life can be predicted by establishing a fatigue failure criterion which is imposed to the damage accumulation model. For specific damage types, the failure value of the damage variable(s) can be determined experimentally.

## 2.3 Failure criteria for fiber-reinforced polymer composites

The subject of failure criteria for fibre reinforced plastic composites has attracted numerous researchers over the last four decades [63]-[70]. The number and different types of approaches that have been proposed clearly demonstrates that failure criteria for fibre reinforced plastic composites is important research topic until today.

Although important progresses have been made, it does not appear that there is any criterion universally accepted by designers as adequate under general load conditions. An evidence of this is recent publication of a special edition of Composites Science and Technology entirely dedicated to failure theories of fibre reinforced plastic composites [71], [72], and the survey performed by C.T. Sun on the industrial use of failure criteria [73].

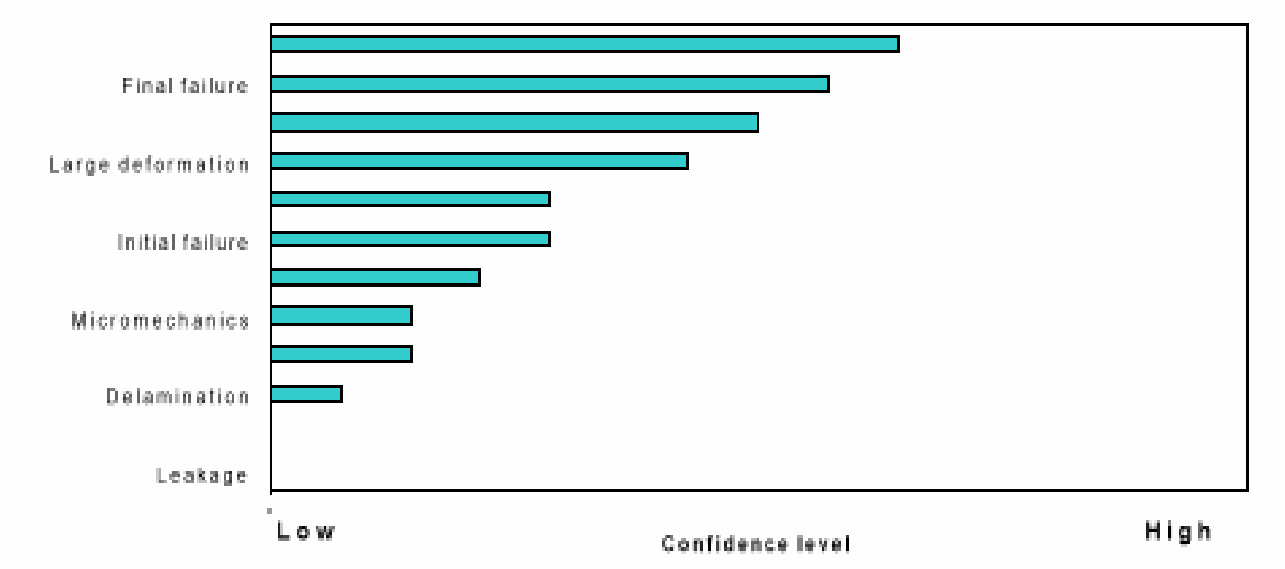


Figure 2 Confidence level displayed by the WWFE theories [72]

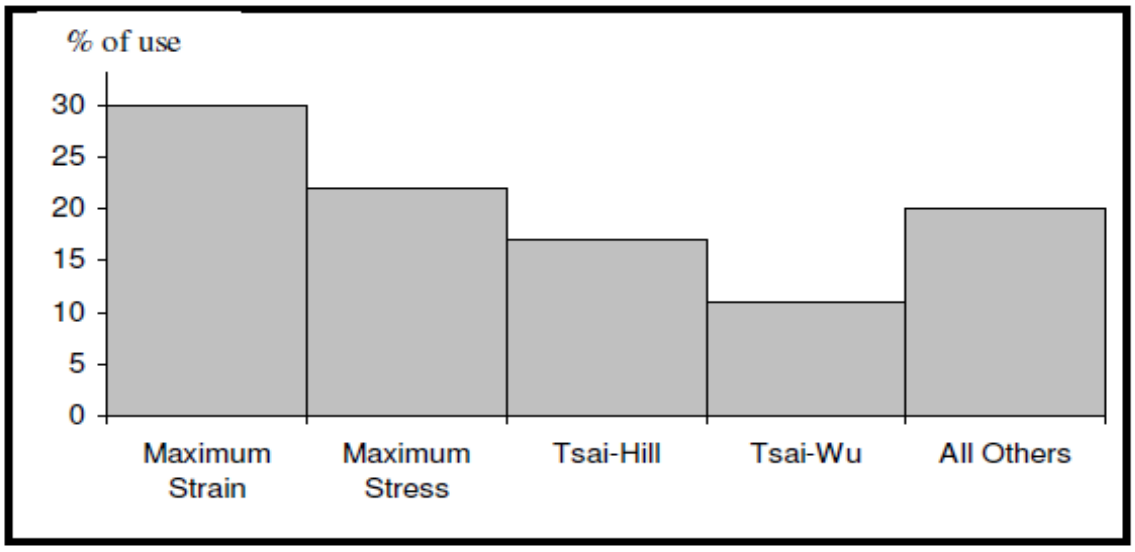


Figure 3 Industrial usage of composites failure criteria [73]

From Figure 2 and Figure 3 the confidence levels of the failure theories used in the World-Wide Failure Exercise need to be improved for some damage mechanisms (e.g. delamination), and that there is no consensus in the industry on the most adequate failure criterion.

Besides failure criteria, there are other issues worth investigation, such as the inclusion of residual thermal stresses, in-situ strengths, non-linear behavior in shear, stiffness degradation models for laminate failure, final failure definition and delamination failure.

### 2.3.1 Lamina failure criteria

The failure criteria proposed to predict lamina failure could be divided in two main groups:

#### 2.3.1.1 Criteria not associated with failure mode

This group includes all polynomial and tensorial criteria, using mathematical expressions to describe the failure surface as a function of the material strengths. Generally, these expressions are based on the process of adjusting an expression to a curve obtained by experimental tests. The most general polynomial failure criterion for composite materials is Tensor Polynomial Criterion proposed by Tsai and Wu [63]. This criterion may be expressed in tensor notation as:

$$F_i \times \sigma_i + F_{ij} \times \sigma_i \times \sigma_j + F_{ijk} \times \sigma_i \times \sigma_j \times \sigma_k \geq 1 \quad \text{Eqn 1}$$

where i, j, k = 1, ... 6 for a 3-D case. The parameters $F_i$, $F_{ij}$ and $F_{ijk}$ are related to the lamina strengths in the principal directions. For practical proposes, and due to the large number of material constants required, the third-order tensor $F_{ijk}$ is usually neglected [64]. Therefore, the general polynomial criterion reduces to a general quadratic expression given by:

$$F_i \times \sigma_i + F_{ij} \times \sigma_i \times \sigma_j \geq 1 \quad \text{Eqn 2}$$

where i, j = 1 ... 6. Considering that the failure of the material is insensitive to a change of sign in shear stresses, all terms containing a shear stress to first power must vanish: $F_4 = F_5 = F_6 = 0$.

Then, the explicit form of the general expression is:

$$F_1\sigma_1 + F_2\sigma_2 + F_3\sigma_3 + 2F_{12}\sigma_1\sigma_2 + 2F_{13}\sigma_1\sigma_3 + 2F_{23}\sigma_2\sigma_3 + F_{11}\sigma^2_1 + F_{22}\sigma^2_2 + + F_{33}\sigma^2_3 + F_{44}\sigma^2_4 + F_{55}\sigma^2_5 + F_{66}\sigma^2_6 \geq 1 \quad \text{Eqn 3}$$

Several other quadratic criteria have been proposed, differing in the way in which the tensor stress components are determined. Other popular and well-known quadratic failure criteria include those proposed by Tsai-Hill [64], Azzi-Tsai [74], Hoffman [75] and Chamis [76]. These quadratic criteria

can be represented in terms of the general Tsai-Wu quadratic criterion varying the parameters $F_i$ and $F_{ij}$ in order to ensure a good fit of the failure surface to the experimental results. These failure criteria are summarized in Appendix A.

Although presenting some noticeable features, such as invariance under rotation of co- ordinates and transformation according to established tensorial relations, these criteria do not consider the different damage mechanisms that promote laminate failure. In fact, these criteria consider the lack of isotropy of composite laminates in terms of micromechanical variables (stresses) using appropriate constitutive equations, but do not account for the lack of homogeneity of these materials. The lack of homogeneity governs the type of failure.

Furthermore, there are some other issues worth noticing when using some polynomial criteria, such as the fact that it is predicted that failure under biaxial tensile stresses depends on the compressive strengths. This is unacceptable from the physical point of view.

In order to deal with the non-homogeneous character of composites a second group of criteria has been proposed:

### 2.3.1.2 Criteria associated with failure mode

These criteria consider that the non-homogeneous character of composites leads different failure modes of the constituents. The criteria are established in terms of mathematical expressions using the material strengths and consider the different failure modes of the constituents. These criteria have the advantage of being able to predict failure modes, being therefore adequate to be used in a progressive damage analysis.

Most of the criteria proposed identify the following failure modes:

- ✓ Fibre fracture.
- ✓ Transverse matrix cracking.
- ✓ Shear matrix cracking.

Failure criteria associated with failure modes can be further sub-divided into two sub-groups:

**1. Non-interactive**

This does not consider interactions between stresses/strains acting on a lamina. This fact typically leads to errors in the strength predictions when multiaxial states of stress occur in a structure. Typical examples of non-interactive criteria are:

**Maximum Strain criterion**

This criterion considers that the composite fails when the strain exceeds the respective allowable, being a simple and direct way to predict failure of composites. Three different conditions of failure are considered in correspondence with a maximum strain in fibre direction, matrix or transversal direction and for shear strains.

Fibre: $\varepsilon_1 \geq \varepsilon^u_{1T}$ or $|\varepsilon_1| \geq \varepsilon^u_{1C}$ …… Eqn 4

Matrix: $\varepsilon_2 \geq \varepsilon^u_{2T}$ or $|\varepsilon_2| \geq \varepsilon^u_{2C}$ ……..…. Eqn 5

Shear: $\varepsilon_{12} \geq \varepsilon^u_{12}$ ……...…… Eqn 6

**Maximum Stress criterion**

This criterion considers that the composite fails when the stress exceeds the respective allowable. As in the previous case, it is a simple and direct way to predict failure of composites and no interaction between the stresses acting on the lamina is considered.

Fibre: $\sigma_1 \geq \sigma^u_{1T}$ or $|\sigma_1| \geq \sigma^u_{1C}$ …… Eqn 7

Matrix: $\sigma_2 \geq \sigma^u_{2T}$ or $|\sigma_2| \geq \sigma^u_{2C}$ ……..… Eqn 8

Shear: $\sigma_{12} \geq \sigma^u_{12}$ ……...……Eqn 9

**2. Interactive**

This considers interactions between stresses/strains acting on a lamina. Examples of interactive failure criteria are:

**Hashin-Rotem Criterion**

This criterion involves two failure mechanisms, one associated with fibre failure and the other with matrix failure, distinguishing between tension and compression [77].

