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Composite Materials for Wind Turbine Blades and Fatigue Analysis

Shoaib Khan Musazai

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Abstract

The typical material which is used for the construction of wind turbine blades is glass fiber composite material. Glass composite material was considered suitable to meet the design requirements of wind turbine blades. The other reason of using glass composite material is its low price compared with other fiber composite materials. The trend to move from onshore installation to offshore installation of wind turbines to harness the faster and steadier wind energy, creates design issues for some components of wind turbine, especially in rotor blades design. To capture more wind energy, rotor blade diameter has to increase which creates design issues but the cost of energy ultimately decreases. As the length of rotor blades increases, the weight also increases which results in the increase of gravitational forces. Glass fiber composite has high density compared with other advance composite materials.

The goal is to choose material with certain desired properties like, light weight to reduce gravitational forces, high strength to resist wind loads, high stiffness to ensure the stability of the shape of blade and low tip deflection, fatigue resistant to withstand cyclic loads. Carbon fiber composite material which has high stiffness, high specific strength fulfills the desired properties and can be used in large wind turbine blades but it is expensive. Carbon hybrid composite materials are found better than glass composite materials in terms of mechanical properties. Hybrid rotor blade is also one of the solution to reduce weight, Hybrid rotor blade means some parts of blade is made up of carbon fiber composites e.g. spar and the rest of the parts from glass fiber composite materials. Basalt fiber composite which has high static and fatigue strength, has good thermal properties and less expensive than carbon fiber, can replace glass fiber composites. Aramid fiber which has high tensile strength but has too low compression strength. Natural composites are suggested for small wind turbines.

Matrix materials, fiber type also has influence on mechanical properties. Epoxy is considered best among other matrix material. There are some factors that affect static and fatigue properties of composite materials. High operation temperature reduce

mechanical properties. Waviness in laminates reduce the compressive properties and laminate thickness also affect the fatigue performance of composite materials.

Contents

Chapter 1 5
Introduction to Composite Materials 5
FRP Composite Materials 6
Particle Reinforced Composites 6
Fiber Reinforced Composites 7
Laminar composites 9
Stress Strain Curves of Matrix and Reinforcement 10
Wind Turbine Composites 11
Polymer Matrix Composites 12
Glass Fiber–Reinforced Polymer (GFRP) Composites 12
Carbon Fiber–Reinforced Polymer (CFRP) Composites 16
Aramid Fiber–Reinforced Polymer Composites 19
Basalt Fiber Reinforced Polymer Composite 21
Hybrid Fiber Reinforced composites 24
Natural fibers Composites 27
Chapter 2 31
Specimens' description 31
Static Properties 33
Carbon composite compression strength 34
Strain Rate Effect 36
Tensile and Compressive Stress Strain Curves 36
Transverse Stress Strain Curves 39
Static Properties in Three Directions 41
Chapter 3 44
Fatigue 44
General Overview of Fatigue 44
Fatigue in Composite Materials 44
Stiffness Reduction by cyclic loading 45
Cyclic loads on Wind Turbine blades and Fatigue life prediction 47
SN Formulation 48
Constant Life Diagram, CLD 50
Phenomenological Approach to predict the Fatigue Life 51

Fatigue Limit in Composite Material 51
Fatigue Strength Comparison for Several Potential Wind Turbine Blade Laminates 53
Static Properties of Materials 54
Tensile Fatigue Results 54
CLD Diagrams 56
Effect of Resin on Tensile Fatigue Properties 56
Effect of Stress Ratio R on Fatigue Properties of WTB materials 58
Effect of fiber type on Fatigue Strength 60
Chapter 4 62
Wind Turbine Design 62
Loads on wind turbine blades 62
Composite layups in Blade structure 65
Use of carbon-hybrids composites in spars-webs comparison with Glass fiber reinforced composite . 66
Chapter 5 68
Factors Effecting Laminate Properties 68
Laminates thickness effect on static and fatigue properties 68
Effect of low and high temperature on static and fatigue properties of laminates 71
Static properties 72
Tensile Fatigue properties R=0.1 73
Fully reversed fatigue R = -1 74
Effect of waviness on static and fatigue compressive properties 75
Static compressive properties 76
Fatigue strength in waviness 78
Conclusion 82
References 83

