Tiina Ojamo

FATIGUE OF THE ORTHOTROPIC LAYER

in Glass Fiber Reinforced Composites

Bachelor's thesis
Degree Programme of Materials and Surface Treatment

May 2012

MIKKELIN AMMATTIKORKEAKOULU
Mikkeli University of Applied Sciences

KUVAILULEHTI

MIKKELIN AMMATTIKORKEAKOULU
Mikkeli University of Applied Sciences

Opinnäytetyön päivämäärä

7.5.2012

Tekijä
Tiina Ojamo

Koulutusohjelma ja suuntautuminen
Materiaali- ja pintakäsittelytekniikka

Nimeke

Ortotrooppisen kerroksen väsyminen lasikuitulujitetuissa komposiiteissa

Tiivistelmä

Opinnäytetyö käsitteli lasikuitulujitettuja komposiitteja ja niiden mekaanisten ominaisuuksien määrittämistä. Lasikuitulaminaattien valmistus kuvattiin ja staattisten sekä dynaamisten kokeiden periaatteet selvitettiin.

Kahta laminaattityyppiä edustavat testikoekappaleet valmistettiin Ahlström Glassfibren Mikkelin tehtaalla. Toinen testattava laminaatti oli lujitettu perinteistä E-lasia käyttäen, toisessa oli käytetty korkean lujuuden omaavaa lasikuitua. Matriisimuovina oli epoksihartsi. Laminaatin valmistajaa kiinnosti selvitys siitä, onko korkean lujuuden omaavaa kuitua sisältävällä laminaatilla selvästi paremmat ominaisuudet kuin vertailumateriaalilla. Tuulimyllyn siiven laparakenteessa käytettävältä komposiitilta vaaditaan erityisesti hyviä lujuus- ja jäykkyysominaisuuksia. Tutkimusongelmaan sisältyi myös kysymys, voiko staattisten kokeiden perusteella ennakoida väsytyskokeiden tuloksia.

Staattisten vetokokeiden tuloksista ilmeni, että korkean lujuuden lasikuitua sisältävä materiaali oli jäykkyydeltään parempi. Kimmomoduulin lukuarvot olivat noin kymmenen prosenttia korkeammat kuin vertailukoekappaleilla. Väsymiskäyttäytymisen ennustamista staattisten kokeiden tulosten perusteella pohdittiin kirjallisuuden ja aiempien tutkimushavaintojen valossa.

Asiasanat (avainsanat)

laminaatti, lasikuitumuovi, lujuus, väsyminen

Sivumäärä	Kieli	URN
46 + 4 (Liite 1)	englanti	

Huomautus (huomautukset liitteistä)

Liitteessä luottamuksellista tietoa.

Ohjaavan opettajan nimi
Tapio Lepistö

Opinnäytetyön toimeksiantaja
Ahlstrom Glassfibre Oy, Mikkeli

DESCRIPTION

MIKKELIN AMMATTIKORKEAKOULU
Mikkeli University of Applied Sciences

Date of the bachelor's thesis

7.5.2012

Author
Tiina Ojamo

Degree programme and option
Degree Programme of Materials and Surface Treatment

Name of the bachelor's thesis

Fatigue of the Orthotropic Layer in Glass Fiber Reinforced Composites

Abstract

This thesis focused on the characterization of glass fiber reinforced composite materials and the determination of their mechanical properties. The manufacture of glass fiber reinforced laminate materials was described and the basic methods of their static and fatigue testing were presented.

Two types of glass fiber reinforced laminate specimens were fabricated by Ahlstrom Glassfibre in Mikkeli and applied in the static tests reported in this thesis. One of the specimen types represented traditional E-glass reinforced laminate, the other was cut from laminate material that had been prepared using high strength glass fiber. The manufacturer of the laminate was interested in finding out whether the high strength glass would yield remarkably better test results and thus be worth considering an appropriate material to be used in wind turbine blade structures. Another, mainly theoretical topic in the context of this thesis, was touched on, namely the question, if the results obtained from the static tests could predict the fatigue behavior of composite material.

The results of the static tests were reported concentrating mainly on the values of the elastic modulus obtained. This preliminary testing indicated that specimens containing high strength glass fiber had better stiffness properties. The improvement in the values of the elastic modulus was approximately ten per cent. The potential fatigue behavior of the specimens tested and the various parameters involved in the fatigue behavior of composites were discussed.

Subject headings, (keywords)

fatigue, glass fiber composite, strength, elastic modulus, orthotropic

Pages	Language	URN
46 + 4 (Appendix 1)	English	

Remarks, notes on appendices

Appendix 1 (p. 1-4) confidential data

Tutor
Tapio Lepistö

Bachelor's thesis assigned by
Ahlstrom Glassfibre Oy, Mikkeli

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LIST OF SYMBOLS

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LIST OF SYMBOLS

E = elastic modulus (Young's modulus)

σ = tensile stress, strength

σ_y = yield strength
σ_u = ultimate strength
σ_F = fracture strength

ε = strain, elongation

ρ = density

V_f = volume fraction

v_f = volume of fibers
v_c = volume of the composite

W_f = weight fraction

w_f = weight of fibers
w_c = weight of composite

ν = Poisson's ratio

P = axial load

L_0 = original gage length

L^* = length of the deformed test specimen

A_0 = cross-sectional area of the test section

G = shear modulus

R = stress ratio

1 INTRODUCTION

The present study deals with glass fiber reinforced (GFR) composites and their mechanical properties. Composites typically consist of two or more materials which together form a new material that has improved characteristics. A composite material consists of two main components: a matrix and reinforcement. In glass fiber reinforced composites the matrix is often constituted by polymers, and glass fiber functions as a reinforcement. The keen interest in composite materials is for the most part due to the demands presented by advanced technology. There are various fields that utilize applications of composites e. g. transportation, building and construction industry, electronics industry as well as sports and leisure. Manufacturers strive to develop new high performance materials. The specific stiffness, strength and fracture toughness of composites are properties that most interest the composite manufacturing technologies. /1, p. 7-8. /

This bachelor’s thesis has two major purposes. First, it aims to provide a description of different types of GFR composites, their manufacture and essential mechanical properties. The basic forms of static and fatigue testing applied in the determination of these properties are introduced. The basic properties of laminates are defined and the analysis of the fiber/matrix relationship in composite structures is discussed from both the micromechanical and macromechanical points of view. The second aim is to carry out static tensile tests for two types of unidirectional glass fiber laminate, describe the test procedure and report the test results. Based on the theoretical background presented, the interpretation and significance of the results are also considered.

There are also two main questions to which the present study wishes to find answers. The first was put forward by Ahlström Glassfibre in Mikkeli, which was the manufacturer of the laminates to be tested. The 84 specimens applied in the tests were cut from two different types of laminate: the RA and RY specimens were prepared from a laminate with traditional E-glass reinforcement, whereas the WA and WY specimens were cut from a laminate that contained high strength glass. The manufacturer was interested in finding out the differences between the test results of the two specimen types. Would it be worthwhile and cost competitive to use the more expensive high strength material in laminate structures? Would the evidently improved strength and stiffness achieved be significant enough? This thesis will focus on the values of the elastic modulus, that is on the stiffness property of the materials. These particular composite laminates prepared by Ahlström Glassfibre were fabricated in order to be used in wind turbine blade structures. The demands for the strength and stiffness properties of the laminate material are understandably high, since blades have to be designed to function under severe loading and high numbers of fatigue cycling. The second interesting question is of a more theoretical kind. Can the values of the elastic modulus obtained in static testing predict the fatigue behavior of GFR composite materials? Since there are no fatigue test results that could be compared with the data of this study, the problem has to be approached on the basis of literature.

Chapters 2-4 of this thesis concentrate on the description of GFR composites and their manufacture. The principles of the experimental determination of their mechanical properties are presented. In addition, examples of the definition of laminate properties by calculation models are introduced. Chapter 5 provides a discussion on the fatigue of laminates. The implications of the fatigue behavior on the design of laminate structures are also touched on. Chapter 6 consists of the report of the static tests that were carried out in the material laboratory of Mikkeli University of Applied Sciences. The results of the tests are presented in Appendix 1, and their interpretation is included in Chapter 7.

2 FIBER REINFORCED POLYMER COMPOSITES

The term composite refers to a combination of at least two distinct materials in which the materials in question function together and complement each other. The component materials do not, however, blend and form a mixture. Instead, their properties work together and create a heterogeneous material, whose performance outstands that of either of the constituent materials. A composite typically consists of two principal components: a matrix and a reinforcing filler, which is usually in the form of fibers or particles. The matrix supports the fibers. Reinforced polymers constitute one of the most important subdivisions among composite materials. The matrix may consist of either thermosetting resins or thermoplastic polymers. The reinforcing filler, in most cases fiber, increases significantly the original stiffness and strength of plastics. It is typical that the mechanical strength of the matrix is relatively low when compared to the reinforcement. The reinforcement, on the other hand, is often stiffer and brittle. If the combination of matrix material and reinforcement is supposed to function properly and maximum benefit is to be gained, as much as possible of the applied stress should be borne by the fibers. The matrix ideally supports the fibers and transmits the external loading to them. /1, p. 80; 2 p. 8. /

It is structurally the best alternative to apply reinforcements in a filamentous form to improve such important properties as strength and stiffness of a plastics composite. A fiber may contain several thousand filaments whose diameter is only a few microns. Fiber length may vary from circa 3mm to hundreds of meters in filament winding applications. A group of filaments is called a strand. Twisted strands form a yarn. Filament bundles which are held together by a binder are mats. A bundle of continuous strands is called a roving. /3, p.17-20; 2, p. 14. /

In a typical polymer composite product the reinforcing fibers, strands, or mats are stacked on top of each other forming layers, which are also called lamina or plies. The structure that is formed is called a laminate. The simplest type of laminate as regards to its fiber direction is the unidirectional laminate with all its fibers oriented at 0˚. In the case of a cross-ply laminate the fibers of every layer are oriented at either 0˚or 90˚. /3, p.22; 4, p.300. /

There are several ways in which composites can be classified. One of them is to divide different composites into groups according to the type of reinforcement applied. Some composites contain continuous long fibers with unidirectional, bidirectional or random fiber orientation. Others possess discontinuous fibers, which have random or some preferential orientation. There are also composites which are reinforced by particles or whiskers. Another way of classification is based on laminate configuration. The composite material may be unidirectional and include layers having the same material and orientation or it can be a laminate possessing some layers that vary in this respect. Some of the layers may have different orientation and they can also consist of a different material. /5, p.2; 3, p. 22. /

In the mechanical models of composite structures it is usually assumed that the material is macroscopically homogeneous and linearly elastic. Homogeneous here refers to the properties of the fiber reinforced layer which are expected to be the same in each point of the plane. Linearly elastic implies the fact that the deformation in the material increases proportional to the loading and disappears when the loading is removed. The assumption of the material's linearly elastic character may be presented when the loading is low enough and short-term. /3, p.26. / The basic tensile stiffness properties of metals are obtained by applying only a few tests. Composites tend to be more complicated. This is due to a directional dependence caused by their anisotropy. The anisotropic character of a material depends on how symmetrical it is. Isotropic materials have countless symmetry planes. Most composites that are used nowadays are two-dimensional. As a result of this they have one plane of symmetry. They are referred to as transversely isotropic. When the structure and mechanics of fiber-reinforced materials are discussed, an orthogonal coordinate system can be applied that has one axis which is aligned with the fiber direction. In Figure 1 direction 1 is the fiber direction, 2 and 3 are the matrix directions. The direction perpendicular to the fibers is also called the transverse direction. /6, p.102; 4, p.41. /

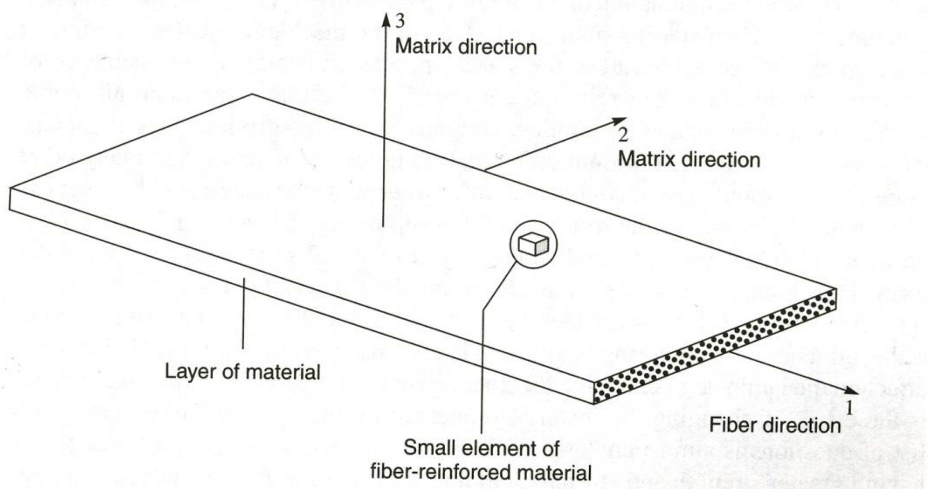


FIGURE 1. A laminate layer and the orientation of the material coordinate system /4, p. 40. /