- Fibre failure in tension: ($\sigma_1 > 0$)

$$\sigma_1 = \sigma^u_{1T} \quad \text{Eqn 10}$$

- Fibre failure in compression: ($\sigma_1 < 0$)

$$-\sigma_1 = \sigma^u_{1C} \quad \text{Eqn 11}$$

- Matrix failure in tension: ($\sigma_2 > 0$)

$$\left(\frac{\sigma_2}{\sigma^u_{2T}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma^u_{12}}\right)^2 = 1 \quad \text{Eqn 12}$$

- Matrix failure in compression: ($\sigma_2 < 0$)

$$\left(\frac{\sigma_2}{\sigma^u_{2C}}\right)^2 + \left(\frac{\sigma_{12}}{\sigma^u_{12}}\right)^2 = 1 \quad \text{Eqn 13}$$

**Hashin Criterion**

Hashin later proposed a failure criterion for fibrous composites under a three-dimensional state of stress. For the matrix failure mode, a quadratic approach was chosen because a linear criterion underestimates the material strength, and a polynomial of higher degree would be too complicated to deal with [65]. Furthermore, the effect of the shear stress is now considered in the tensile fibre mode:

- Fibre failure in tension: ($\sigma_1 > 0$)

$$\left(\frac{\sigma_1}{\sigma^u_{1T}}\right)^2 + \left(\frac{\sigma^2_{12}+\sigma^2_{13}}{(\sigma^u_{12})^2}\right)^2 = 1 \quad \text{or} \quad \sigma_1 = \sigma^u_{1T} \quad \text{Eqn 14}$$

- Fibre failure in compression: ($\sigma_1 < 0$)

$$-\sigma_1 = \sigma^u_{1C} \quad \text{.....Eqn 15}$$

- Matrix failure in tension: (($\sigma_2 + \sigma_3$) > 0)

$$\left(\frac{\sigma_2+\sigma_3}{\sigma^u_{2T}}\right)^2 + \frac{\sigma^2_{23}+\sigma_2\sigma_3}{(\sigma^u_{23})^2} + \frac{\sigma^2_{12}+\sigma^2_{13}}{(\sigma^u_{12})^2} = 1 \quad \text{..... Eqn 16}$$

- Matrix failure in compression: (($\sigma_2 + \sigma_3$) < 0)

$$\left[\left(\frac{\sigma^u_{2C}}{2\sigma^u_{23}}\right)^2 - 1\right]\frac{\sigma_2+\sigma_3}{\sigma^u_{2C}} + \left(\frac{\sigma_2+\sigma_3}{2\sigma^u_{23}}\right)^2 + \frac{\sigma^2_{23}+\sigma_2\sigma_3}{(\sigma^u_{23})^2} + \frac{\sigma^2_{12}+\sigma^2_{13}}{(\sigma^u_{12})^2} = 1 \quad \text{..... Eqn 17}$$

**Puck**

Two different types of failure or fracture are considered: inter-fibre fracture (matrix cracking) and fibre fracture.

The most noticeable difference between this criterion and the ones proposed by Hashin is that three modes of matrix cracking are considered, differing in the angle between the fracture plane and the lamina, as well as in the type of load which causes the fracture, as shown in Figure 4.

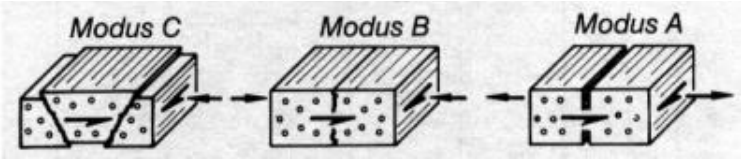


Figure 4 Inter-Fibre Fracture Modes A, B and C [78]

# Chapter Three

# 3 Research Methods, Materials and Procedures

## 3.1 Materials

### 3.1.1 Matrix

#### 3.1.1.1 Epoxy Resin

For this thesis work epoxy resin is used as matrix with a brand name of System # 2000 Epoxy Resin, which is purchased from the local fiber glass production industry in Addis Ababa, Ethiopia. Epoxy resin is one of the most exciting polymer types and which is used in advance to produce composite material with different reinforcing elements. Its extensive use is mainly due to their superior mechanical properties, excellent adhesion, good possibility utilizing addition- type reaction, low cure shrinkage and low cost.

#### 3.1.1.2 Hardener

Epoxy resin is cured by adding a catalyst, which causes a chemical reaction without changing its own composition as well as property. The catalyst initiates the chemical reaction of the epoxy resin and monomer ingredient from liquid to solid state. Therefore, the hardener (curing agent) used for this specific project/research work is hardener with a brand name of System # 2060 Hardener, which is purchased from local market.

### 3.1.2 Sisal fiber

The required amount of sisal plant leaves for this thesis work are collected from highland part of Ethiopia specifically, from around Dessie, after cutting at their base from the harvest and the fibers are extracted from the given plant manually with the use of knife. Initially the leaves trimmed in longitudinal direction into strips for ease of fiber extraction. The peel is clamped between the wood plank and knife and hand- pulled through in longitudinal direction gently, removing the resinous material as shown in the figure below. After extraction process, the extracted fiber washed with pure

water in order to remove and separate unwanted dusts from the fiber and it has been dried with sun and eventually the required fine fibers are obtained. This fiber is will now be ready for fabrication of the test specimen.

a) b) c)

Figure 5 (a) Sisal leaves after cut (b) Extraction process (c) The extracted fiber

### 3.1.3 Sodium hydroxide

Sodium hydroxide, also known as caustic soda, has the molecular formula NaOH and is a highly caustic metallic base and alkali salt. Pure sodium hydroxide is a whitish solid, which is available in pellets, flakes, granules, and as a 50% saturated solution [79]. Sodium hydroxide is soluble in water, ethanol and methanol. This alkali is deliquescent and readily absorbs moisture and carbon dioxide in air. Although molten sodium hydroxide possesses properties similar to those of the other forms, its high temperature comparatively limits its applications. Sodium hydroxide is used in many industries, mostly as a strong chemical base in the manufacture of pulp and paper, textiles, drinking water, soaps and detergents [79]. In this work we used NaOH in pellets form, purchased from local suppliers with the brand name and code of Rankem, S0290 respectively and performed chemical treatment of sisal fiber.

## 3.2 Sample Preparation Procedure

### 3.2.1 Preparation of sisal fiber

As the main work of this thesis is to evaluate the effect of fiber orientation, careful alignment of fibers with respect to their length and angle is very important. Generally, the fiber is cut into two different fiber lengths. Most of the fiber used for this thesis work is utilized to prepare different composite samples with varying ply orientation. Thus, most of it is cut with a larger length. The mold which is used to prepare the sample composite has an area of 230 x 230 $mm^2$. Therefore, for the sake of conformity with the mold size the given sisal fiber has been cut with 230 mm fiber length. Some amount of the fiber which is enough to prepare at least two randomly oriented short fiber composite samples is cut at a relatively smaller length. This later sample is required to be made out of chopped fibers just to make comparison with the other, long and aligned, fiber composites. Thus, it is cut with 10mm fiber length.

Figure 6 The Sisal fiber cut with the mold size

### 3.2.2 Alkali treatment of sisal fiber

Alkali treatment is the simplest method of chemical treatment of fibers; it leads to the increase in the amount of amorphous cellulose at the expense of crystalline cellulose. The important modification occurring here is the removal of hydrogen bonding in the network structure. The following reaction takes place as a result of alkali treatment.

$$Fiber - OH + NaOH \longrightarrow Fiber\text{-}O^{-}Na^{+} + H_2O$$

Sodium hydroxide is the most commonly used chemical for cleaning/bleaching the surface of cellulosic fibers. In order to improve the adhesion between the fiber and matrix, chemical treatment of the fiber is important. Romina Del Rey et al [80] have done experiment to show the effect of Sodium Hydroxide Treatments on the Tensile Strength and the Interphase Quality of Hemp Core Fiber-Reinforced Polypropylene Composites. And their result showed that 10% NaOH treatment gives relatively better tensile strength. It is obvious that this experiment is not done on sisal fiber. Some researchers simply take 10 % NaOH when doing experiments related with sisal-based composites. But because similar research is not done on sisal fiber, it would be at least better to take a 10% NaOH solution from the above researchers on Hemp Core Fiber-Reinforced Polypropylene Composites. Therefore, all the Sisal fiber was soaked in 10 wt.% NaOH solution for 24 hours before it is cut into different sizes. In order to neutralize excess NaOH the treated fiber was washed using distilled water until the PH indicator points at 7. This treated Sisal fiber was then exposed to sun light for two days and dried before using it as reinforcement in the production of the composite.

The treatment steps are summarized as follows.

1. The first step is sisal fiber mercerization. It is a process of treating sisal fiber with 10wt% NaOH solution at room temperature for 24hrs. 4 liters of distilled water is used for this process.

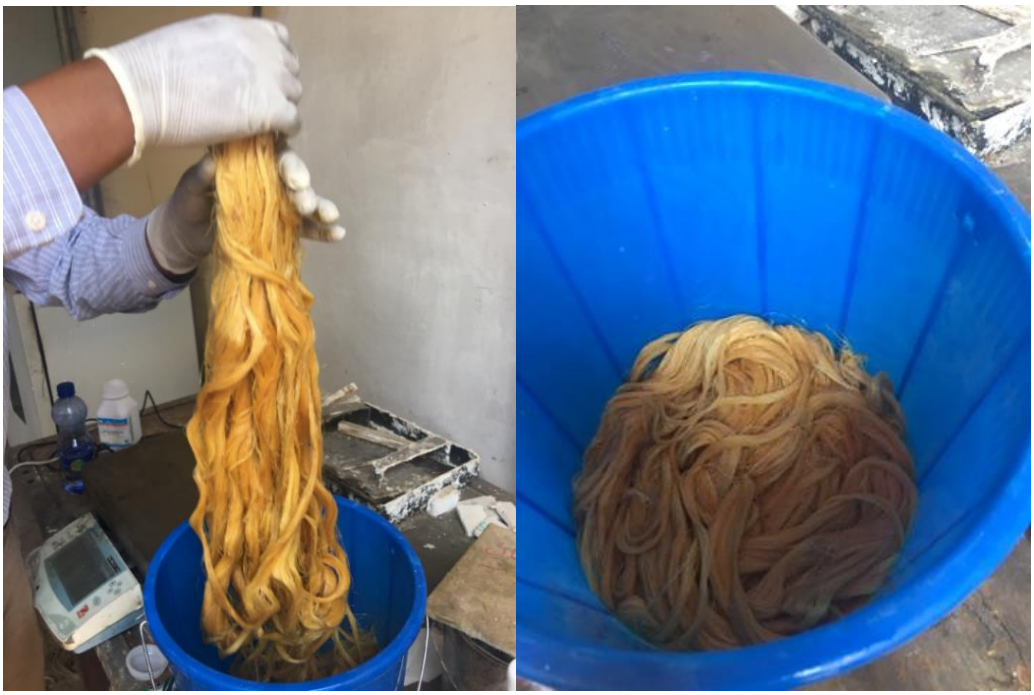

Figure 7 Sisal fiber soaked in NaOH solution for 24hrs

2. Next rinse the sisal fiber with water to remove the soda excess until PH ~ 7 will reach.

Figure 8 Pure Sisal fiber after mercerization

### 3.2.3 Weight fraction and volume fraction of the composite

The volume of the composite has been defined by the length, width and depth of the mold, which is prepared for molding the composite material and the total volume of the composite is also the sum of the volume sisal and epoxy resin.

$V_C = L * W * D$ ……. Eqn 18

$V_C = V_S + V_E$ ……. Eqn 19

Where: $V_C$ is volume of the mold / the composite,

$V_S$ *is volume of sisal and*

$V_E$ is volume of epoxy resin,

L is length of the mold

W is width of the mold, and

D is depth is the mold

The density of the composite was calculated in accordance with the law of mixture to be applied and was obtained first by adding the volume fraction of the epoxy resin and sisal fiber with the fiber- matrix ratio being 30/70 all the time. After calculating the density of the composite material, the total mass of the composite is calculated.

Density of the composite:

$$\rho_c = \frac{M_c}{V_c}$$ ……. Eqn 20

Where: $M_C$ is mass of composite

$V_C$ is volume of composite

We can define the volume of the composite from the above density equation:

$$\frac{M_C}{\rho_C} = \frac{M_S}{\rho_S} + \frac{M_E}{\rho_E} \quad \text{..... Eqn 21}$$

Where: $M_S$ is mass of Sisal, $M_E$ is mass of Epoxy,

$\rho_S$ is density of sisal = 1.33 gm/$cm^3$ and

$\rho_E$ is density of Epoxy = 1.2 gm/$cm^3$

Note: The density mention above for sisal fiber is not for the local Ethiopian sisal fiber. This value is taken because there is no available information about the density of Ethiopian sisal fiber.

Mass composition of the composite is percent mass composition of the fiber plus percent mass composition of Epoxy.

$M_C = x\% * M_S + y\% * M_E$ ..... Eqn 22

Where: $x$% is mass fraction of sisal fiber and $y$% is mass fraction of Epoxy resin so that $x + y = 1$.

The mass and volume composition of the composite material during test sample preparation is calculated as follows:

$volume\ of\ the$ mold $or\ composite, V_C = L * W * D$

$V_C = 230 * 230 * 5 = 264{,}500\ mm^3 = 264.5\ cm^3$

The main purpose of this thesis is to show the effect of changing the fiber orientation not the fiber matrix ratio. For this reason, as it is mentioned in the literature review section, the fiber- matrix ratio to be used for this thesis is fixed to be 30/70. This ratio is not found by using Ethiopian sisal fiber. But since there is no available study using Ethiopian sisal fiber, 30/70 ratio is taken for this study. The mass composition of the composite material for each fiber orientation has been summarized in the table below.

Table 3 : Fiber- matrix mass composition

| Orientation | Composition (%) | | Mass Fraction(gm) | | No of samples |
|---|---|---|---|---|---|
| | Sisal fiber | Epoxy resin | Sisal fiber | Epoxy resin | Plates |
| $[0^0/90^0]_2$ | 30 | 70 | 94 | 219.5 | 2 |
| $[0^0/45^0]_2$ | 30 | 70 | 94 | 219.5 | 2 |
| Random (Chopped) | 30 | 70 | 94 | 219.5 | 2 |

### 3.2.4 Preparing the sample

#### 3.2.4.1 Preparation of Epoxy and Hardener

Epoxy of System #2000, mixed with hardener System #2060 is used to prepare the composite plate. Two percent of hardener is mixed with the prespecified epoxy resin. Hardeners include anhydrides (acids), amines, polyamides, dicyandiamide etc. The mixture of epoxy and hardener are stirred for about one minutes continuously. The mixing is performed in the mixing container (Bowl). The bowl is made of Nickel to prevent melting of the Bowl during the exothermic reaction. This process is undertaken slowly to avoid any excess air bubbles in the resin.

#### 3.2.4.2 Hand-lay-up

Hand-lay-up method was adopted to fill up the prepared mold with an appropriate amount of epoxy resin mixture and layers of sisal fibers. The process consists of building up or placing layers of composite fiber in a sequenced layup using a matrix of resin and hardener. The quantity of accelerator and catalyst added to resin at room temperature for curing was 2% by volume of resin each. Fiber deformation and movement should be minimized to yield good quality composites. Therefore, at the time of curing a compression pressure of 50 bar (5MPa) was applied on the mold. In order to force the air gaps formed between the fibers and resin, the lay-up was gently squeezed by the hydraulic press and kept for several hours to get the perfect samples. Fiber orientation is the most important factor that is being analyzed here.

Three samples are prepared with different ply orientation and each sample except the one with random orientation is made up of 4 layers. Yet the mass composition for all the sample composites is the same as it is displayed on the above table.

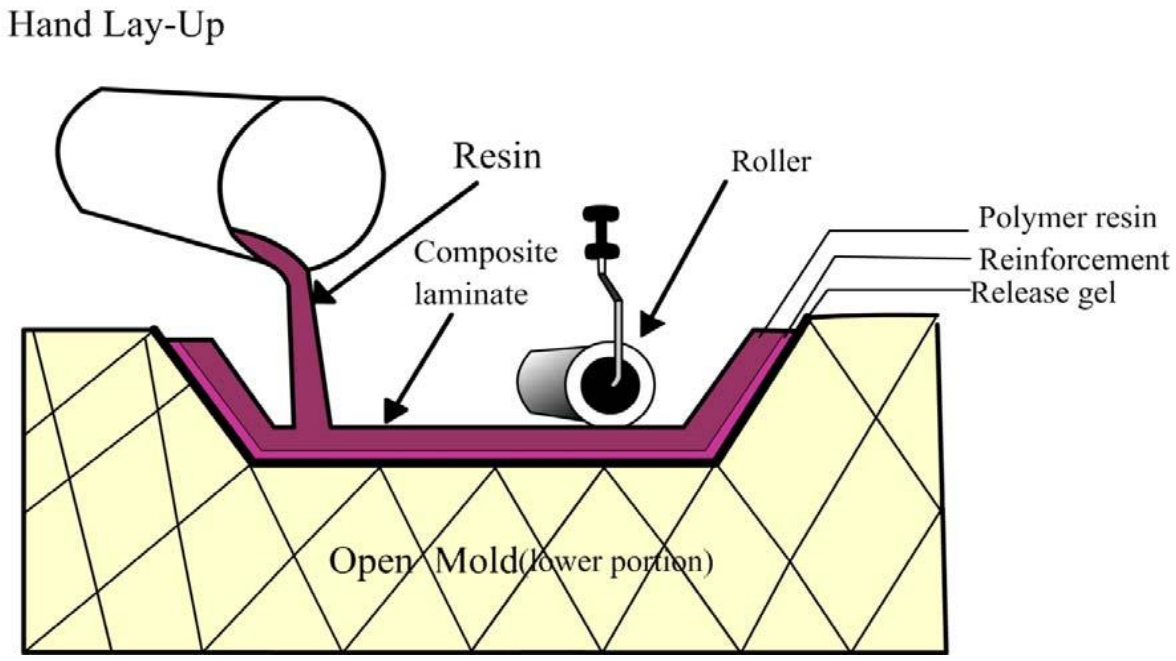


Figure 9 Hand-lay-up technique

**Materials Required for Hand-lay-up technique**:

- Mold
- Release Agent
- Resins
- Reinforcing Fibers
- Roller

**1. Mold**

Generally, a mold must be used for making parts using the lay-up process to place the layer in or on in order to obtain the desired shape. For this specific work the mold used is 230x230x20 mm in size, it consists of the basic parts, such as base plate, cover frame and the lower plate. The Base plate is a thin plate which is placed inside the frame. Base plates are used to cover, compress the

fiber after the epoxy is applied, and to avoid the debris from entering the composite parts during the curing time.

**2. Mold release agents**

These agents are used to prevent the resin from sticking to the mold when we want take out the final composite sample from the mold. There are several types of mold release used depending on the mold material and desired characteristics of the finished part. Some of the release agents used in industry are:

- Waxes
- spray releases
- release films
- internal releases (added to gel coat or resin system)

The most common type and used for this thesis work is paste wax (oil) for better surface finish of the composite. Release agents are usually applied to the composite molds or tooling in a separate designated area as they can act as a contaminate if accidentally integrated into the composite layup.

**3. Resins**

The resin acts as the matrix of the composite to 'bind' the composite materials together and transfer the component stresses that may act on the part to the fibers in the composite. The fibers are designed and selected to handle the designed stresses imposed.

Some resins commonly used in industry are:

- Unsaturated polyesters
- Specialty and High-performance Thermosets (vinyl esters)
- Epoxies

For this thesis work, System #2000 Epoxy and hardener resin is used.

**4. Reinforcing Fibers**

There are many different fibers that can be used to make up a composite and each material can be obtained in different formats. Both variables are design options that are available according to the design constraints of the final product and make up a significant part of the material selection

process. The fiber material under investigation in this research is already known and it is Sisal fiber.

### 3.2.5 Composite buildup procedure

An initial preparation of all the materials and tools that are going to be used is a fundamental standard procedure when working with composites. This is mainly because once the resin and the hardener are mixed, the working time (prior to the resin mix gelling) is limited by the speed of the hardener chemically reacting with the epoxy producing an exothermic reaction. Also, as part of the initial preparation, the sisal fiber was cut according to the shape and size of the part.

#### 3.2.5.1 Mold preparations

Before starting with the lay-up process an adequate mold preparation must be done. Mainly, this preparation consists of cleaning the mold and applying a release agent in the surface of it to avoid the resin to stick. The following activities are performed in this step.

- ✓ the mold was cleaned with a clean cloth
- ✓ the release agent was applied and spread in the surface of the mold
- ✓ Wait for a certain time to set up the release agent
- ✓ The surface is polished with clean cloth

Figure 10 The mold, as fibers are being put on it for a trial production.

### 3.2.5.2 Lay-up processes

All the materials are prepared, the workstation is ready and the mold preparation is done; the lay-up process can now be started. At first, the resin is mixed with the hardener. The portion of the hardener is kept at 2%. The portions can be either measured by weight or by volume but it is important to follow these proportions exactly as this is a complete chemical reaction and all components must react completely for maximum strength of the matrix.

Next an adequate quantity of mixed resin & hardener is deposited in the mold and a brush or roller is used to spread it around all surface. The weight percentage of the fiber and epoxy is kept constant.