The study of the stress-strain behavior of a composite material concentrates on the response of a single layer. If each individual fiber in the composite had to be taken into account, the analysis would be a lot more difficult. The composite material does, however, not have identical properties in all directions. The characteristics of the fiber reinforced layers are oriented, but not in an arbitrary manner. It is clear that in the 1 direction (Figure 1) the material is stronger as well as stiffer than in the 2 and 3 directions. Also, since the 2 and 3 directions are perpendicular to the fiber direction, their properties may not be equal to each other. A material that has differing properties in three mutually perpendicular directions is orthotropic. A layer of a laminate can also be referred to as orthotropic. Unidirectional laminates are an example of particularly orthotropic materials. All their fibers are oriented at 0˚. Most composite laminates used in practical applications possess orthotropic symmetry. /4, p.41. /

The matrix of a composite has several functions. It binds the reinforcing fibers together, distributes the loads, increases the chemical resistance and possibly the fire behavior of the material and also gives the product its shape /2, p.31/. Most of the plastic composites that are used in construction are fabricated using fiber reinforced thermosets. Among the most important properties of thermosets is their low viscosity i.e. ability to wet out the reinforcement. Also pot life, which is the time between mixing the matrix resin with catalyst and accelerator and the moment it reaches the maximum allowable viscosity, plays a key role. The tensile elongation at break of the cured resin should be higher than for the reinforcement that is used. In addition safety of use and environmentally friendly composition are essential. The most widely used laminating resins are unsaturated polyester resins. They can be cross-linked or cured through the unsaturated links so that they give hard, infusible and insoluble thermoset solids. Epoxy resins are the second important group. The best mechanical properties can in fact be achieved by applying epoxies. A basic epoxy resin may contain small quantities of mineral fillers, additives and curing agents. / 2, p.32-3. /

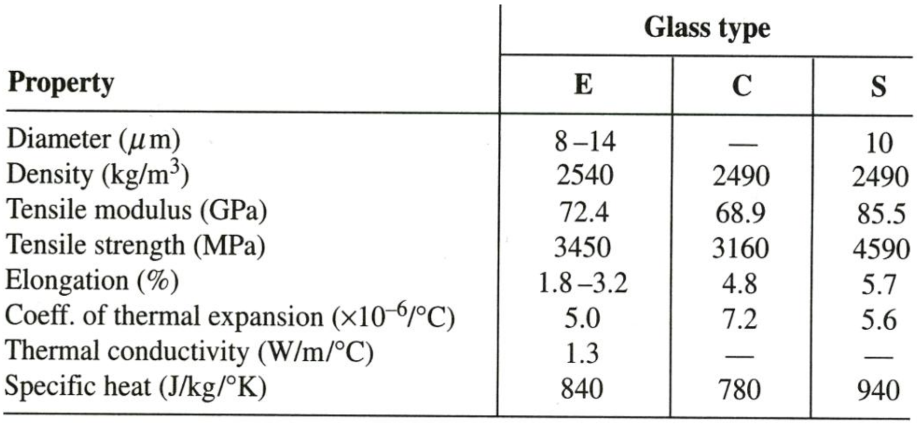
Reinforcements are used to strengthen cured resin systems. In fact any fibrous material can be used, but actually the number of fibers used is quite small. The best-known reinforcing fibers are glass, carbon fibers and aramids. The most important mechanical properties of a reinforcement are its elastic modulus (E) and ultimate tensile strength (σ). The elastic modulus (E) can be defined as “the ratio of the stress or load applied to the strain or deformation produced in a material that is elastically deformed” / 7, p.15 /.The ultimate tensile strength (σ) of a material refers to the highest stress sustained in a tension test /7, p.24 /.When a suitable reinforcement has to be chosen for a composite material, these properties are often presented as proportional to density. They are referred to as specific characteristics i.e. specific stiffness (E/ρ) and specific strength (σ/ρ). In the case of composites the specific characteristics, especially the specific strengths of reinforced polymers, are significantly higher than the corresponding values of metals. The best result in strength and stiffness is achieved when unidirectional continuous fibers are used. /3, p.370-373. / The mechanical properties of the end product are also to a great extent affected by the bonding between reinforcement and matrix. It is usual to prefer a strong bond between matrix and reinforcement. It is, however, possible that in some cases the toughness of a material, which actually means its ability to absorb energy, is increased by a weak bond between matrix and fiber. On such occasions energy is absorbed due to slipping between matrix and fiber. / 6, p. 70-71. /

The most important reinforcement both commercially and for industrial applications is glass fiber. Continuous filament glass fibers started to be applied as reinforcement in the 1950s, even though they were produced commercially in the UK as early as in about 1930. Glass in the form of fibers is relatively inexpensive. This undoubtedly accounts for the fact that glass covers more than 95% of all use of reinforcements. It has been estimated that globally its application to reinforce plastics will increase 3-5% each year. In Finland glass fiber was until 2011 manufactured by Ahlstrom Glassfibre in Karhula. Ahlstrom manufacturing plant in Mikkeli produces, for example, various glass fiber composite products, glass fiber tissue and industrial nonwovens. /3, p. 74. / The test specimens of the experimental part of this study were manufactured at Ahlstrom Glassfibre Mikkeli plant. The static tests which will be reported in this thesis form part of a larger project, in which high quality glass fiber laminates with significantly better fatigue properties are tested in order to be used in wind turbine blade production.

2.1 Types of Glass Fiber and Their Manufacture

There are a number of different types of glass which can be converted into fibers that can function as reinforcement. Commercially only a few basic compositions are worth using. ‘A’ or Alkali glass used to be commonly applied as the basic material in glass fiber production. Nowadays ‘E’ or Electrical grade glass is used in most applications. E-glass is a low alkali content borosilicate glass. It has good electrical and mechanical properties as well as significant chemical resistance. Also C-glass is an especially chemical resistant glass. It is used in the manufacture of surfacing tissues to bring additional chemical resistance e.g. in corrosive environments. There is also a variety, the ECR-glass developed by Owens Corning Fiberglass, in which the good mechanical qualities of E-glass and the chemical resistance of C-glass combine. In addition, ‘R’ and ‘S’ glasses are produced as fibers to provide advanced composites with extra strength. They are high strength glasses that are used, for example, in aerospace applications. /8, p. 312. / The compositions and properties of some of the glasses are presented in Table 1.

TABLE 1. Properties of glass-based fibers /4, p. 21/



Property	Glass type		
	E	C	S
Diameter (μm)	8 –14	—	10
Density (kg/m^3)	2540	2490	2490
Tensile modulus (GPa)	72.4	68.9	85.5
Tensile strength (MPa)	3450	3160	4590
Elongation (%)	1.8 –3.2	4.8	5.7
Coeff. of thermal expansion ($\times 10^{-6}$/°C)	5.0	7.2	5.6
Thermal conductivity (W/m/°C)	1.3	—	—
Specific heat (J/kg/°K)	840	780	940

There are two main types of process to produce continuous filament glass fibers. Either marbles or direct melt can be worked at. Today direct melt is preferred. When it is applied, molten glass is drawn through numerous bushings that are accurately dimensioned in a platinum alloy crucible (Figure 2). A constant head of glass is kept under accurate temperature control. Sizing is an important part in the production. The processability of the fibers is determined by the size. It also prevents any inter-fiber abrasion. One of its functions is to hold the filaments together, when they are processed into yarns and fabrics. Normally a size consists of four components. First, there is a coupling agent, which promotes the bonding between the matrix resin and the fiber. Usually it is an organic silicon compound or silane. Secondly, a film forming polymer is acting as a binder. Often a polyvinyl acetate emulsion is applied. Thirdly, a lubricant - usually an acid amine is needed. The fourth component includes other materials, e.g. antistatic additives, which are used to give desired properties to the fibers. A gathering shoe collects together all the fibers and combines them. Before its end use, the water content of the fiber has to be diminished. This is possible by drying the fiber in the oven. /4, p.19-21. /

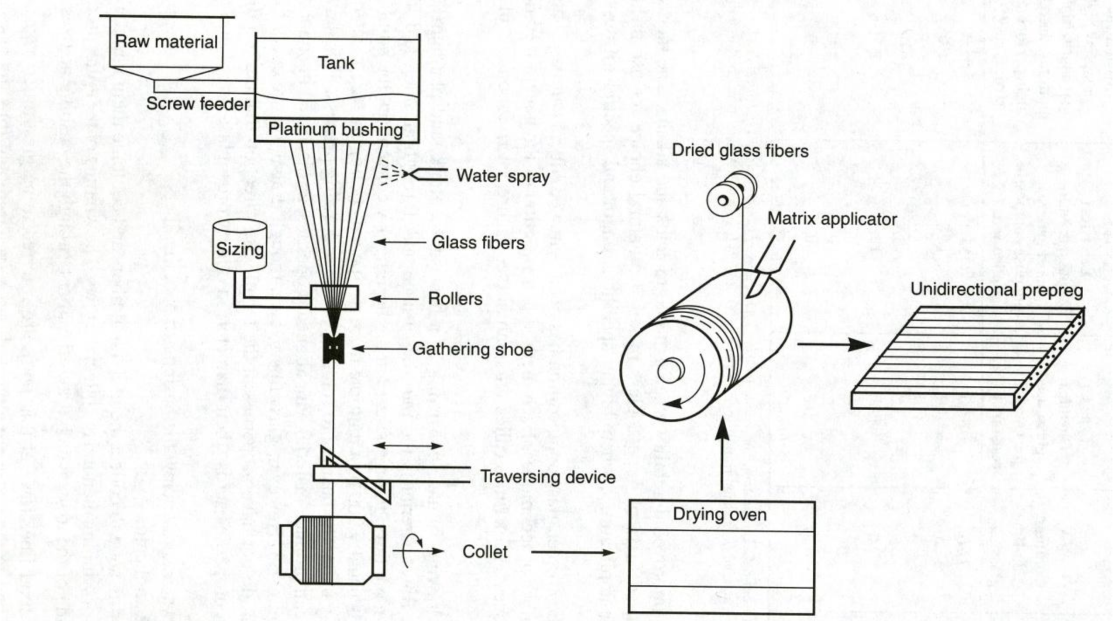


FIGURE 2. Glass fiber production / 4, p. 20/

In Europe fibers are classified by using fiber diameter named ‘tex’. This refers to the weight of 1000 m of a strand which is composed of circa 200 filaments. Continuous filament glass rovings contain one or more strands (200 filaments) of fibers parallel wound, without twist, onto a spool or cheese (Figure 3).

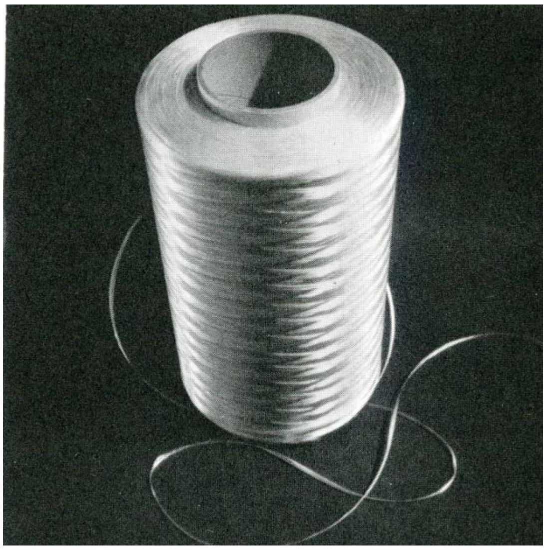


FIGURE 3. A roving cheese. /8, p. 314/

The size of the spool and number of strands are dependent on end use. Different types of roving are manufactured for different processes. /8, p. 313-314. / When advanced composites are developed and produced, various parameters have to be taken into account. The glass composition is one of the most important parameters when higher strength fiber is aimed at. A finer filament diameter usually associated with a low tex, does not always bring the highest strength. /9, p. 298. /

It is usually fairly easy to choose a type of reinforcing glass fiber. In case no particular property like extra lightness or stiffness of the end product is required, it is natural to end up with the inexpensive E-glass. S-glass produces a little lighter end product without unreasonable growth in raw materials costs. The Finnish standards for reinforced plastics and standards for pipes and tanks approve as reinforcement only E-glass or a better reinforcement. /3, p. 371. / Advantex was developed in 1997 to improve the cost-performance ratio of composites. Moreover, the Hiper-tex group of high performance reinforcements was introduced in 2006. In this product range Windstrand enabling up to 35% higher strength was intended particularly for wind turbine blades manufacture. /9, p.297. /

2.2 Manufacture of Glass Fiber Reinforced Composites

Several basic methods exist for manufacturing thermoset composite products. They can be varied and also combined in numerous ways. The properties of the product are naturally dependent on the method of manufacture. For this reason it is worth developing the production processes and methods. In this way it is possible to achieve desired characteristics such as high fiber volume, required orientation of fibers and flawless structure (no pores, good adhesion, homogeneity). / 10, p.145. /