The first layer of fiber reinforcement is then laid. This layer is wetted with resin and then softly pressed using a brush or a roller to make the resin that was added in the previous step wick up through the sisal fiber. If the fiber is not completely wet, more resin can be added over the top and spread around. At this stage a second layer of sisal fiber is added and special care was taken to eliminate all air bubbles as much as possible. This is accomplished by rolling any air bubbles out with a small hand rolling tool. This step is repeated until the desired thickness is obtained. As the sisal fiber layers are added to build laminates, the individual layers are oriented at varying angles.

(a) (b)

Figure 11 A trial Sisal fiber arrangement on the mold surface (a) - $[0^0,45^0]_2$, (b) – $[0^0,90^0]_2$

After all the layers are put on the mold, putting the upper plate of the mold, it will be pressed by using the press machine for consolidation and it is then left for 3 hours. The composite gets dried up within this time period after which the sisal fiber and the resin adhered each other tightly in the presence of hardener.

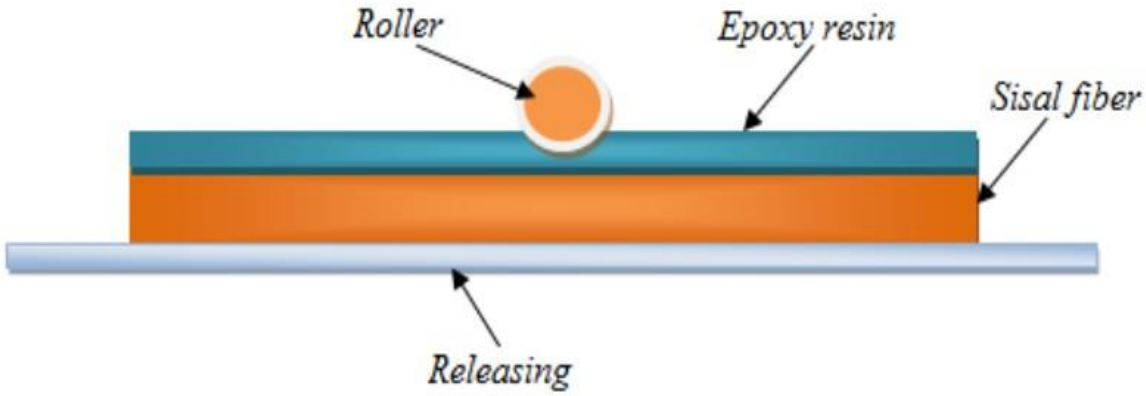


Figure 12 Sisal fiber reinforced epoxy composite molding

Figure 13 The sample inside the mold is being pressed by standard hydraulic press machine

#### 3.2.5.3 Curing

The samples can be cured at elevated temperatures using an oven (usually around 160 degrees F) or at room temperature. For this project, we left it to cure at room temperature and kept it in place until the next day. Now we have the sample composites ready for the next step.


Figure 14 Prepared samples with different fiber orientation

## 3.3 Experimental Procedures and Test

There are a lot of ways of performing fatigue tests. Regardless of the material type, one can use the different options to do the test. Some of the methods that can enable us to see the fatigue life of materials are through the use of, tensile-tensile fatigue test, where the material will be exposed to a cyclic tensile loading or bending fatigue test, where the material test will be carried out under a cyclic transversal loading condition. The later one has also different ways of doing it, such as three-point bending test and four-point bending test.

Studies comparing the fatigue results from various fatigue testing methods have tended to produce conflicting conclusions with regard to the relationship between tensile-tensile fatigue and bending fatigue [81], [82].

Di Benedetto et al. [80] found that the tensile fatigue method produced shorter fatigue lives when compared with bending tests. In contrast, Read and Collop [81] found good agreement between the tensile fatigue, two-point trapezoidal cantilever and uniaxial tension–compression test configurations for a range of asphalt mixture types. They attributed the good correlation between tensile fatigue and bending fatigue to the extended fatigue life associated with the rest periods used with the tensile fatigue loading but warned that this good agreement may only be valid for the specific test conditions used in their research. The bending test gives relatively better fatigue result according to these previously conducted researches. But, even if that was not the case, due to its simplicity and availability, three-point bending fatigue test is used in this research work.

### 3.3.1 Specimen preparation

All the plates that we have produced are now to be cut into smaller pieces so that we can fit them into the test machine. The American Society of Testing Materials (ASTM) recommends ASTM D 790 as a standard for the specimen to be used in the three-point bending test. The dimensional description of this standard is displayed down below.

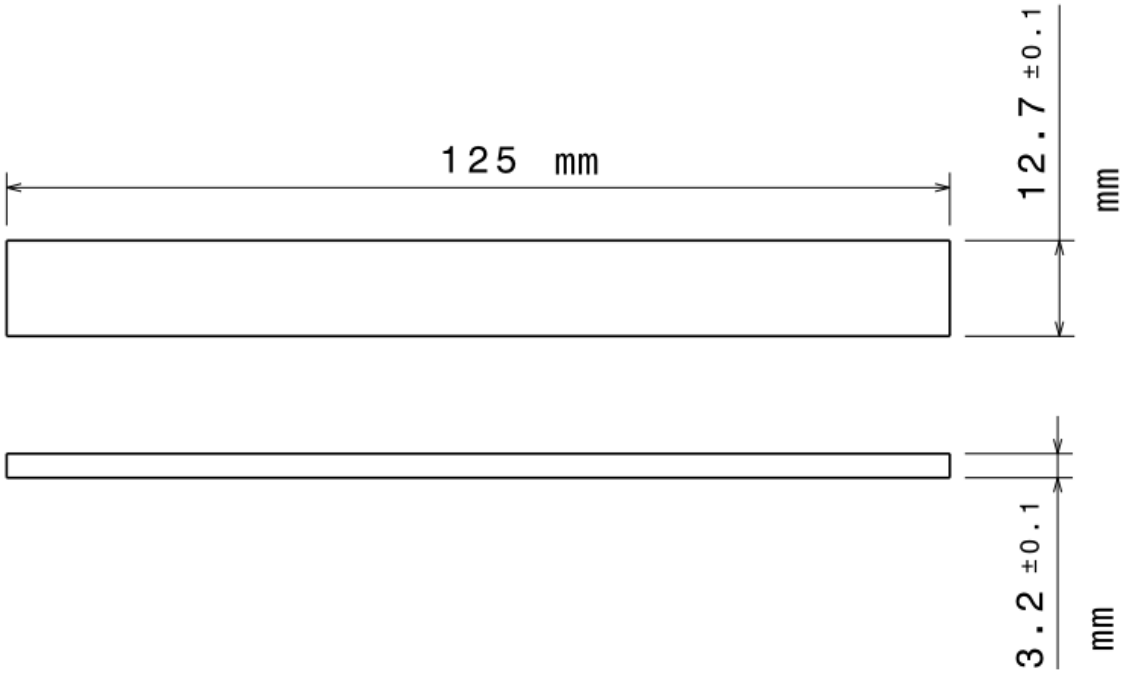


Figure 15 Dimension of ASTM D 790 Specimen for Three-point bending test


Figure 16 Specimens cut according to ASTM D 790 Standard with the gauge length indicated

### 3.3.2 Experiment Instruments

The Instron Series 4400 Universal Testing Instrument is a material testing instrument designed to test the strength of a wide variety of materials. The system is made up of a load frame, in which a specimen of the test material is mounted, that applies a tension or compression load to the specimen, and a control console that provides the calibration, test setup, and test operating controls. The control console is compact enough to mount directly on the load frame, eliminating the need for a separate support table or workbench.

The Control Console includes an operator's front panel with controls that offer complete communications with the system through a numeric keypad, push- button selection switches and Liquid Crystal Displays (LCDs). Suitable for both dynamic and static testing, Instron machines are being widely used in many experiments.

For this research, the mechanical testing was conducted using an Instron machine (Model 4483) equipped with a three-point bending system. This machine also incorporates an extensometer to measure the deflection of the specimen while the load is being applied.

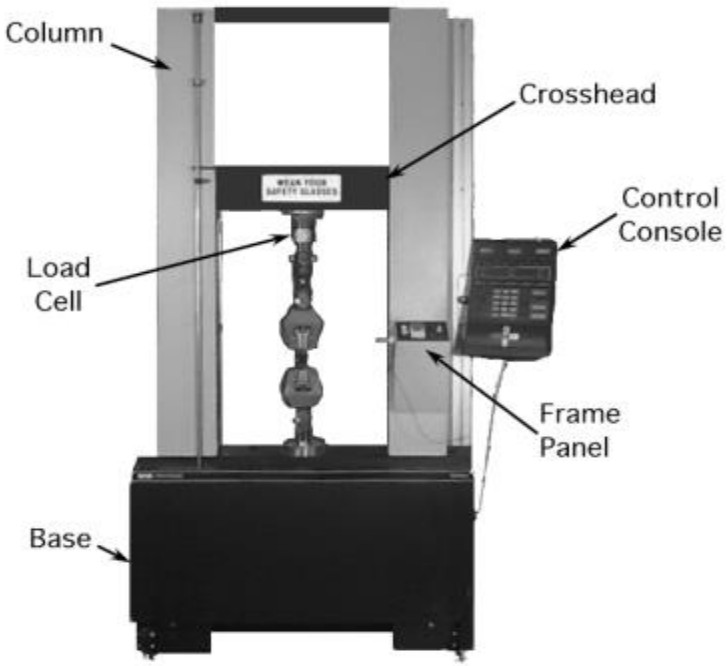


Figure 17 Instron, model 4483 load frame

### 3.3.3 Static Flexural Test

This specific test is mainly aimed at finding the appropriate loading condition that will be applied in the fatigue investigation of the material. Three randomly selected specimens are taken from each group with the standard gauge length of 125 mm.

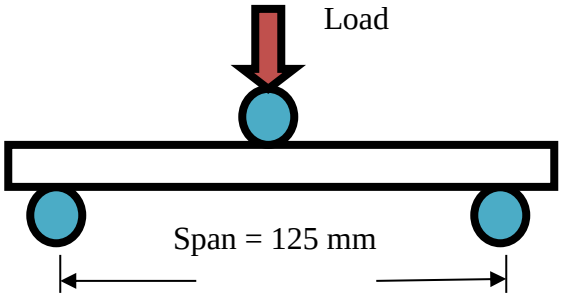


Figure 18:Schematic representation of three-point bending test

The test was carried out at room temperature. Each of the specimens were intentionally subjected to an increasing load until failure with the machine operating at a cross head speed of 2mm/min. According to ASTM D790 the rate of crosshead motion is calculated by the following equation and the machine is then set for this rate.

$$R = ZL^2 / 6d \quad \text{……Eqn 23}$$

where:

*R* = rate of crosshead motion, mm /min,

*L* = support span, mm,

*d* = depth of beam, mm, and

*Z* = rate of straining of the outer fiber, mm/mm/min. *Z* is equal to 0.0025.

The calculated value is 2.0345 mm/min. In no case shall the actual crosshead rate differ from that calculated using Eqn 23, by more than 10 %. Therefore, 2 mm/min is still fine to apply.

Through this test, the maximum and minimum loads that are taken by each specimen in their group are identified. The test setup is displayed below.

Figure 19 Fatigue / Static flexural test setup

### 3.3.4 Fatigue test

Fatigue test is a method for determining the characteristic of materials under fluctuating loading condition. This test is involved with the application of cyclic loads to the specimens and finding the number of cycles before it failed.

The result of the static flexural test is very important for the fatigue investigation of the material. It allows us to identify the load carrying capacity of the randomly selected specimens from which we will choose a representative load that can be applied during the fatigue test. The static flexural test result gave us the maximum and minimum load capacity for each group of specimens. If we are going to pick the maximum load from each group and apply it during the fatigue test, we know that the specimen will fail right away without enabling us to have a cyclic loading condition. We don't want to take the risk of breaking the specimens after one cycle.

Therefore, the minimum representative load must be selected from the static test result of each group of specimens. With that in mind, a minimum load of 150N, 220N and 150N are chosen for $[0,90]_2$, $[0,45]_2$ and Random specimens respectively. Then, percentage of these loads are applied on the respective group of specimens and the corresponding number of cycles before failure is registered.

This test was performed at the Materials Mechanics Center (MMC) of the Faculty of Mechanical Engineering, Technion, Israel Institute of Technology at a room temperature of about $23^0$ Celsius. It is conducted in the same way as the static test except the alternating load. With the help of the extensometer, a limit was set on the deflection, as an indication of failure (permanent deflection) without total breakage. Most of the specimens reached the limit which can be considered as some sort of fatigue failure. The frequency is set to be 5Hz with the cross-head speed being 2mm/min.

It is obvious that many sources of stress will factor into the fatigue performance of a component. This includes the design stress from mechanical sources (applied forces, pressures, or deflections), thermal stresses (elevated environmental temperatures or internally generated by heating), vibration, impact, and even residual stresses from forming or machining operations. Many of these sources are highly variable and unpredictable. Therefore, adaptation to various stress ratios may be an important criterion for wider applications although most of S-N models have been developed for particular stress ratios. According to Ibrahim Burhan and Ho Sung Kim [83], the stress ratios are divided into four ranges: R = 0 – 1 under tension-tension (T-T) loading, R = 0 – -1 under tension-compression (T-C) loading, R = -1 – -∞ under compression-tension (C-T) loading, R = -∞ – -1 under compression-compression (C-C) loading.

In this study, the specimens are rectangular and when it was tested under cyclic loading, the upper part of the material was under compression and the lower part was under tension with respect to the neutral axis. Unlike a material of cylindrical cross-section which is subjected to constant bending stress, not all the points are subjected to both tension and compression in this specimen. But, since it is subjected to some sort of fully reversed stress, the best possible stress ratio R is -1.

# Chapter Four

# 4 Result and Discussion

## 4.1 Experimental Result

### 4.1.1 Static Flexural Test result

The three-point bending flexural test provided us values of the maximum and minimum load carrying capacity, the flexural strength and flexural modulus of elasticity of the materials. The flexural property of the $[0^0,90^0]_2$, $[0^0,45^0]_2$ and Random group of specimens are shown below. The automated flexural testing machine helped us generate the Load – Displacement curves using the data obtained from the experiment. This curve highlights the relationship between the applied load and the deflection that the specimens made until failure.

Table 4 : Flexural property of $[0^0,90^0]_2$ specimens.

| *File Name* | *Max Load [N]* | *Delta [mm]* | *Width [mm]* | *Thickness [mm]* | *Flexural Strength [Mpa]* | *Flexural Modulus [Mpa]* |
|---|---|---|---|---|---|---|
| 0_90_st_1 | 222.12 | 10.09 | 12.70 | 3.20 | 139.73 | 7593.21 |
| 0_90_st_2 | 150.17 | 7.75 | 12.70 | 3.20 | 95.68 | 6684.45 |
| 0_90_st_3 | 186.06 | 6.20 | 12.70 | 3.20 | 121.86 | 11008.49 |

For a three-point bending test with the specimen having rectangular cross-section, the testing machine uses the following two known equations to calculate the flexural strength and the flexural modulus of the specimens respectively.

$$\sigma = 3FL / 2wd^2 \quad \text{.....Eqn 24}$$

$$E_b = L^3m / 4wd^3 \quad \text{.....Eqn 25}$$

Where:

σ = Flexural strength [MPa]

$E_b$ = flexural modulus in bending [Mpa]

F = Maximum force applied [N],

L = Length of the specimen[mm],

w = Width of the sample [mm] and

d = Depth of the sample [mm].

m = Gradient (i.e., Slope) of the initial straight-line portion of the load deflection curve, (N/mm)

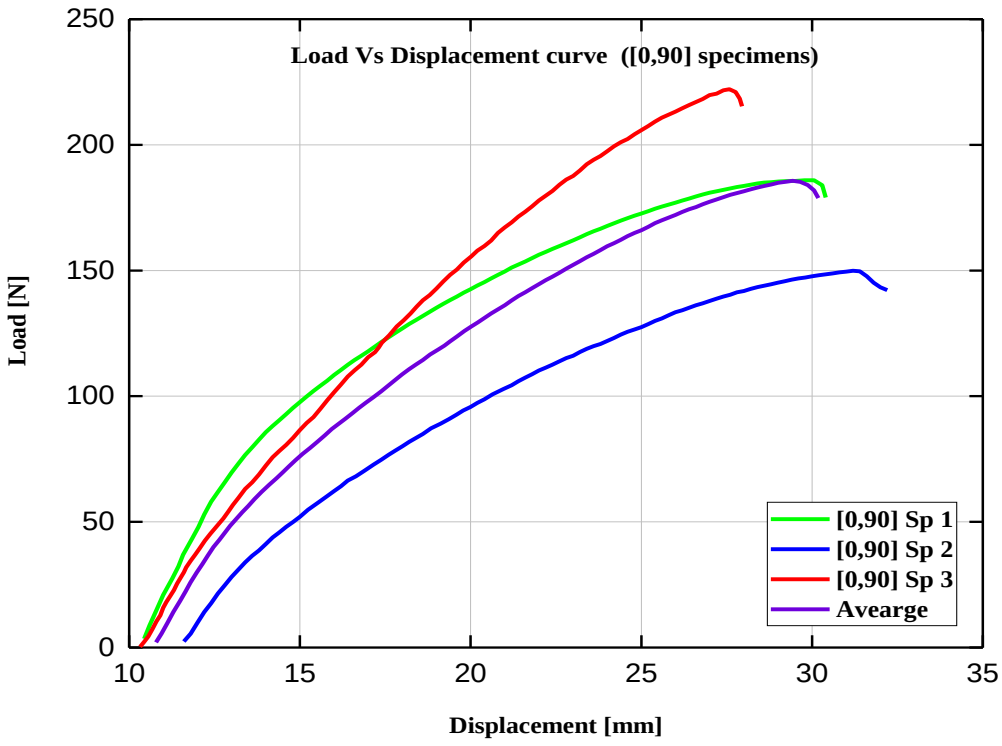


Figure 20 Load (N) vs Displacement (mm) curve for $[0^0,90^0]_2$ specimens

Table 5 : Flexural property of $[0^0,45^0]_2$ specimens

| *File Name* | *Max Load [N]* | *Delta [mm]* | *Width [mm]* | *Thickness [mm]* | *Flexural Strength [Mpa]* | *Flexural Modulus [Mpa]* |
|---|---|---|---|---|---|---|
| 45_st_1 | 224.91 | 8.10 | 12.70 | 3.20 | 154.17 | 10660.76 |
| 45_st_2 | 233.79 | 8.35 | 12.70 | 3.20 | 143.83 | 9099.00 |
| 45_st_3 | 222.01 | 7.87 | 12.70 | 3.20 | 141.88 | 9950.66 |

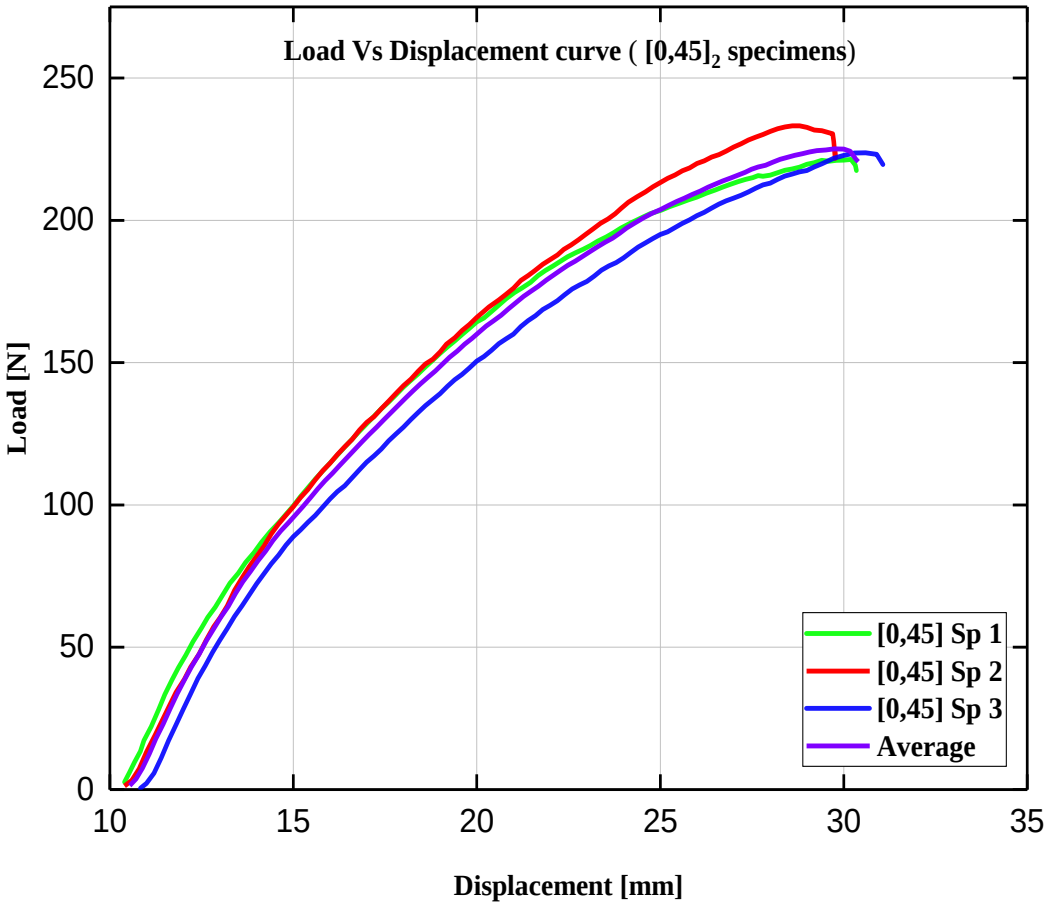


Figure 21 Load (N) vs Displacement (mm) curve for $[0^0,45^0]_2$ specimens

Table 6 : Flexural property of [Random] specimens

| *File Name* | *Max Load [N]* | *Delta [mm]* | *Width [mm]* | *Thickness [mm]* | *Flexural Strength [Mpa]* | *Flexural Modulus [Mpa]* |
|---|---|---|---|---|---|---|
| R_st-1 | 149.54 | 8.81 | 12.70 | 3.20 | 73.44 | 4034.44 |
| R_st-2 | 168.50 | 7.24 | 12.70 | 3.20 | 65.49 | 3937.36 |
| R_st-3 | 161.16 | 7.68 | 12.70 | 3.20 | 70.39 | 4171.21 |