Resin systems are produced by mixing the resin and necessary catalysts and inhibitors together. These systems have a number of mechanical and thermal properties. The functions of a resin system are firstly, to hold the fibers together and in that way help to distribute the load evenly, and secondly, to protect the fibers from abrasion and also corrosion after curing. /11, p.107-8./ When composites are processed, the fibers and the resin mixture are pressed into the required shape and size in the mold. After that the mixture is left to cure in order to become permanently hardened. The main types of processing illustrated by Figure 4 are: contact molding, filament winding, pressure bag molding, pultrusion, matched-die-molding and continuous laminating. The processing can also be divided into open mold processing and closed mold processing. In the former only one mold is applied and the material is in contact with the mold on one surface only. The technique is frequently exploited in civil engineering applications. In the case of closed mold processing, the product is formed inside a closed space formed by two molds. Open mold processes are manual, with the exception of filament winding, whereas closed mold processes are semi-automatic or automatic. /12, p. 331-2. /

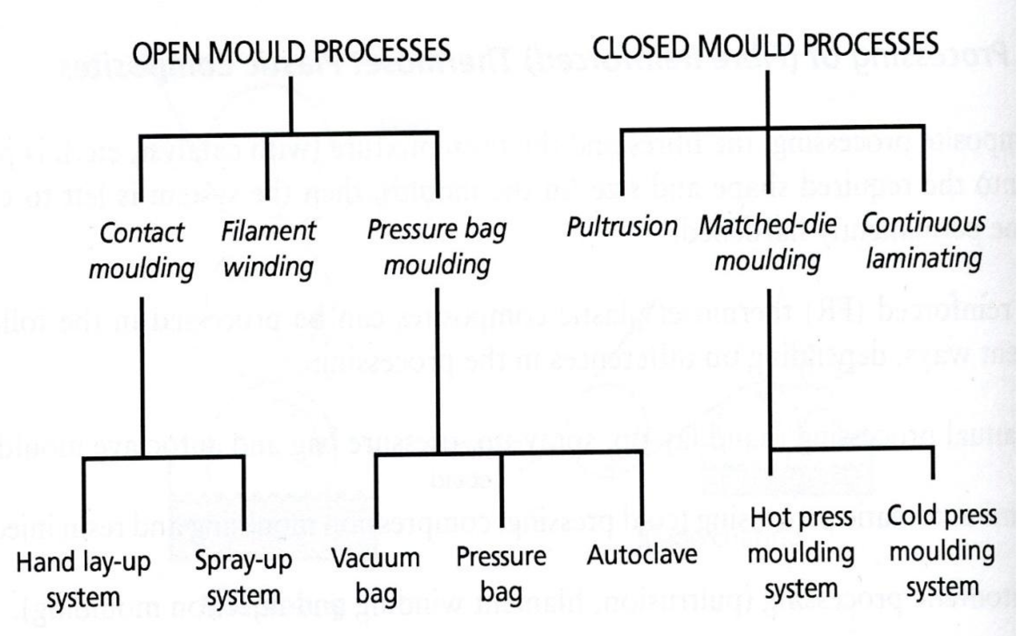
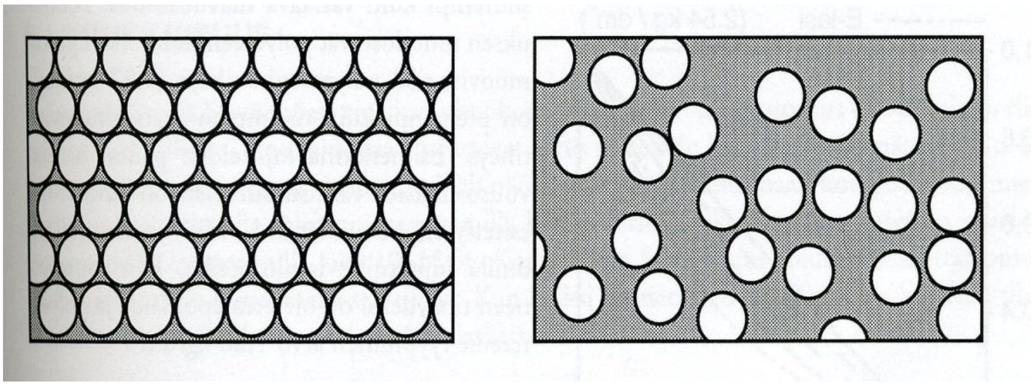


FIGURE 4. The main types of processing glass fiber /12, p. 332/

The amount of fibers in a composite can be announced in terms of the volume fraction V_f. This is the ratio of the volume of the fibers, v_f, to the volume of the composite v_c. /1, p.83. / The theoretical upper limit of fiber content is related to the highest possible packing density of round unidirectional fibers (Figure 5a), which is about 91v %. In practice the fibers have always dispersed unevenly (Figure 5b). There is also always resin material between the fibers transmitting the load from one fiber to another. The realistic upper limit for fiber content in a unidirectional fiber reinforced structure is therefore 65-70 v %. /3, p. 231. /



(a) (b)

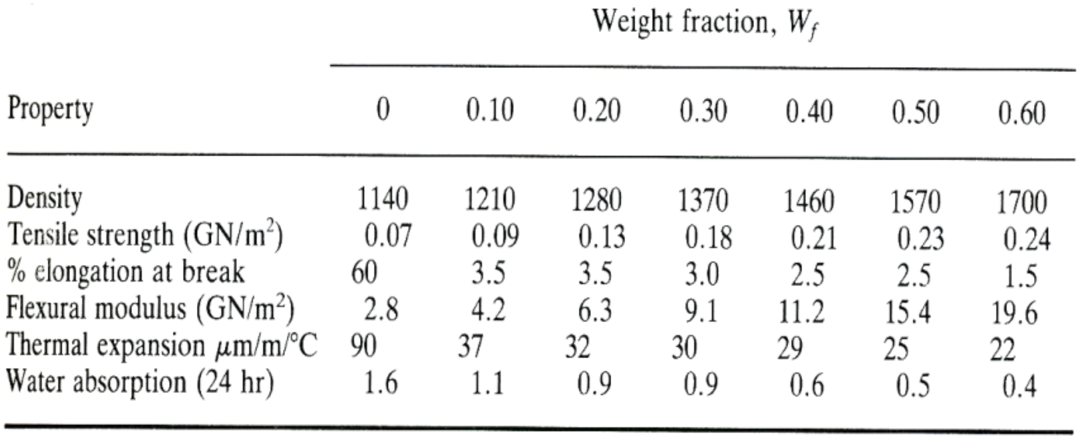
FIGURE 5 (a) and (b). The theoretical highest possible packing density of round unidirectional fibers in a composite (a) and the typical packing density of fibers in practice (b) /3, p. 231/

The weight fraction, W_f is related to the volume fraction in the following way:

$$W_f = \frac{w_f}{w_c} = \frac{\rho_f}{\rho_c}\frac{v_f}{v_c} = \frac{\rho_f}{\rho_c} V_f \ , \qquad (1)$$

where ρ is the density, and the subscripts $_f$ and $_c$ refer to fibers and composites /1, p. 83/. Weight fractions play a key role, e.g. when raw materials are measured out. In the context of the study of mechanical properties it is essential to know the volume fractions. When composites are manufactured, it is frequently necessary to convert weight fractions into volume fractions and vice versa. In normally used laminates the density of the reinforcement is nearly always higher than that of the matrix-resin combination. /3, p. 231-2. / Table 2 shows how the characteristics of polyamide are affected by the fiber content.

TABLE 2. Effect of fibre content on properties of glass reinforced nylon 66 /1, p.83 /



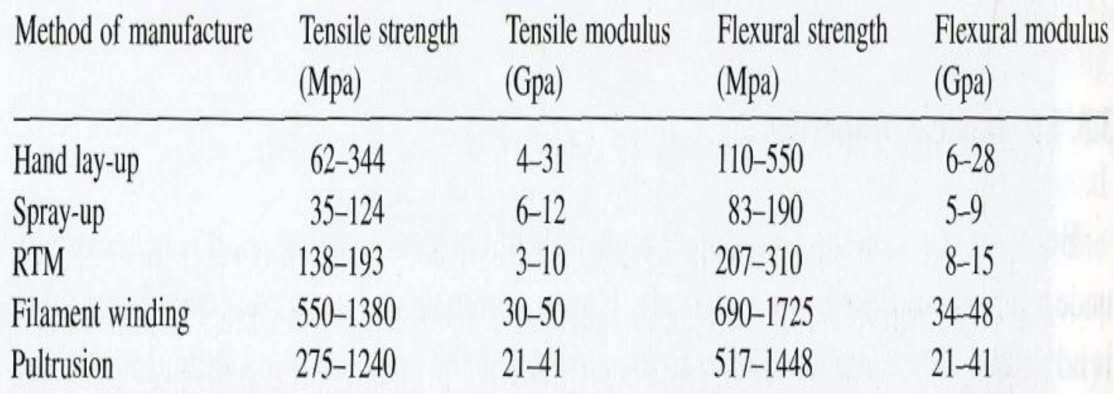
	Weight fraction, W_f						
Property	0	0.10	0.20	0.30	0.40	0.50	0.60
Density	1140	1210	1280	1370	1460	1570	1700
Tensile strength (GN/m^2)	0.07	0.09	0.13	0.18	0.21	0.23	0.24
% elongation at break	60	3.5	3.5	3.0	2.5	2.5	1.5
Flexural modulus (GN/m^2)	2.8	4.2	6.3	9.1	11.2	15.4	19.6
Thermal expansion $\mu m/m/°C$	90	37	32	30	29	25	22
Water absorption (24 hr)	1.6	1.1	0.9	0.9	0.6	0.5	0.4

Glass fiber reinforced (GFR) composites can be divided into two classes according to their reinforcing fiber content and length and the size of the end product. Commodity composites are produced in large quantities and used in normal everyday life. They are usually manufactured of polyester resin or engineering polymers and reinforced with E-glass fiber. Their fiber content by weight is about 30%. High performance composites are, as a rule, made of epoxy resin or specific thermoplastics and have often been reinforced with long R-glass fibers. The reinforcing fiber contents are high, in general over 50%. The mechanical properties of high performance composites are significantly better than those of standard metals. /2, p.11. /

3 EXPERIMENTAL DETERMINATION OF THE MECHANICAL PROPERTIES OF GFR COMPOSITES

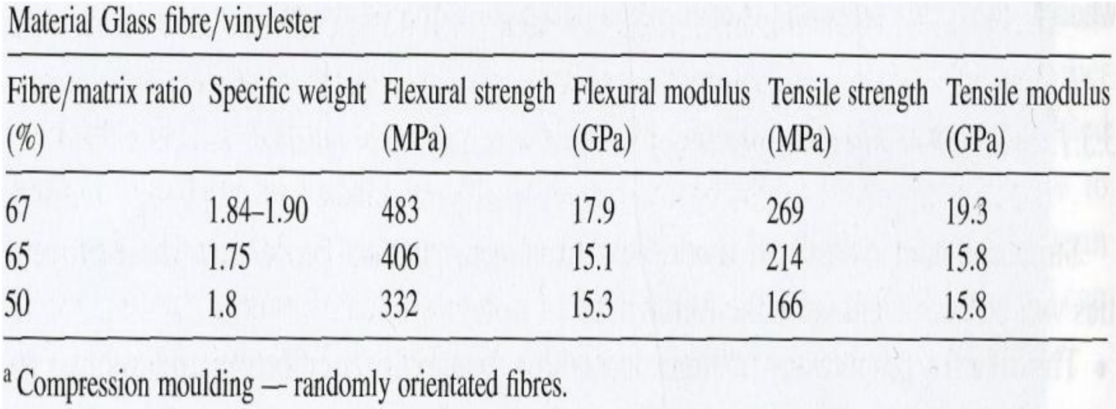
Structural composites possess numerous mechanical properties. These properties usually depend on four factors: the relative proportions of fiber and matrix materials i.e. the fiber/matrix volume or weight ratio, the method of manufacture, the mechanical properties of the components and the fiber orientation within the polymer (unidirectional, bi-directional, off-axis or randomly orientated). There is also always an amount of porosity left in the composite, which may have a noticeable effect on the properties of the end product. /3, p. 231-233. / Table 3 shows some typical mechanical properties of GFR composites manufactured by different techniques. Table 4, on the other hand, illustrates the variation of the properties, when the fiber/matrix ratio is changed, but the method of manufacture and the components of the composite remain the same. /13, p.51-2. /

TABLE 3. Typical mechanical properties of glass fibre composites manufactured by different fabrication methods /13, p. 52/



Method of manufacture	Tensile strength (Mpa)	Tensile modulus (Gpa)	Flexural strength (Mpa)	Flexural modulus (Gpa)
Hand lay-up	62–344	4–31	110–550	6–28
Spray-up	35–124	6–12	83–190	5–9
RTM	138–193	3–10	207–310	8–15
Filament winding	550–1380	30–50	690–1725	34–48
Pultrusion	275–1240	21–41	517–1448	21–41

TABLE 4. Typical mechanical properties of glass fibre/vinylester polymer^a /13, p.52/



Material Glass fibre/vinylester

Fibre/matrix ratio (%)	Specific weight	Flexural strength (MPa)	Flexural modulus (GPa)	Tensile strength (MPa)	Tensile modulus (GPa)
67	1.84–1.90	483	17.9	269	19.3
65	1.75	406	15.1	214	15.8
50	1.8	332	15.3	166	15.8

[a] Compression moulding — randomly orientated fibres.