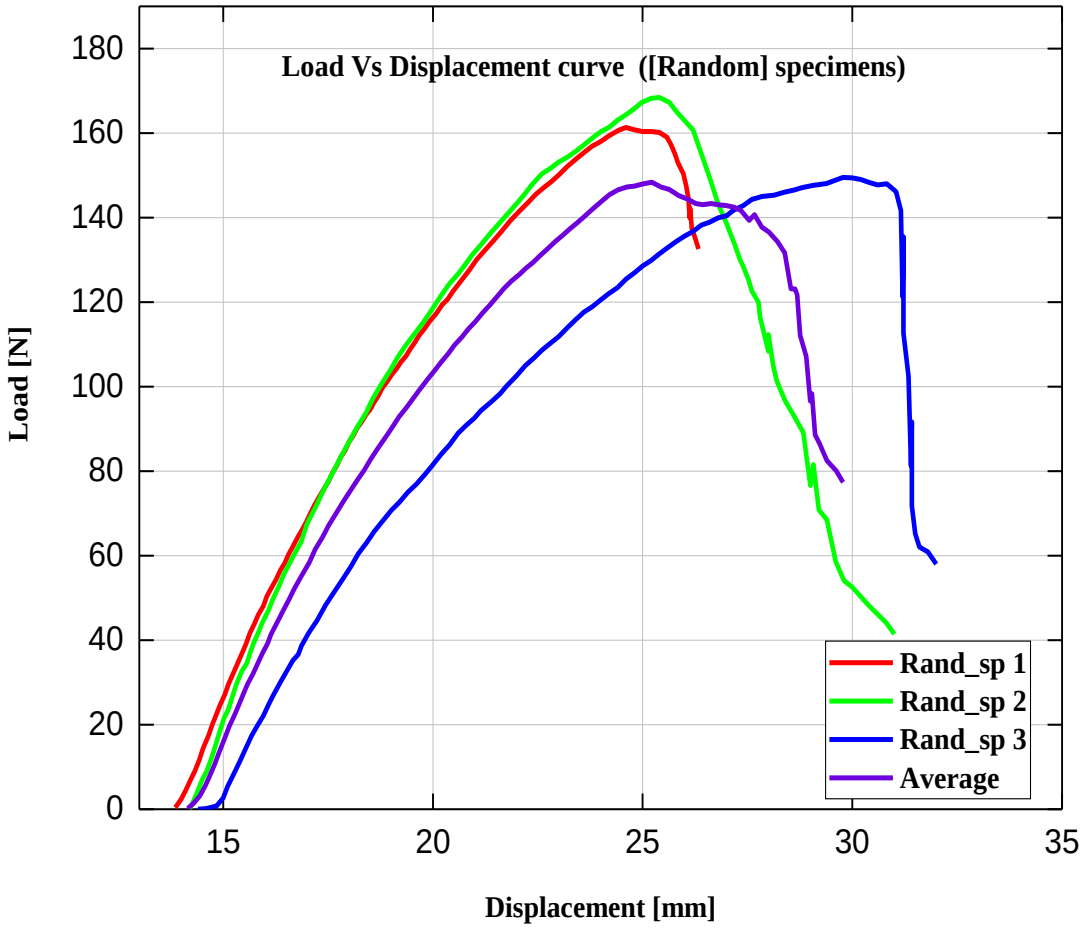


Figure 22 Load (N) vs Displacement (mm) curve for [Random] specimens

As we have seen from the above results, although different, each of the $[0^0,45^0]_2$ and [Random] specimens generated a closer result in terms of maximum load capacity, Flexural strength and Modulus of Elasticity. The $[0^0,45^0]_2$ specimens provided us with better results overall, thus, this configuration has better Flexural properties than the others. Whereas the [Random] specimens have the least Flexural properties. Out of the randomly selected and tested specimens, the maximum load taken by the specimens are 222N, 233N and 168N for $[0^0,90^0]_2$, $[0^0,45^0]_2$ and [Random] specimens respectively.

Moreover, each of the $[0^0,45^0]_2$ specimens failed in a closer deflection of 30 mm but the $[0^0,90^0]_2$ and [Random] specimens displayed a more scattered deflection from 10 mm to 30 mm when failed. The maximum displacement is exhibited in the $[0^0,90^0]_2$ specimens.

### 4.2.2 Fatigue test result

The applied load was organized and the corresponding number of cycles were found as shown in the tables below.

Table 7 : Fatigue test results of $[0^0,90^0]_2$ specimens

| Maximum representative load = 150N | | | | |
|---|---|---|---|---|
| Flexural Load (N) | Flexural Stress (N/m^2) | Cycles | # specimens | Failure Mode |
| 37.5 | 984251.9685 | 1.69E+06 | 1 | Limit |
| 52.5 | 1377952.756 | 1.36E+06 | 1 | Limit |
| 75 | 1968503.937 | 8.60E+05 | 1 | Limit |
| 97.5 | 2559055.118 | 3.63E+05 | 1 | Limit |
| 112.5 | 2952755.906 | 3.20E+04 | 1 | Limit |
| 120 | 3149606.299 | 2.53E+04 | 1 | Limit |
| 135 | 3543307.087 | 1.20E+04 | 1 | Limit |

Table 8 : Fatigue test results of $[0^0,45^0]_2$ specimens

| Maximum representative load = 220N | | | | |
|---|---|---|---|---|
| Flexural Load (N) | Flexural Stress (N/m^2) | Cycles | # specimens | Failure Mode |
| 55 | 1443569.554 | 1.08E+06 | 1 | Limit |
| 77 | 2020997.375 | 9.04E+05 | 1 | Limit |
| 110 | 2887139.108 | 6.40E+05 | 1 | Limit |
| 143 | 3753280.84 | 3.76E+05 | 1 | Limit |
| 165 | 4330708.661 | 2.00E+05 | 1 | Limit |
| 176 | 4619422.572 | 1.34E+05 | 1 | Limit |
| 198 | 5196850.394 | 2.11E+03 | 1 | Limit |

Table 9 : Fatigue test results of Randomly oriented specimens

| Maximum representative load = 150N | | | | |
|---|---|---|---|---|
| Flexural Load (N) | Flexural Stress (N/m^2) | Cycles | # specimens | Failure Mode |
| 37.5 | 984251.9685 | 1.55E+06 | 1 | Limit |
| 52.5 | 1377952.756 | 1.25E+06 | 1 | Limit |
| 75 | 1968503.937 | 8.00E+05 | 1 | Limit |
| 97.5 | 2559055.118 | 3.45E+05 | 1 | Limit |
| 112.5 | 2952755.906 | 4.16E+04 | 1 | Limit |
| 120 | 3149606.299 | 2.91E+04 | 1 | Limit |
| 135 | 3543307.087 | 4.15E+03 | 1 | Limit |

After the test is conducted, the specimens are displayed in the picture below. Almost all specimens have undergone a plastic deformation but not a total breakage. Only one of the randomly oriented specimens has broken during the test while the rest of the specimens from all the groups have failed without breakage by deforming plastically. With a 5 Hz loading frequency, it takes quite a lot of time for each individual specimen to break during the test. Because of this, some deformation limit was set. And once the specimens reach this limit, that will be considered as some sort of failure.

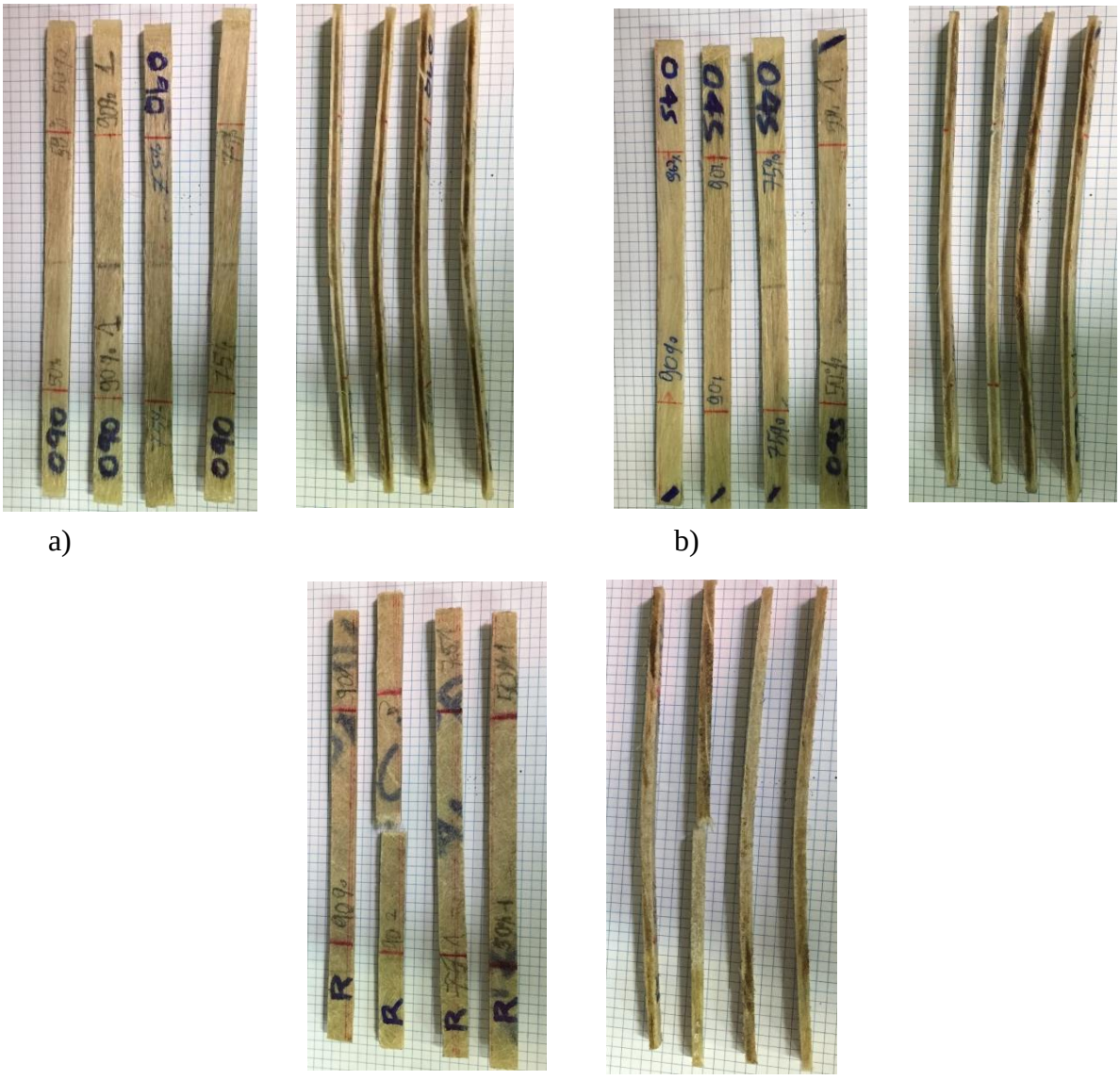

Figure 23 Fatigue failure of a) $[0^0,90^0]_2$, b) $[0^0,45^0]_2$ and, c) [Random] specimens