The mechanical short term properties of laminates and laminate layers are defined by carrying out tests. The tests in the case of layers are generally run using laminates that consist of several layers aligned to the same direction. Laminate tests are also carried out to ensure the validity of the results obtained in calculating the strength and stiffness values of the material. The various types of tests that are normally run include, for example, tests determining tensile, flexural or compressive strength and modulus as well as tests of interlaminar shear strength and impact strength. Tensile tests are run in order to determine the ultimate tensile strength (σ) and the elastic modulus (E) of a material. Also Poisson’s ratio (ν) may be measured. The determination of these values is of particular importance, since the stiffness of the material is essentially represented by its elastic modulus and Poisson's ratio. /3, p. 294. / The experimental part of the present thesis concentrates solely on static tensile tests. In the following, however, both static and fatigue tensile tests, will be discussed in more detail.

3.1 Tensile Tests

In general, strength refers to the ability of a structure to resist loads without failure. Failure can take place because of rupture due to excessive stress. It may also occur as a result of excessive deformation. Tensile properties refer to the ability of materials to resist pulling or stretching forces. Tests are performed in order to define the load-deformation behavior of materials. The tensile test is started by mounting the specimen in a testing machine grips. The loading rate varies depending on the standard between 2-10 mm/min. An electromechanical extensometer is attached on the specimen to measure the extension (elongation) that will take place over the gage length. Before testing the specimen is marked in order to define the original gage length, L_0. Gage length is not equal to specimen length. An axial load P causes an elongation in the specimen between the gage marks. While the specimen is pulled, the testing machine measures and records the load P. In many cases the extensometer directly measures the elongation ΔL, where $L*$ is the length of the deformed test specimen:

$$\Delta L = L * - L_0 \tag{2}$$

A stress-strain diagram can be plotted by using the values of stress and extensional strain. The values used are the engineering stress (σ) i.e. the load divided by the original cross-sectional area of the test section, and the engineering strain (ε) i.e. the elongation divided by the original gage length:

$$\sigma = \frac{P}{A_0} \quad , \quad \varepsilon = \frac{L* - L_0}{L_0} \tag{3}$$

It is possible to deduce the elastic modulus of a material by reading the stress-strain diagram. The ratio of stress to strain in a chosen linear region of the diagram is called the elastic modulus. It is obtained by:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{4}$$

The interpretation of a stress-strain curve can be of valuable use in predicting material behavior in different engineering structures. /14, p.36-41./ Figure 6 presents a stress-strain curve including the features that are typically found in a loading curve.

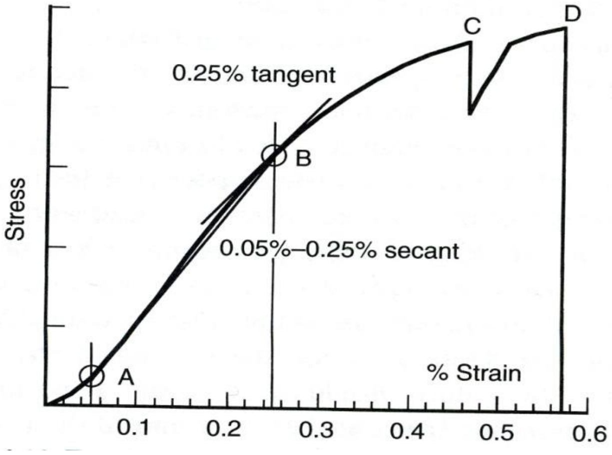


FIGURE 6. A stress-strain curve /15, p.64/

The tensile strength (ultimate strength), tensile modulus (elastic modulus), and elongation (ultimate strain) can thus all be obtained from the normal tensile-strain test. The condition of stress here represents uniaxial tension. Also Poisson's ratio (v) can give valuable information. It refers to 'the ratio of lateral unit strain ($\Delta\ \varepsilon_y$) to longitudinal unit strain ($\Delta\ \varepsilon_x$) under the condition of uniform and uniaxial longitudinal stress within the proportional limit' /16, p. 9/ and can be obtained as follows:

$$v_{xy} = \frac{\Delta\varepsilon_y}{\Delta\varepsilon_x} \tag{5}$$

There are three possible ways to calculate the elastic modulus from a non-linear loading curve shown in Figure 6. First, the modulus may be taken as a tangent to the initial part of the curve. Secondly, a tangent can be constructed at a specified strain level. The third option is constructing a secant between points A and B. Poisson's ratio may also be calculated in case longitudinal and transverse data are obtained. The same upper and lower strain limits as in the case of calculating the elastic modulus can be applied. / 15, p.65. /

As regards to anisotropic composites, the tensile properties differ in the fiber and the cross-fiber direction. They are obtained by applying samples which are cut with their long axis parallel to the fiber direction. As a rule, tensile specimens are always pulled in the long direction. /6, p.197/

The manufacture and application of test specimens in tensile tests are discussed in Chapter 6.

3.2 Fatigue Tests

Fatigue refers to the degradation or failure of the mechanical properties of material after repeated application of strain. In the case of composites, owing to the anisotropic nature of the material, a complex failure mechanism is involved and severe damage may be caused. It is important to be able to predict the fatigue behavior of composite materials to be able to design and manufacture structures that can tolerate damage as well as possible. For this purpose also the long-term properties of composites should be taken into account. This can be done if the basic mechanisms of material degradation under mechanical loads are recognized. /13, p. 55. /

The fatigue of materials and combinations of materials is generally measured by subjecting the sample to a fluctuating stress. Figure 7 illustrates a superposition of a constant mean stress and a sinusoidally varying stress.

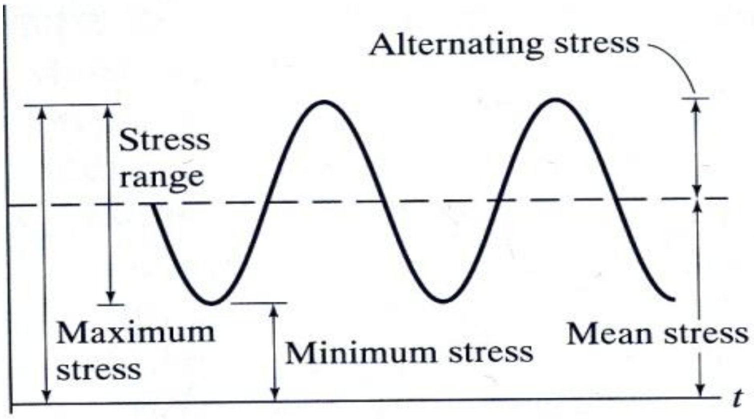


FIGURE 7. A sinusoidally varying stress /14, p. 745/

Fatigue tests are in most cases tensile or tension/compression tests, in some cases also flexural tests. The specimens used in fatigue tests are similar to those applied in static testing. The development of fatigue under static and fatigue loading is basically of the same nature. The difference lies in the fact that fatigue loading at a certain stress level is going to cause extra damage. This additional damage will depend on the cycle frequency. /13, p. 55. /

3.3 S-N Relationship

The necessary information on fatigue behavior is provided by the relationship between the applied cyclic stress *S* and the number of cycles to failure *N*. When this relationship is plotted in graphical form, the result is known as an *S-N* curve. The *S-N* curve, which is also called the endurance curve, is based on a series of tests on identical test specimens. The curve expresses the strength of the material as a function of load cycles with mean stress σ_m or stress ratio *R*. Figure 8 presents a stress-cycles curve for unidirectional fiber reinforced composites. The fatigue resistance of a composite seems to be determined by the compliance of the material. /13, p.60. /

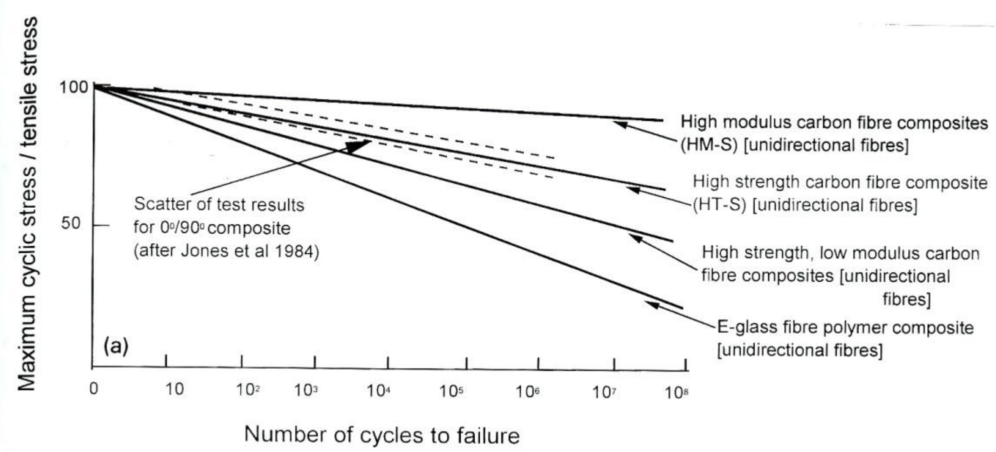


FIGURE 8. A stress-cycles curve for unidirectional fiber reinforced polyester (FRP) composites. /13, p. 61/

The most widely used form of S-N curves is S against $\log_{10}N$. The S-N relationship in composite laminates is for the most part dependent on the properties of the constituent materials. The static strength of composites depends mostly on the strengths of the 0° plies.

Since in connection with tensile loading, the fibers carry practically all the load, the tensile fatigue behavior of a unidirectional composite material could be assumed to be totally dependent on the fibers. The fibers being usually not especially sensitive to fatigue loading, good fatigue behavior should be expected. It has been experimentally shown that it is principally the strain in the matrix that determines the slopes of the stress-strain curves. This is because the fatigue limit of the matrix is lower than that of the fibers. As a consequence, plots of mean strain rather than stress versus log cycles are often more informative in the case of composite materials. The use of very stiff fibers, such as carbon fibers, produces low strains and consequently shallow S-N curves, whereas the use of less stiff fibers, such as glass, leads to greater matrix strains and steeper S-N curves. The lower modulus of glass fiber allows composite strains which are significant enough to cause early matrix damage and in that way speeds up fatigue as is shown in Figure 10. /13, p.62. /

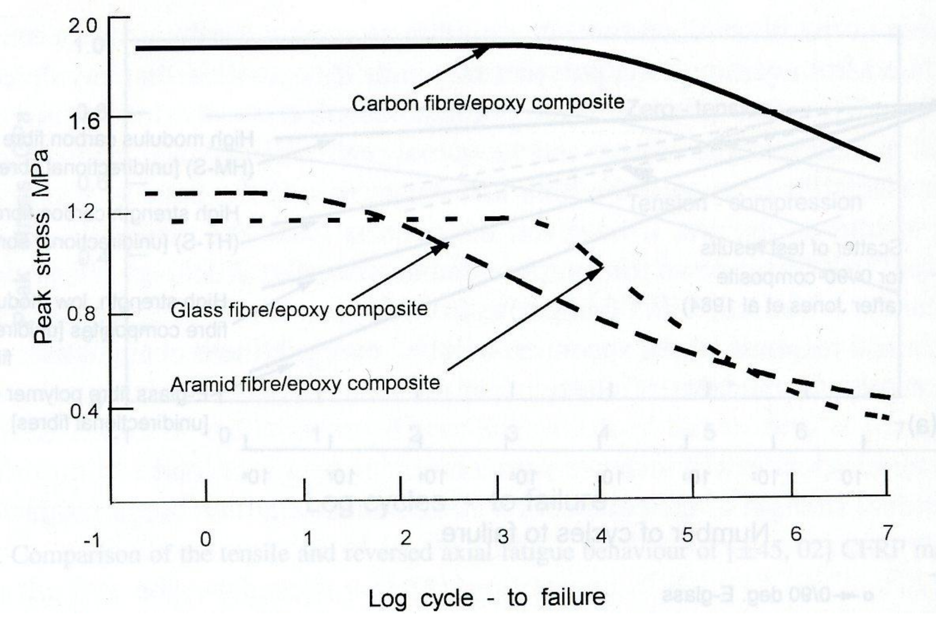


FIGURE 10. Fatigue behavior variation of composites due to differences in fiber stiffness /13, p. 62/

The fatigue failure of materials is a random phenomenon. The result of this is that however carefully controlled the experiments are, at any selected amplitude, often a larger scatter in the number of cycles to failure occurs than had been predicted. There is a good reason for this. It relates to the fact that even though it is convenient to consider a material homogeneous, on a microscopic scale things appear differently. If the material is studied carefully, it becomes evident that it contains a number of internal defects such as microcracks, dislocations etc. When the same cyclic stress amplitude is applied to specimens, which appear identical, it is highly unlikely that each of them will fail after exactly the same number of stress cycles. In reality the conditions of the fatigue cracks in each specimen differ greatly. For this reason, although fatigue data is generally presented as a single plot on an *S-N* curve, it should be understood that this plot should not be regarded as an exact prediction of a material's fatigue life at a given stress amplitude. *S-N* curves are usually created on the basis of a large number of test results which have been analyzed by applying a statistical method. / 17, p. 550-1. / Most of the methods were developed to be used for metallic structures. In the context of composite structures, they have to be modified so that the special features of composite damage could be taken into consideration. Several studies related to the structural safety and reliability of composites exploit the Weibull distribution (See e.g. 7, p.733-734) to describe the statistical variability of the strength and fatigue life of the materials. /18, p. 17-18. /

4 DEFINITION OF LAMINATE PROPERTIES BY CALCULATION MODELS

In the following some of the properties of basic laminate structures will be considered, first on the basis of micromechanical models and later from a macromechanical point of view. The micromechanical models concentrate on the behavior of fiber reinforced layers. They are applied to predict the characteristics of composite materials. The properties of both fiber and matrix have to be considered. The approach is known to be successful in predicting the stiffness properties of materials. The models for composite strength have not been equally effective. /5, p.61. /

4.1 Longitudinal Modulus

In the case of an isotropic material, stiffness is exclusively represented by the modulus of elasticity E and Poisson's ratio υ. The stiffness of the combination of fiber and matrix, which are both as such isotropic, is represented by five elastic properties:

E_1 : modulus of elasticity in the fiber direction
E_2 : modulus of elasticity in the direction transverse to the fibers
G_{12} : inplane shear modulus
G_{23} : out-of-plane shear modulus
υ_{12} : inplane Poisson's ratio

The listed functions are all functions of the fiber volume fraction. E_f is the elastic modulus of the fiber. (Figure 11). /5, p.67- 8. /

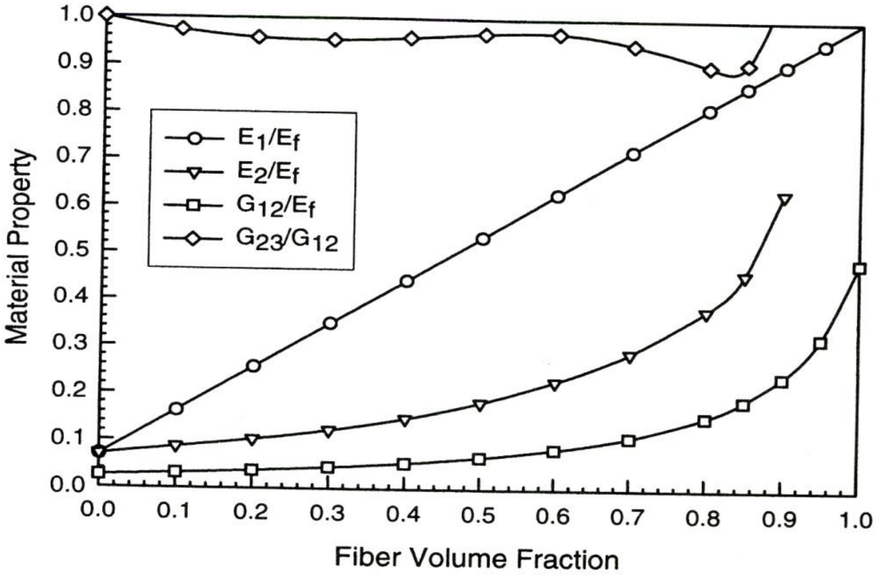


FIGURE 11. The functions of fiber volume fraction /5, p. 68/

The longitudinal modulus i.e. modulus of elasticity in the fiber direction can be accurately predicted by applying the rule of mixtures formula (ROM). ROM is based on the assumption that the strains in fiber direction are identical in the matrix and the fiber. This contains the implication that the bond between fiber and matrix is perfect. /5, p.68. / This is illustrated in Figure 12.

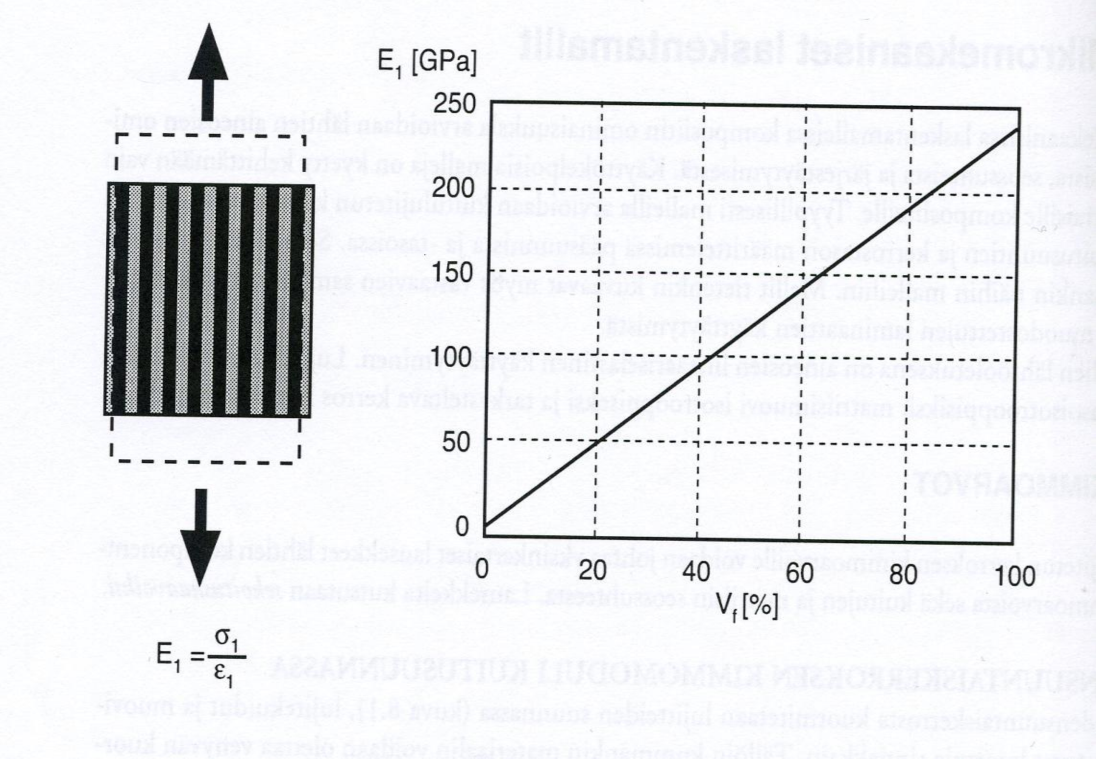


FIGURE 12. The elastic modulus of a unidirectional layer in fiber direction as a function of fiber volume fraction according to ROM (carbon fiber and epoxy matrix) /3, p.322/

The matrix and the fibers are expected to elongate the same, when the material is stretched along the direction of the fibers. The elongation (ε) can be expressed as follows

$$\varepsilon_{f1} = \varepsilon_{m1} = \varepsilon_1 \tag{6}$$

The lower index *f* refers to the fiber and *m* to the matrix. The loads F_f and F_m carried by the components corresponding to the elongation are

$$F_f = A_f \sigma_{f1} = A_f E_{fL} \varepsilon_{f1} = A_f E_{fL} \varepsilon_1 \tag{7}$$
$$F_m = A_m \sigma_{m1} = A_m E_m \varepsilon_{m1} = A_m E_m \varepsilon_1 \, ,$$

where A_f and A_m refer to the entire cross section area of fibers and matrix , E_{fL} is the longitudinal modulus of the fiber and E_m is the modulus of the matrix material. From these the ROM formula is obtained as follows:

$$E_1 = \frac{\sigma_1}{\varepsilon_1} = \frac{F/A}{\varepsilon_1} = \frac{F_{\mathrm{f}} + F_{\mathrm{m}}}{A\varepsilon_1} = \frac{A_f\ E_{\mathrm{fL}} + A_{\mathrm{m}}\ E_{\mathrm{m}}}{A} \tag{8}$$
$$= V_{\mathrm{f}}E_{\mathrm{fL}} + V_{\mathrm{m}}E_{\mathrm{m}} = V_{\mathrm{f}}E_{\mathrm{fL}} + (1 - V_{\mathrm{f}})\ E_{\mathrm{m}} \quad ,$$

where V_{f} and V_{m} are the relative proportions of fibers and matrix in the cross section i.e. the volume fractions of the components. According to the formula, the longitudinal modulus in fiber direction is obtained by adding together the moduli of the reinforcement and the matrix in the proportion of their volume fraction. On the whole, longitudinal modulus tends to be a fiber dominated property. The stiffness of the material increases linearly while the volume fraction of the reinforcing fiber increases. /3, p. 321-2; 5, p. 69-70. /

4.2 Longitudinal Tensile Strength

It is possible to postulate the simplest imaginable model for the tensile strength of a continuous fiber reinforced composite by assuming that all the fibers have exactly the same tensile strength. Even though in reality the strength of all fibers is not similar, it is also assumed here that the strength of all the fibers is the fiber average strength σ_{fa}. Secondly, it is assumed that the fibers and the matrix both behave linearly until failure. Most polymers do not actually behave in this way, since their load-rate dependency creates further complications. The third theoretical assumption considers fibers brittle in respect to the matrix. This doesn’t always hold true e.g. in the case of E-glass, which outstands most resins when elongation to failure is investigated. The fourth assumption is not merely theoretical: fibers are stiffer than the matrix in the case of materials other than ceramic matrix composites. If these four assumptions are realized, the composite is likely to break as soon as the stress to which the fibers are subjected reaches their strength σ_{fa}. After that the matrix cannot carry the load. Consequently, the composite elongation to failure ε_{cu} is identical with the fiber elongation to failure ε_{fu}. The matrix has not failed yet, since as a more compliant component it can carry higher strains (Figure 13).

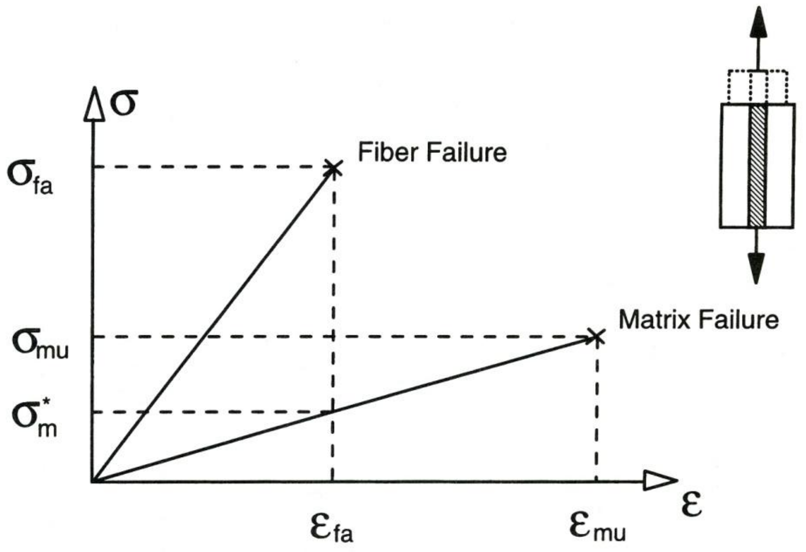


FIGURE 13. Micromechanics of the strength of a fiber reinforced composite when uniform fiber strength is assumed /5, p. 86/

It can therefore be assumed that the longitudinal tensile strength is dependent on the strength of fibers. This is represented by the following formula:

$$\sigma_{1t} = \sigma_{fa} V_f + \sigma_m^* (1 - V_f) , \quad (9)$$

where the stress in the matrix at failure is

$$\sigma_m^* = \sigma_{fa} E_m / E_f \quad (10)$$

The tensile strength is thus

$$\sigma_{1t} = \sigma_{fa} [V_f + E_m / E_f (1 - V_f)] \quad (11)$$

The assumption in the above equation is that the strain in the matrix and fibers is similar. It is also implied that once the fibers fail, the matrix cannot sustain the load. This will lead to the failure of the composite. In the case of composites with particularly low fiber volume fraction, the matrix may be able to carry the load after the fiber failure. /5, p. 85-6. /

4.3 Macromechanics of the Orthotropic Layer

Macromechanics can be defined as the study of the behavior of composite materials, which starts with the assumption that the material is homogeneous. The properties of the material components are regarded as those of the composite as a whole. /19, p.85. / Composite structures which are built to be used in practical applications are generally built with laminates that have several layers with more than one orientation. The orientations of the layers have to be considered in laminate fabrication. The purpose is to produce laminates that can carry loads. That is why such orientations are chosen that provide the highest values of strength and stiffness.

Composite materials are significantly stronger and stiffer in fiber direction than in other directions. Every fiber reinforced composite layer can be considered orthotropic in material axes (see Chapter 2). A unidirectional fiber-reinforced composite which has three planes of symmetry that coincide with the coordinate planes may be considered orthotropic. One plane of symmetry is perpendicular to the fiber direction, and the other two can be any pair of planes orthogonal to the fiber direction and among themselves. /5, p.66 -7. / (Figure 14).