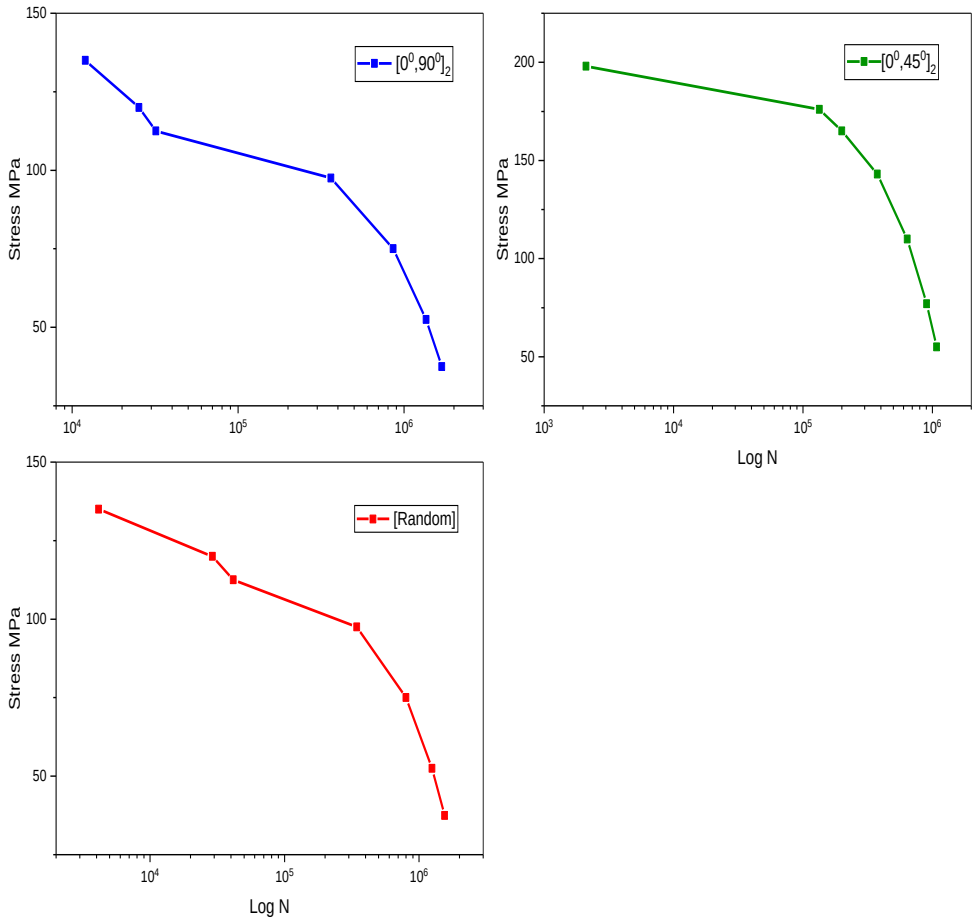


Figure 24: Individual S-N curves for each group of specimens

Below is the stress versus number of cycle curve. For ease of comparison, the above individual S-N curves are merged together. Due to the hugeness of the number of cycles on the abscissa, the graph is plotted using logarithmic scale. The S-N curve is one of the few methods that shows the fatigue characteristic of the material. From this curve, it is shown that the higher the load we apply on the material on a cyclic basis, the faster the rate of failure.

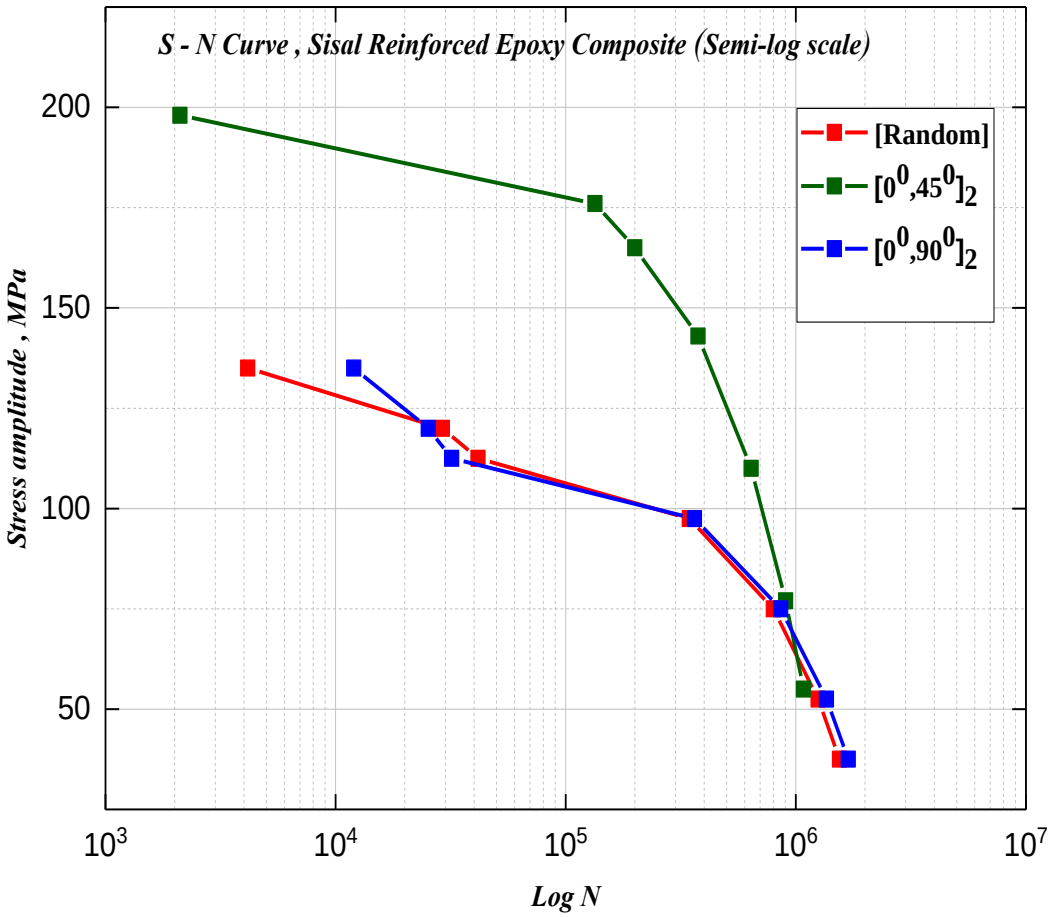


Figure 25 Stress vs Number of Cycle (S-N) Curve in Semi-Log scale

The fatigue data is also plotted using a linear scale. This scale gave us a curve which resembles more like the typical S-N curves if not completely exact. We did not get this in logarithmic scale because the material that we are dealing with is a composite material. The most common S-N curve that we know comes from steel and other metals and their fatigue behaviour is completely different than that of composite materials as we can see it from the graph here.

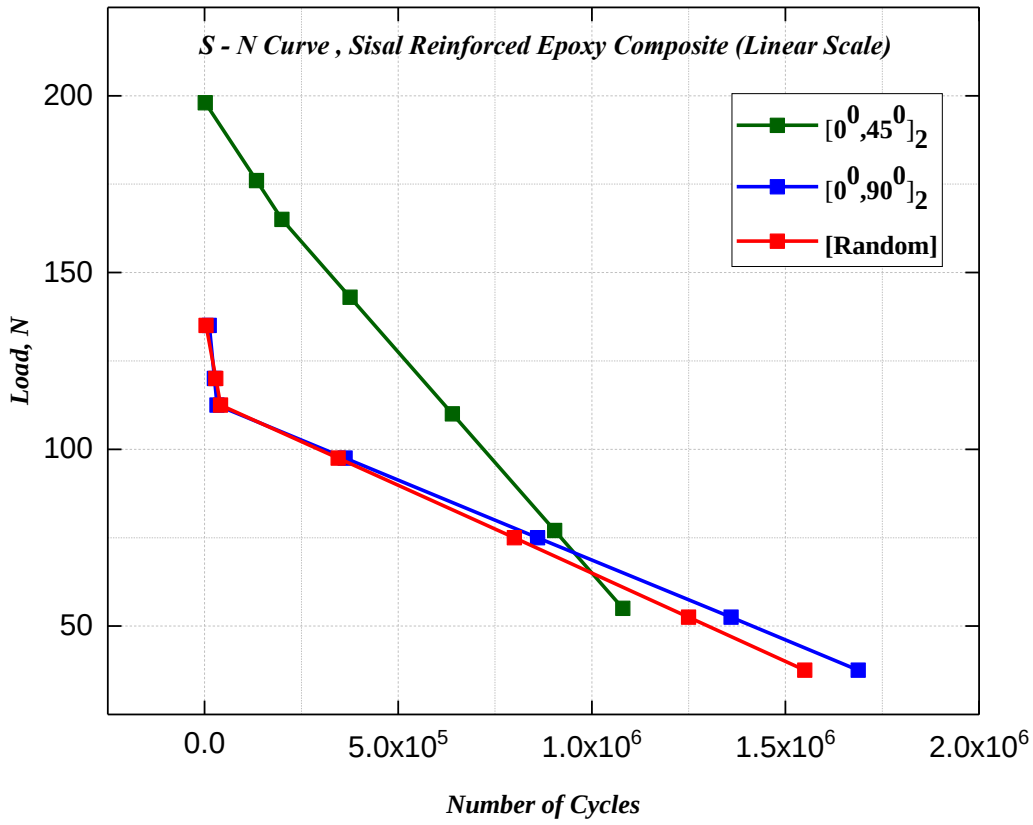


Figure 26 Stress vs Number of Cycle (S-N) Curve in Linear scale

The above S-N curve shows that $[0^0,90^0]_2$ and [Random] specimens tend to have a similar curve. That is because that we have taken a similar maximum representative load of 150N for both specimens. But still, they show some differences. If we draw horizontal lines so that it touches each nodes of the curves, the line will exactly pass through the nodes of both curves. That shows they both have accepted the same amount of load. The difference will be visible vertically. If we look at the linear curve above, there exists a gap between the red and blue dots. And the gap increases as the stress amplitude decreases. The maximum gap being found when the load applied is below 50N. This gap is the difference in number of cycles of each specimen. They have closer life cycle but $[0^0,90^0]_2$ has a better life comparatively. The worst of all is $[0^0,45^0]_2$. Even though it

can withstand a higher load statically, it has a much lower number of cycles compared to the other specimens. This may be due to the maximum load it can take at a time.