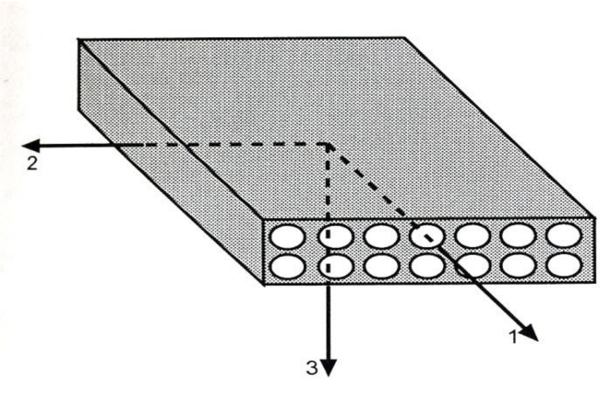


FIGURE 14. The principal planes 12, 13 and 23 of an orthotropic FRP layer /3, p.326/

The following constants are required to describe an orthotropic material:

- elastic moduli E_1, E_2 ja E_3, which indicate the tensile and compressive strength in axial loading to directions 1, 2 and 3

- Poisson’s ratios v_{ij}; ij = 12, 13 and 23, which indicate the strain in the j-direction when stressed in the i-direction

- shear moduli G_{12}, G_{13} ja G_{23}, which indicate the shear strength, when planes 12, 13 and 23 are under stress

The behavior of a linear elastic orthotropic layer can be determined by applying five elastic moduli: E_1 and E_2 in the main directions, shear modulus (G_{12}), and Poisson’s ratios (v_{12} and v_{21}). Four of these are independent, but the moduli and Poisson’s ratios can be connected by deduction.

$$E_1 v_{21} = E_2 v_{12} \tag{12}$$

The values of the elastic moduli can be calculated, when the properties of the components of the composite material and the structure are known. If necessary, more accurate values are determined experimentally. /3, p. 326. /

Fiber reinforced materials are, as a rule, laminated into plates and panels that constitute the actual basic items of engineering structures. So far the analyses of these structures have mainly been based on either theories that were originally developed for isotropic materials or on the “classical lamination theory” (CLT). The theory consists of a number of formulas and equations which can be applied to analyze the stress-strain behavior of individual lamina as well as to calculate the stiffness of a laminate. /19, p.147-156; 4, p. 217-228. / However, the classical theory has proved unsatisfactory, for example in the interpretation of inter-laminar behavior. Numerous compensating theories have been proposed to overcome the limitations of these attempts to characterize laminate behavior. Computational techniques make it possible to adopt a three-dimensional approach to the challenge of analyzing laminated composite materials. 3D analytical modeling is able to take into account three-dimensional variations of stresses and strains and thus provide more accurate predictions of material behavior. Analyses include equilibrium equations of stresses, strain-displacement relations and stress-strain relations.

5 FATIGUE OF LAMINATES AND DESIGN CRITERIA FOR COMPOSITE STRUCTURES

As a rule, reinforced fiber composites are subject to progressive fatigue degradation because of failure of the fibers, fiber stacking sequence or type of fatigue loading. The damage propagation under fatigue and static loading is similar except that the fatigue loading at a given stress level will cause extra damage. This will obviously be dependent on the cycle frequency. Four principal failure mechanisms of polymeric composites under fatigue loading can be recognized: fiber breakage due to interface debonding, matrix cracking, interface shear failure with fiber pull-out and brittle failure.
These failure mechanisms may also occur as combinations causing fatigue damage resulting in reduced fatigue strength and stiffness. When fatigue stress is high, cracks can initiate during the first loading cycle and accumulate with increasing number of cycles. /13, p. 56. /

When subjected to tensile loads, unidirectional continuous fiber composites have good fatigue properties that are typically linear to failure when loaded parallel to the longitudinal fiber. Advanced fiber composites under tensile stress in the fiber direction are insensitive to fatigue even at stresses which approach the static fracture strength. For other types of stresses and with other fiber orientations the fatigue of composites may be even more complicated than that of metals. /18, p. 25. / If the composite contains off axes plies, numerous damage mechanisms may occur under loading. The internal load is redistributed and the stress-strain response becomes non-linear. /13, p. 55. /

Figure 15 illustrates an interpretation of fatigue development process in composites. Two major stages can be differentiated. Firstly, individual plies experience homogeneous and non-interactive cracking. The second stage consists of damage in zones of crack interaction which is increasing. The Characteristic Damage State (CDS) is the point where transition from the first stage to the second stage occurs. CDS is characterized by a clear crack pattern. According to this model the evolution of damage in a composite laminate generally progresses from initial matrix cracking and crack coupling/interfacial debonding to states of delamination and fiber breaking, the final state being fracture of the composite material. /18, p. 20. /

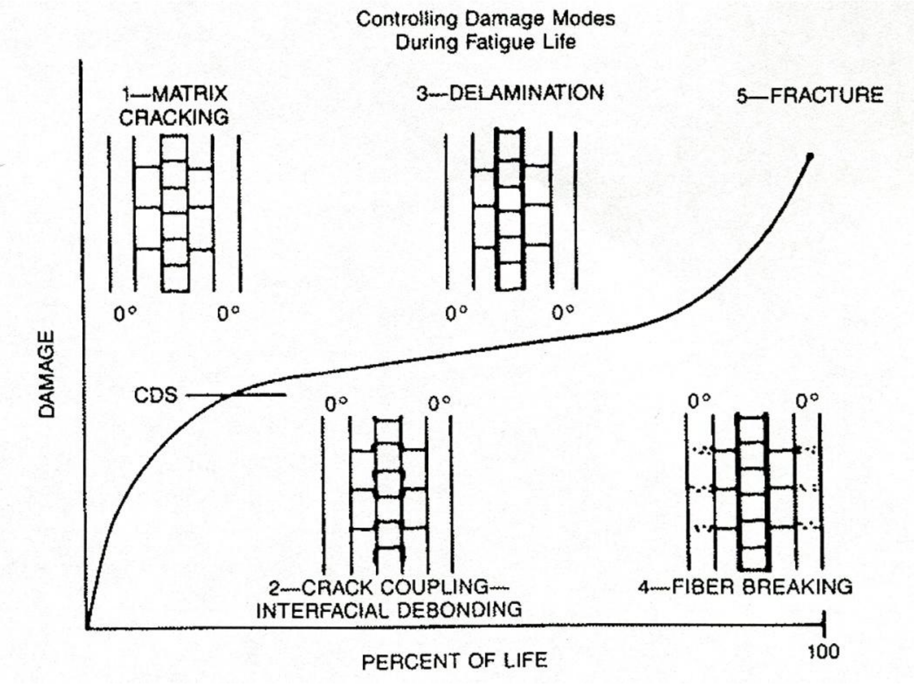


FIGURE 15. Fatigue development process in composites /18, p. 20/

Advanced polymer composite materials are manufactured in the form of laminates. These tend to be weak in the through-thickness direction. This weakness can increase the likelihood of delamination between the layers of the composite under in-plane loading and can cause failure in areas of stress concentration. Delamination may occur in the very early stages of fatigue life and propagate rapidly from the free edge towards the inside of the laminate. In most GFR materials, debonding may occur after a small number of cycles, even at low stress levels. If the material is translucent the development of fatigue damage may be observed. The first signs are that the material becomes opaque, whenever it is subjected to a load. Gradually the opacity becomes permanent and easy to observe. Eventually resin cracks turn visible but the structure or the specimen is still able to bear the applied load until localized severe damage causes failure of the component. Glass reinforced plastics thus typically give a clear visual warning of fatigue failure. In some cases the matrix may possess longer fatigue endurance than the reinforced material, but in other cases the opposite is true. In most cases the fatigue endurance of a GFR composite material is reduced by the presence of moisture. /1, p.138-139. /

5.1 The Effect of Reinforcement on Laminate Fatigue

Bare reinforcing fibers are generally tested by fiber manufacturers as part of quality control procedure. Even though the properties of a composite as a whole are decisive, testing fibers by running different physical, chemical and mechanical tests is seen as a necessary method of developing and screening composites. /6, p.186./ On the whole, fiber reinforced composites exhibit high values of tensile strength. Fibers typically possess a lower strain-to-failure value than the matrix. Fracture of a composite material generally occurs when the fibers fail. The interpretation of reinforcement behavior is, however, not straightforward. A problem is created by the variability of fiber strength. High strength filaments characteristically differ from each other in this respect. Varying fiber strengths result in two important consequences. First, the strength of a group of fibers is not equal to the sum of the strengths of the fibers in question. Neither is it the mean strength of the fibers. Secondly, fibers that are first to break under loading simultaneously initiate a chain reaction. Perturbations of the stress field will appear near the break. This will bring along fiber-matrix interface shear stresses that will transfer the load across the interface. Stress concentrations are introduced to neighboring unbroken fibers. Stress distribution described above may be the cause of several modes of failure.

Fiber tensile strength is usually given in the form of the average strength of a group of fibers representing a particular fiber type. In practice the determination of the strength is carried out by impregnating a bundle of the fibers in question with a polymer and loading it to failure. The average fiber strength, which is obtained in this way, is defined by the maximum load divided by the cross-sectional area of the fibers. /7, p.192-3./ The maximum strength that has been measured in single fiber tests (ASTM D3379) may yield values reaching 3,5 GPa for E-glass and 4,8 GPa in the case of S-glass. Values like this cannot, however, be realized in a composite. There are factors involved in the numerous stages of processing that reduce the strength of fibers to approximately 1,75 GPa for E-glass and 2,10 GPa for S-glass. /5, p.18. /

Talreja /18, p.61-2/ discusses the investigation of fatigue damage in unidirectional glass/epoxy composites reported by Dharan (1975), who described the way in which damage process falls in three regions along the fatigue life axis (Figure 16).

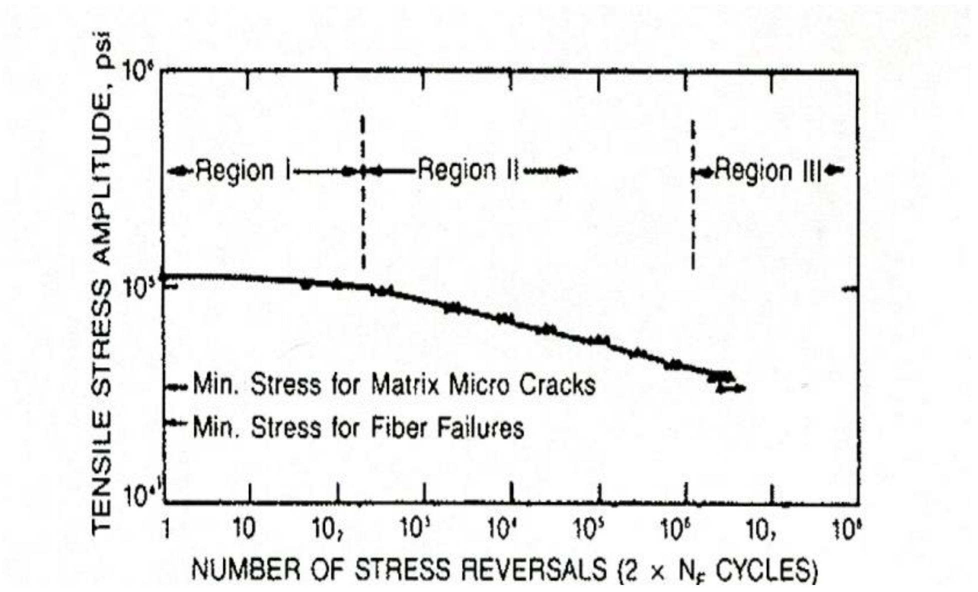


FIGURE 16. The 3 regions of fatigue damage process /18, p. 61/

Region I, which extends to 200 cycles, was dominated by fiber failures that were caused by high stresses. The fiber failures coalesced locally at different sites and grew with cycling until the adjacent zones of fiber failures joined together, weakening that way the specimen and leading to failure. Region II consisted of the range from 200 cycles to 10^6 cycles. Here the number of fiber failures was not large enough to lead to failure. However, the matrix cracks that had initiated at the surface, grew inwards by first breaking the fibers. Later they grew along the fiber/matrix interface. Region III beyond 10^6 cycles exhibited no fiber failures. Talreja points out that Dharan never tested the validity of his view concerning the rate controlling mechanism in Region II. He did suggest that the crack growth rate was controlled by stress corrosion cracking of glass fibers at the tip of a matrix crack. Talreja goes on to compare Dharan's analysis with Mandell et al. /20, p.96-102./, who presented an entirely different explanation for the rate controlling mechanism. They found out that the slope of the S-N curve in tension-tension fatigue normalized by the ultimate tensile strength for a group of different glass fiber composites was roughly identical with the value for unimpregnated glass strands. This was considered a proof of the strength degradation of glass fibers as the underlying cause. It was suggested that fiber surface friction and wear could be the mechanism involved. An attempt was made to decrease friction between fibers by testing fiber strands in silicone oil. The procedure did not, however, produce any significant improvement in the fatigue degradation rate. The question concerning the rate controlling mechanism in Region II of fatigue of GFR composites was not satisfactorily solved by either of these studies. /18, p. 61-2. /

5.2 The Effect of the Environment of Use on Fatigue Strength

The environmental durability of a composite structure is an essential issue in the development of reinforced materials. The data collected from studies concerning the subject has mainly focused on the aircraft and ship industries during the past four decades.
Tsai /21, p.749-767/ presents a list of the major degradation mechanisms caused by environmental exposure. The first to be mentioned is the loss of strength of the reinforcing fibers due to a stress-corrosion mechanism. Another important mechanism consists of the degradation of the fiber-matrix interface, which results in the loss of both adhesion and interfacial bond strength. The third major factor is connected to the previous two, namely the permeability of the matrix material to corrosive agents, for example water vapor. The fourth phenomenon is related to the viscoelastic dependence of matrix modulus and strength on time and temperature. In addition to the above mechanisms caused by environmental effects, there is the combined influence of temperature and moisture accelerated degradation.

Composite materials should ideally survive in various environments. While subjected to the above mentioned mechanisms of degradation they may be exposed to e.g. humidity or water immersion, salt spray, temperature variation, fire, in some cases also jet fuel, hydraulic fluid or stack gas. Humidity or water immersion may lead to degraded stiffness and strength. In most cases the fatigue endurance of a GFR polymer is reduced by the presence of moisture. /1, p.139/. The tensile strength of composite materials is lowered by chemical corrosion. The corrosion resistance of a material is dependent on the composition of the material and the time of exposure. /5, p.18. /

Temperature is undoubtedly one of the prime environmental factors affecting the mechanical properties of GFR laminates. The thermal durability of fibers depends on their type. The tensile strength of glass fibers reduces at elevated temperatures but can be considered constant up to 275˚C. The durability of the composite material depends on the matrix type /5, p.18/. Therefore, in the case of usual laminates, the thermal durability is restricted by the matrix resin, which will soften at increased temperatures.

Decrease of temperature will increase the stiffness and also to some extent the strength of the matrix and make it brittle. Since the reinforcing fibers and the matrix polymer in most cases possess different coefficients of thermal expansion, changes in temperature characteristically induce additional strains in the structure. /10, p. 142-3. /

Humidity may soften the matrix polymer and affect its mechanical properties. It can produce swelling strain in the structure. Particularly the edges of the laminate allow moisture to proceed into the structure along the fiber-matrix interface and destroy the fiber-matrix bond. All in all, hygrothermal strain due to thermal expansion and swelling strain caused by moisture, is often responsible for changes in the measurements and shape of a laminate structure. /10, p. 167. /

5.3 Design Criteria for Composite Structures

When components made of composite material are designed, both material design and structural design are involved, in many cases simultaneously. Important properties such as stiffness and thermal expansion may be varied during the process. The properties of fibers and matrix materials may be combined and thus achieve the desired values. Even though micromechanical formulas are excellent at predicting the stiffness of a material, they are not as successful, when strength is to be determined. For this reason experimental data is essential. Using experimental results in design makes in some cases micromechanical modeling futile. On the other hand, considerable investments are required to generate the data. The first stage of designing a structure is to define the properties of the individual layers of which the laminate consists. The laminate can be characterized by combining the properties of its layers. If, however, for example in the case of a particular fiber, the matrix material or the manufacturing process is changed, unpredictable consequences may result. Thus new and up-to-date experimental data is generally needed for successful design. /5, p.9-10. /

Talreja (18, p.169-179) discusses the progress of damage in composite laminates under mechanical loads and concentrates on the crucial events in the damage process that should be considered when structures are designed. The criteria that are generally applied in the case of static loading are the first ply failure criterion and the strength (total failure) criterion. Composite laminates experience yielding, fracture and instability when they are subjected to static loads. Among the parameters representing these events are yield stress, fracture toughness, critical crack size and buckling stress. Under static loads, the materials response can be interpreted as initiation of matrix cracking in one or more plies as the first critical event. The parameter applied in the definition of this event is the threshold stress (or strain). The last critical event is fracture (separation) of laminate. It is the consequence of fiber failures in plies that are most closely aligned with the major tensile stress. The parameter used to define this event is strength. At low constraint, the laminate can sustain a noticeable load beyond the first ply failure. In the case of full constraint, the laminate fails before there is any matrix cracking. The deformational response of a structure is, however, mostly determined by stiffness, which may be considered the potential third criterion. In case the relationship between crack density and load is determined either by calculation or experimentally, it is feasible to calculate the degradation of a stiffness property for a given load. When structural design is based on stiffness degradation, the likelihood of failure may be defined as the probability of stiffness degradation to a critical value.

There are two main glass fiber composite databases for wind turbine applications. The first is the DOE/MSU developed in the U.S. by J.F.Mandell and D.D Samborsky , and the second is the European database. As to trends in glass fiber fatigue behavior the two databases are mostly in agreement. The DOE/MSU database provides static and fatigue data for potential blade materials by varying the parameters of fiber content, fabric architecture and percent in testing potential blade materials. The failure of wind turbine blades is usually caused by fatigue either by some structural factor or a major flaw in the material applied. The basis applied in comparing the different materials is the maximum initial strain which produces a lifetime of 10^6 cycles. The test programs carried out may sometimes present results that require a thorough analysis. For example, it was discovered in an experiment that the tensile fatigue performance of the test material became much less fatigue resistant as the fiber volume content was increased beyond the range of 35-45%. The reason for the sharp decrease in fatigue resistance while the fiber content was increased evidently lay in the transition to a condition where the laminate fails due to fatigue immediately after the matrix cracks. The finding was analyzed in the light of results received from a FEM analysis, which showed that if there is a matrix layer between the fibers of plies next to each other, it may to a great extent decrease the stress concentration in the 0° strands close to the points of matrix cracking in adjacent plies. While the fiber content is increased, the tight strands of the fabrics are squeezed together, which in turn leads to matrix crack inducing early failure in tensile fatigue. The designers and manufacturers of wind turbine blades could thus, on the basis of this analysis, conclude that glass fiber laminates are susceptible to remarkable degradation in their fatigue properties, if fibers are forced very close to one another. / 22, p. 1-2. /

Nowadays various software tools are applied in the design of wind turbines. The design of a blade is made easier and more accurate by e.g. interactive 3D visualization, which provides the designer with immediate feedback of potential changes in the process. Material properties as well as layer thicknesses and sequences may be displayed. The model helps to define the laminate layers and suggests the way they should be stacked in order to form a successful reinforced structure. Moreover, the blade model can be subjected to a structural analysis. It is possible to define, for example, strain and stress based on strength evaluation and carry out fatigue analyses based on time series./23./

6 STATIC TENSILE TEST OF GLASS FIBER EPOXY COMPOSITE

One of the aims of this thesis was to carry out static tensile tests for two types of unidirectional laminate, report the results obtained as well as discuss their interpretation in the light of the theoretical background presented above. In the case of reinforcing fibers, unidirectional tapes are considered the most adequate form for testing mechanical properties. For this purpose, the cured laminate material is normally machined into test specimens. /7, p. 285. /

Factors that influence the tensile response of glass fiber reinforced epoxy resin specimens include e.g. the methods of materials preparation, the size and shape of the specimens as well as specimen alignment and gripping. In addition, the application of the testing method and the testing conditions may affect the results. The desired specimen dimensions as well as the procedure for preparing and testing the specimens have been prescribed by various standardization organizations. In this study the International Standard (ISO) 527-5 instructions for “test conditions for orthotropic and unidirectional fiber-reinforced plastic composites” were applied /24/. In the following a standard static tensile test and the specimens and test equipment applied in the test will be described. The mechanical properties obtained in the test will be presented in the Appendix (p. 1-4) and discussed in Chapter 7.

6.1 Test Specimens

The unidirectional glass fiber reinforced laminate plates from which the test specimens were cut were manufactured at Ahlstrom Glassfibre in Mikkeli. The laminate was prepared by applying vacuum assisted resin infusion (VARIM) (see Ch. 2.2). The technique consists in applying low pressure to draw the resin into a mold which contains the reinforcing fiber. An airtight vacuum bag functions as a counter mold. The system was preferred here, because it makes it easier to control fiber orientation. /2, p. 65. / The epoxy resin Hexion 135i was selected. The curing agent was L 137i. The laminates were structurally orthotropic with all rovings at 0˚direction. Two varieties of glass fiber were used in the fabrication of the laminates. The fiber volume of both products was approximately 60%. One of the laminate types to be tested was made by using traditional E-glass with sizing type R 338, the other contained new generation high strength glass. The main purpose of carrying out the static tests was to compare the values of the elastic modulus of the two types of laminate. The hypothesis was that the high strength glass would outstand the traditional glass fiber as regards to stiffness i.e. the value of the elastic modulus.

The successful preparation of tensile specimens is demanding. The measurement results may be greatly affected by specimen configuration. Typically more isotropic specimens allow a greater number of configurations. In the case of these unidirectional specimens a straight-sided configuration was chosen. Laminate tabs were bonded to the ends of both sides of the specimens in order to distribute the gripping stress. Their function is to prevent failure that might be caused by the grip jaws damaging the specimen surface. /6, p.197; 17, p. 493. / The tensile specimens used in the test are described in more detail in ISO 527-4 and -5 /24/. The standard procedure was followed according to which a micrometer was used in measuring the dimensions of the test specimens. The average of three readings of width and thickness for each of the specimens was calculated. The calculated measurements and shape of the specimens are shown in Figures 17, 18a and 18b.

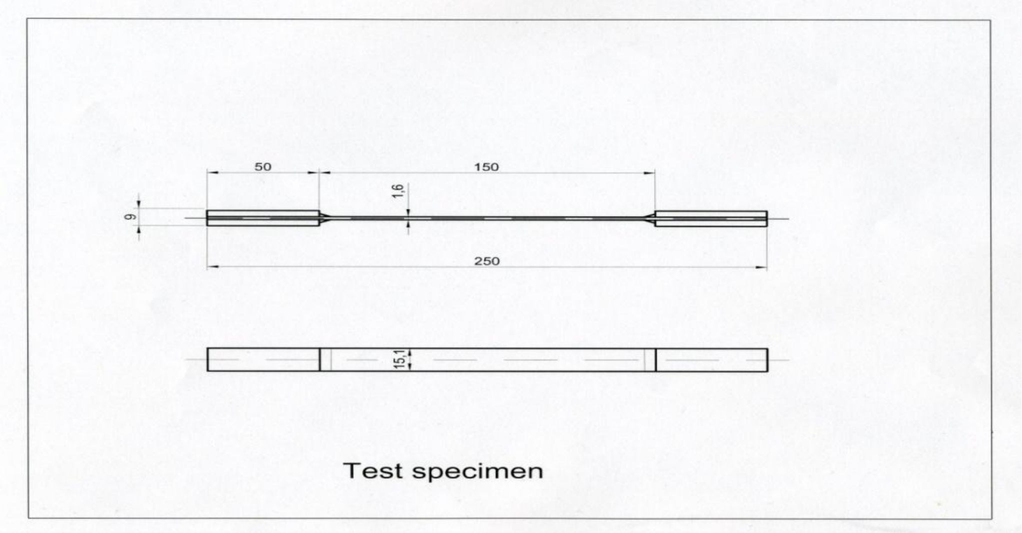


FIGURE 17. Test specimen

average thickness: 1,6 mm

average width: 15,1 mm

length (distance between tabs): 150 mm

FIGURE 18a. Test specimen

FIGURE 18b. Test specimen

6.2 Test Equipment

In this static test the servo hydraulic frame MTS 810 100kN with a 25 kN probe was used (Figure 19). The test machine was connected to a desktop computer for machine control as well as for data processing.

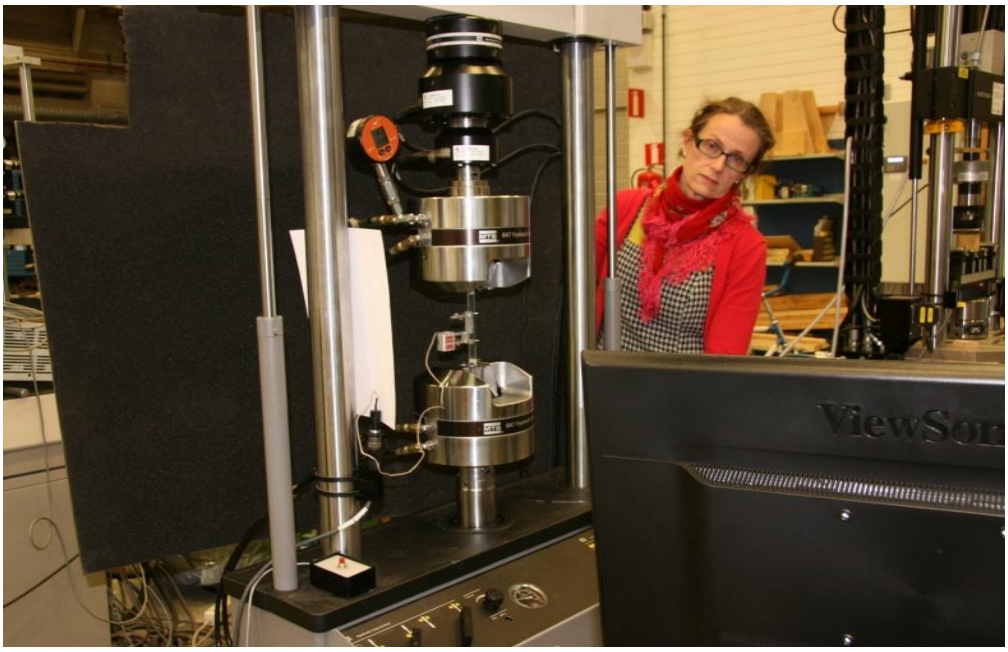


FIGURE 19. The test machine

An extensometer is used to measure the extremely small deformations occurring in the elastic range /17, p. 493/. In this example of tensile testing the extensometer MTS 634.31F – 24 shown in Figure 20 provided the measurements.