Generally, having accepted a maximum load, the $[0^0,45^0]_2$ configuration have only experienced 2/3 of the fatigue life of $[0^0,90^0]_2$ and [Random] specimens.

# Chapter Five

# 5 Conclusion and Recommendation

## 5.1 Conclusion

In this research work, Sisal fiber reinforced epoxy composite is prepared and tested under cycling loading condition. The fiber has been manually produced and passed through a lot of steps before it is combined with the epoxy. These steps are revised as follows.

- Harvesting the sisal plant
- Extracting the fiber manually and removing residues from it
- Treating the fiber with chemical and neutralize it with water
- Straightening the fiber and cutting it according to the mold size

Two percent Hardener was added to the Epoxy just before the final fiber is combined with it. The Sisal-Epoxy composite was then produced in different fiber orientations and with four layers using a hand lay-up method. Three composites were prepared with orientations of $[0^0,90^0]_2$, $[0^0,45^0]_2$ and [Random]. Since our intention in this research is to show the effect of fiber orientation in the fatigue reaction of the material, it does not really matter what kind of orientation we choose as long as they are different. Each group of composites were cut in to smaller pieces using ASTM standard for three-point bending test. The pieces were then subjected to static loads and the maximum load carrying capacities of the specimens were identified. The static test gave us maximum load capacities of 222N, 233N and 168N for $[0^0,90^0]_2$, $[0^0,45^0]_2$ and [Random] specimens respectively. But we chose the minimum static loads from each group as a maximum representative load for the fatigue test. The minimum loads found are 150N, 220N and 150N for $[0^0,90^0]_2$, $[0^0,45^0]_2$ and [Random] specimens respectively. By coincidence, out of all the randomly selected specimens for static test, the $[0^0,90^0]_2$ and [Random] were found to have the same minimum static load. Then percentage of these representative loads were applied cyclically during the fatigue test. From the data generated in static and fatigue tests, it was found that the $[0^0,45^0]_2$ fiber orientation resulted in a better flexural property such as transversal load capacity, flexural strength and modulus of elasticity. In average, the [Random] specimens have gained only 60% of the flexural strength of the $[0^0,90^0]_2$ specimens. Whereas the $[0^0,90^0]_2$ specimens are capable of

having 80% of the flexural strength of $[0^0,45^0]_2$ specimens. And $[0^0,90^0]_2$ fiber orientation exhibited the best fatigue life with the $[0^0,45^0]_2$ orientation having resulted in the lowest life at about 64% of the life of $[0^0,90^0]_2$ orientation. The randomly oriented specimens had the lowest flexural property but better fatigue reaction than that of $[0^0,45^0]_2$ specimens at about 92% of the life of $[0^0,90^0]_2$ orientation.

Similar researches have been conducted on other, most common, natural fiber reinforced epoxy composites such as Kenaf reinforced epoxy composite, Jute reinforced epoxy composite and Hemp reinforced epoxy composite. For instance, the research done by M. J. Suriani et al [84] shows that Kenaf reinforced epoxy composite can stay for up to $10^6$ life cycle. Similar fatigue research carried out by Padmaraj N H et al [85] shows that jute reinforced epoxy at 40% stress level can work for up to an average $10^5$ life cycle.

Generally, although the fatigue investigation of these materials might be carried out in different ways, such as different weight composition, fiber orientation, fatigue testing methods, etc., these natural fiber materials tend to have closer, if not higher, fatigue life with that of Sisal reinforced epoxy composite. The Sisal reinforced epoxy composite can stay for more than $10^6$ life cycle in all the three fiber orientation cases. This indicates that Sisal epoxy composite can also be an alternative material in applications where the above natural fiber composites are used or vice versa.

## 5.2 Recommendation

Although further static and fatigue investigations must be carried out on the sisal-epoxy composite through different ways, weather using finite element analysis or re-doing the experiment using different testing techniques and/or applying the material and seeing its reaction, based on our experimental result, $[0^0,90^0]_2$ and $[0^0,45^0]_2$ fiber orientations are generally recommended for two different application areas. For applications that experience static bending load, $[0^0,45^0]_2$ fiber orientations are better to use whereas $[0^0,90^0]_2$ fiber orientations are best suited for cyclic loading applications.

## 5.3 Future Works

As mentioned in the recommendation section, the material must be tested over and over again until it is proven to be confidential to use. But, beyond this, there are a lot of things that must be studied to contribute more to the materials acceptance. Some of these works are mentioned below.

- Effect of fiber reinforcement structures such as unidirectional, fabric, mat, or braiding on the fatigue and static behavior of sisal reinforced epoxy composite.
- Investigation on the influence of environmental conditions such as temperature and moisture absorption in the life cycle of sisal reinforced epoxy composite.
- Influence of Loading conditions such as stress ratio R and cycling frequency and boundary conditions on the mechanical and fatigue property of sisal reinforced epoxy composite.

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# APPENDIX A

*Table 10 Polynomial Failure Criteria*

| | Tsai-Wu | Tsai-Hill* | Azzi-Tsai* | Hoffman | Chamis*† |
|---|---|---|---|---|---|
| $F_1$ | $\frac{1}{\sigma_{1T}^u - \sigma_{1C}^u}$ | 0 | 0 | $\frac{1}{\sigma_{1T}^u - \sigma_{1C}^u}$ | 0 |
| $F_2$ | $\frac{1}{\sigma_{2T}^u - \sigma_{2C}^u}$ | 0 | 0 | $\frac{1}{\sigma_{2T}^u - \sigma_{2C}^u}$ | 0 |
| $F_3$ | $\frac{1}{\sigma_{3T}^u - \sigma_{3C}^u}$ | 0 | 0 | $\frac{1}{\sigma_{3T}^u - \sigma_{3C}^u}$ | 0 |
| $F_{12}$ | $\frac{-1}{2\sqrt{\sigma_{1T}^u \sigma_{1C}^u \sigma_{2T}^u \sigma_{2C}^u}}$ | $-\frac{1}{2}\left(\frac{1}{\sigma_1^{u\,2}} + \frac{1}{\sigma_2^{u\,2}} - \frac{1}{\sigma_3^{u\,2}}\right)$ | $\frac{-1}{\sigma_1^{u\,2}}$ | $-\frac{1}{2}\left(\frac{1}{\sigma_{1T}^u \sigma_{1C}^u} + \frac{1}{\sigma_{2T}^u \sigma_{2C}^u} - \frac{1}{\sigma_{3T}^u \sigma_{3C}^u}\right)$ | $\frac{-K_{12}}{\sigma_1^u \cdot \sigma_2^u}$ |
| $F_{13}$ | $\frac{-1}{2\sqrt{\sigma_{1T}^u \sigma_{1C}^u \sigma_{3T}^u \sigma_{3C}^u}}$ | $-\frac{1}{2}\left(\frac{1}{\sigma_3^{u\,2}} + \frac{1}{\sigma_1^{u\,2}} - \frac{1}{\sigma_2^{u\,2}}\right)$ | 0 | $-\frac{1}{2}\left(\frac{1}{\sigma_{3T}^u \sigma_{3C}^u} + \frac{1}{\sigma_{1T}^u \sigma_{1C}^u} - \frac{1}{\sigma_{2T}^u \sigma_{2C}^u}\right)$ | $\frac{-K_{13}}{\sigma_1^u \cdot \sigma_3^u}$ |
| $F_{23}$ | $\frac{-1}{2\sqrt{\sigma_{2T}^u \sigma_{2C}^u \sigma_{3T}^u \sigma_{3C}^u}}$ | $-\frac{1}{2}\left(\frac{1}{\sigma_2^{u\,2}} + \frac{1}{\sigma_3^{u\,2}} - \frac{1}{\sigma_1^{u\,2}}\right)$ | 0 | $-\frac{1}{2}\left(\frac{1}{\sigma_{2T}^u \sigma_{2C}^u} + \frac{1}{\sigma_{3T}^u \sigma_{3C}^u} - \frac{1}{\sigma_{1T}^u \sigma_{1C}^u}\right)$ | $\frac{-K_{23}}{\sigma_2^u \cdot \sigma_3^u}$ |
| $F_{11}$ | $\frac{1}{\sigma_{1T}^u \cdot \sigma_{1C}^u}$ | $\frac{1}{\sigma_1^{u\,2}}$ | $\frac{1}{\sigma_1^{u\,2}}$ | $\frac{1}{\sigma_{1T}^u \cdot \sigma_{1C}^u}$ | $\frac{1}{\sigma_1^{u\,2}}$ |
| $F_{22}$ | $\frac{1}{\sigma_{2T}^u \cdot \sigma_{2C}^u}$ | $\frac{1}{\sigma_2^{u\,2}}$ | $\frac{1}{\sigma_2^{u\,2}}$ | $\frac{1}{\sigma_{2T}^u \cdot \sigma_{2C}^u}$ | $\frac{1}{\sigma_2^{u\,2}}$ |
| $F_{33}$ | $\frac{1}{\sigma_{3T}^u \cdot \sigma_{3C}^u}$ | $\frac{1}{\sigma_3^{u\,2}}$ | 0 | $\frac{1}{\sigma_{3T}^u \cdot \sigma_{3C}^u}$ | $\frac{1}{\sigma_3^{u\,2}}$ |
| $F_{44}$ | $\frac{1}{\sigma_{23}^{u\,2}}$ | $\frac{1}{\sigma_{23}^{u\,2}}$ | 0 | $\frac{1}{\sigma_{23}^{u\,2}}$ | $\frac{1}{\sigma_{23}^{u\,2}}$ |
| $F_{55}$ | $\frac{1}{\sigma_{13}^{u\,2}}$ | $\frac{1}{\sigma_{13}^{u\,2}}$ | 0 | $\frac{1}{\sigma_{13}^{u\,2}}$ | $\frac{1}{\sigma_{13}^{u\,2}}$ |
| $F_{66}$ | $\frac{1}{\sigma_{12}^{u\,2}}$ | $\frac{1}{\sigma_{12}^{u\,2}}$ | $\frac{1}{\sigma_{12}^{u\,2}}$ | $\frac{1}{\sigma_{12}^{u\,2}}$ | $\frac{1}{\sigma_{12}^{u\,2}}$ |

$\sigma_1^u$, $\sigma_2^u$, $\sigma_3^u$: normal strength of the lamina in the 1, 2 and 3 directions.
$\sigma_{23}^u$, $\sigma_{13}^u$, $\sigma_{12}^u$: shear strengths of the material in the 23, 31 and 12 planes.
* $\sigma_1^u$, $\sigma_2^u$, $\sigma_3^u$: $\sigma_{1C}^u$, $\sigma_{2C}^u$, $\sigma_{3C}^u$ or $\sigma_{1T}^u$, $\sigma_{2T}^u$, $\sigma_{3T}^u$ depending on the sign of $\sigma_1$, $\sigma_2$and $\sigma_3$ respectively.
† $K_{12}$, $K_{13}$ and $K_{23}$: strength coefficients depending on the material.