FIGURE 20. The extensometer attached to the test specimen

6.3 Test Procedure

The static tests were carried out in MUAS material laboratory in November 2011. The original purpose of the manufacturer had been to submit the very same specimens to fatigue testing as well. This plan could not, however, be carried out due to specimen characteristics. It was discovered that the structure of the specimens did not allow fatigue testing. The first three specimens that were subjected to a dynamic test failed almost immediately.

Tensile tests (See also 3.1) normally consist of measuring displacement or strain in the manner instructed by the applied standard. When strain gages are involved, it is essential to obey the recommended procedure. Gage length can be defined as “the length over which deformation is measured for a tensile specimen”. The strain is obtained by dividing the deformation over the gage length by the gage length. /7, p.12. /

The gage length should always be shorter than the length of the specimen. Gages should also be accurately aligned. A minute misalignment can cause remarkable errors in the results. The gage length applied in the test was 50 mm.

After the specimen was measured and otherwise prepared and inspected, it was mounted in the grips of the test machine. It was important to avoid axially stressing the specimen, while the grips were being tightened. In order to avoid grip failures the grip pressure was kept low. The centerline of the specimen was aligned with the axis of the testing machine in order to avoid bending and asymmetric loading. Next the extensometer was attached onto the center of the specimen and the initial gage length was measured. As instructed in ISO 527, a displacement rate of 2mm/min was applied. /15, p. 63. /

The 84 specimens that were tested represented two main types of GFR laminate. The ones named RA (20 items) and RY (21 items) were prepared from a laminate material with traditional E-glass reinforcement. Those labeled WA (22 items) and WY (21 items) contained high strength glass, which was assumed to give extra strength and stiffness to the laminate composite. The static tests that were run, simultaneously provided the first stage in an investigation, in which the purpose was to examine how the strength and elastic modulus of particular types of fiber would affect the tension-tension fatigue of unidirectional laminate material. The following procedures were carried out.

E-glass (RA/RY specimens):
Tensile stress of 70-80% to failure. For 6 specimens no measurements were made. Repeated loading and definition of elastic modulus between 0,05 – 0,25%

High strength glass (WA/WY specimens):
Tensile stress for all specimens up to 0,3 % strain. Tensile stress of 70 - 80% to failure. For 6 specimens no measurements were made. Repeated loading and definition of elastic modulus between 0,05 - 0,25%.

The elastic modulus of the tested specimen materials was calculated from the load elongation records and the cross-sectional area measurements (see Chapter 3.1).

6.4 Test Results

The results of the tests and the calculated values of the elastic modulus are presented in the Appendix. The interpretation and significance of the results are discussed in Chapter 7.

7 DISCUSSION

Various studies of the behavior of GFR composites have been carried out. The application of the test results is, however, often not simple and straightforward. First, it is not easy to find data that could be exploited as such in a particular investigation. Secondly, the great number of different parameters affecting the fatigue behavior of composites complicates the interpretation of the test results.

Usually four fairly typical stages can be distinguished in the deformation of a unidirectional fiber-reinforced composite while the load to which it is subjected is increased. In the beginning both the fibers and the matrix deform elastically. Next the fibers continue deforming elastically while the matrix begins to deform plastically. In the following phase both the fibers and the matrix deform plastically. In the end the fracture of fibers is followed by the fracture of the whole composite material. Variation in the realization of the stages may be due to brittleness of either the fibers or matrix. The fracture of the composite may take place either due to fiber failure or matrix failure depending on their relative ductility. Also the fiber/matrix bond has a major role in the behavior of a composite. Due to high stress the bond may be broken. The fracture of a single fiber can also propagate across the matrix through other fibers and eventually lead to the fracture of a composite. /19, p.128-131. /

The same composite material may exhibit significant deformation when subjected to a particular load while having high strength under other modes of loading. When a materials test is carried out, it is important to minimize or rather eliminate any interaction that might cause disturbance between the test equipment and material. Moreover, during the test procedure, as pure a state of stress as possible should be produced. Whether or not such a state can be realized in practice, is an unresolved question. The nearest approximation is achieved while testing a very long and thin filament. /15, p. 44-46. /

One of the problems related to materials testing and thus also the tests performed in the context of the present study, is the evident uniqueness of each test specimen. The values of different properties derived in a mechanical test are bound to vary according to the state of the internal order in the specimen. That order depends, among other things, on factors involved in the manufacturing process. Variations in material state prevail at the molecular or atomic stages and, as a rule, their number decreases after the processing stage. In fiber reinforced composites the reordering process typically takes place in the matrix and at the fiber/matric interfaces. Most variation, however, occurs in the distribution of fibers. It may change randomly during the manufacturing stage, or it may be altered on purpose by the fabricator in order to produce a certain mechanical effect. Moreover, since there are practically an infinite number of potential spatial arrangements of fibers and fiber volume fractions, it raises the question of whether it is actually possible to regard any particular fiber/matrix combination as a typical representative of a material state. If one gathers a list of property values derived from a mechanical test using a particular set of specimens, the results may not have a very wide field of relevance. On the other hand, the alignment and distribution of the reinforcement are often arranged in the composite so that certain requirements and desired attributes in the end product could be realized. For example, in the case of the RA/RY and WA/WY specimens of this study, the data that was obtained from the test specimens that had been cut from laminates prepared for wind turbine blade manufacture, was assumed to reflect the load bearing capability of the blade structure as a whole. / 25, p. 5, 9. /

When the quality of mechanical properties data is evaluated, there are particular factors that should be considered. It is evident that the degree of the precision and accuracy of measurements will affect the distribution of values obtained. There are bound to be minor variations in the structure of test specimens. These individual features will in most cases influence the results. A sophisticated statistical analysis cannot compensate for the mistakes caused by wrongly manufactured specimens and/or a test that has been conducted against instructions. In the case of tensile testing it is required that the testing machine should be axial. Precise uniaxial alignment of fibers guarantees the maximum tensile modulus that can be attained in that direction. However, in the analysis of values obtained, it is important not to draw any hasty conclusions on the basis of a single favorable result. An advantage achieved in one property may present itself as a disadvantage, when it is associated with another property. For example, the above mentioned precise uniaxial alignment of fibers has the opposite effect on the modulus in a transverse direction. /25, p.20-23./ In the static test carried out using RA/RY and WA/WY specimens it was essential that the force was acting along the longitudinal axis of symmetry. The strain had to be measured on a gage section which was remote enough from the grips so that they didn’t have any effect on the result. The extensometer had to be carefully attached in order to make sure it wouldn’t slip and thus affect the measurement of values.

The test specimens of both types RA/RY and WAWY had tabs bonded to their both ends. Their function was to enable the alignment of the test specimen in the test machine. The correct positioning was important, since mistakes made while mounting the specimen in the grips of the machine might be the cause of misalignment and induce stress concentrations. The quality of the test specimens was high enough for them to pass the static tensile tests without failure. The manufacturer of the test specimens was prepared to use the same specimens in the consequent dynamic testing as well. The experiment was, however, not successful. The test specimens should have originally been strengthened by stitches. The attempt to run fatigue tests had to be interrupted after the first three specimens had fractured starting from inside the grips.

Two questions were presented in the introduction of this thesis. The first was put forward by the manufacturer of the laminate and the specimens that were tested. The static tests which were carried out constituted a part of a larger project, in which the fatigue behavior of particular types of unidirectional GFR laminate was investigated. As the new laminate material had to be evaluated, the first stage was to carry out static tests in order to obtain necessary preliminary data before starting the fatigue testing. The major interest of the manufacturer lay in the question whether the use of the more expensive high strength glass fiber (WA/WY specimens) would be worthwhile in the fabrication of laminates to be applied in wind turbine blade manufacture. In the context of the present study the question could be translated into the form: Were the values of the elastic modulus *(E)* obtained from the test results significantly higher in the case of WA/WY specimens than in the case of RA/RY specimens, which had been prepared from GFR laminate that contained traditional E-glass? The results shown in the Appendix reveal that there was a difference of approximately 10 % in the values of the elastic modulus. Obviously the stronger fiber explained the somewhat higher values of the WA/WY group. In the case of WA/WY specimens the distribution of the values of elastic modulus was smaller than in the results of RA/RY specimens. On the basis of these results it could thus be assumed that there was a clear difference in the stress-strain behavior under static loading between the two types of GFR laminate. Further testing should naturally be carried out in order to find out the wider significance of these findings.

The second item of interest was the question of whether the values of elastic modulus obtained in the static tests could predict the results of fatigue testing. The question can be considered in the light of both the theoretical background presented in the previous chapters and the results obtained from the static tensile tests. As stated before, fatigue degradation of GFR composites may be due to failure of the fibers, the stacking sequence of fibers or the type of fatigue loading. The damage propagation under static and fatigue loading is alike except that the fatigue loading at a given stress level causes additional damage. This will depend on the cycle frequency. Unidirectional continuous fiber composites have normally good fatigue properties when subjected to tensile loads. High strength fiber composites under tensile stress in the fiber direction resist fatigue even at stresses which are close to the static fracture strength. In the event of other types of stresses and with different fiber orientations the fatigue of composites may be complex and not so easy to predict. Composites which contain off axes plies, may be subject to numerous damage mechanisms under loading.

So far numerous studies of stiffness based characterization of fatigue damage have concentrated on the values of the elastic modulus and possibly Poisson’s ratio. Talreja /18, p. 73-81/ points out that an investigation of fatigue damage would actually require the measurement of changes in more than one or two stiffness components. He presents an experimental procedure to record the changes of not only the longitudinal elastic modulus and two Poisson’s ratios but also the shear modulus. He also refers to the fact that a full-scale analysis of laminates requires concentration on the changes in the stiffness properties of the individual laminae caused by fatigue. This may be challenging, since they do not behave independently in the laminate, but are affected by the adjacent laminae.

To sum up, the slightly higher values of the elastic modulus obtained in the measurements confirmed that the WA/WY specimens contained higher strength fiber. The lower distribution of values could refer to the more uniform quality of the laminate material. It could also be explained by the type of the fiber used or factors related to the manufacturing process. The reduction in the strength and stiffness of a GFR laminate usually results from fatigue damage, and the overall effect on its properties will always depend on the composite design, manufacturing process and nature of loading. Even though certain regularities are certain and evident, it is not always strictly defined when, where and how glass reinforcement improves the fatigue behavior of the base material. The interpretation of test results is, however, challenging due to the variety of different parameters involved.

8 CONCLUSION

Tensile tests are basically performed to find the best possible materials for engineering structures. It is considered that the tensile properties of composites can be measured in order to be able to, at least to some extent, predict and define material behavior in different loading conditions. The static tensile test that was carried out as part of this study focused on the definition of the elastic modulus of the laminate materials under inspection. The tests carried out on two types of laminate specimen yielded results that were probably not against the expectations of the manufacturer. If a reinforcement is presented as ‘a high strength glass’, the assumption presumably is that it will prove to be in various ways better than the traditional lower cost glass fiber. The point of interest must have been the exact amount of improvement in, for example, the stiffness properties that could be demonstrated by running the tests. The difference of approximately 10 % in the values of elastic modulus between the two types of laminate was clearly shown by the test results. The manufacturer of the material will obviously have to consider, if it is cost-effective to replace the traditional fiber material with the high strength reinforcement.

The test procedure reported was just a minor part of a larger experimental project, in which composite materials and their fatigue properties are investigated. The number of tests carried out so far is definitely not large enough to provide quantitative information about the material. The major static strength and stiffness properties of GFR composites depend on various factors including the fiber type and content, the orientation of the fibers, as well as the matrix material. One could imagine that the higher values of elastic modulus automatically predict an improved performance of the material during severe loading and high numbers of fatigue cycles. The long-term behavior of composite materials is, however, not a clear-cut and simple phenomenon. As Talreja / 18, p. 3/ remarks, the analyses of composite fatigue behavior should adopt an interdisciplinary approach which could combine the physics of damage and the mechanics of solids. In that way the various parameters involved could be taken into account more extensively and the fatigue behavior of GFR composites might be more accurately predicted.

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