Chapter 1

Introduction to Composite Materials

A new class of materials emerged during the mid-20th century that are artificially made by combining different materials with different properties that results in better properties than those of the individual ones used alone. These materials are called Composite Materials. Composite Materials provide huge opportunities for designing large variety of materials to meet the required properties for different kind of applications. Composite Materials have wide range of applications in Aerospace, Bioengineering, Automotive, Marine and Wind industries. These industries are searching for materials which are light weight, strong, stiff, impact resistant, erosion and corrosion resistant. Strong monolithic materials are dense compared to composite materials. Scientists and engineers have created a lot of composite materials in order to get improve mechanical characteristics such as stiffness, toughness, high and low temperature strength. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished part. Composites also exist in Nature and are called natural composites, for example wood composites. Wood consists of strong and flexible cellulose fibers surrounded and held together by a stiffer material called lignin.

Composite materials are composed of two or more constituents. Many composite materials are composed of two constituents, reinforcement and matrix. Reinforcement is in the forms of fibers, particulates. Reinforced phase of composite material is stronger and harder and provides strength and stiffness to composite materials. Matrix phase is a continuous phase that surrounds the reinforced particulate or fiber. The matrix (continuous phase) have several functions, it gives shape to the part, it keeps the fibers or particulates in proper orientation and place, it transfers loads to the fiber and protect the fiber reinforcement from surface damage and environment effect. The matrix phase has low strength and stiffness. The properties of composites depend on the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. Dispersed phase geometry means the shape, size, distribution, and orientation of particle. Composite Materials are classified into three main types. Particle-reinforced, fiber-reinforced, and structural composites.

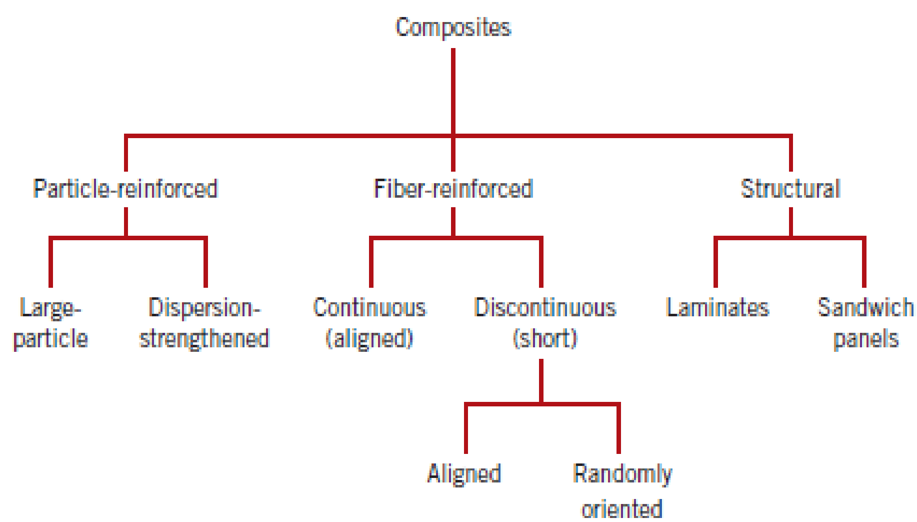

Fig 1.1. Composite materials classification (William D. Callister)

FRP Composite Materials

Particle Reinforced Composites

Particulates dimension in Particulate Reinforced composites are approximately equal in all direction. Particles are in different regular or irregular shapes and geometries. Reinforced particles should be small and evenly distributed throughout the matrix in order to get effective reinforcement. Volume fraction of reinforcement influence the mechanical properties of composites materials. Increasing the percentage of particulate content improve the mechanical properties. Particle composites are weaker and less stiff than continuous fiber composites. Advantage of particulate composite is its low cost. The disadvantage of particulate reinforced composites are difficult processing and brittleness. Due to difficulty in processing it contains less reinforcement.

Particle Reinforced composites are sub-classified into two classes, large particle reinforced composites and dispersion strengthened composites. In large particle composites, the interaction of particle and matrix is not on molecular level. Reinforced particle impedes the movement of matrix in the vicinity of particulates. Improved mechanical behavior can be achieved by strong bonding of matrix and particle interface. In dispersed strengthened composites, particles are much smaller in diameter. In dispersed strengthened composites the interaction of particle and matrix occurs on molecular level. Dispersed particle hinders the dislocation motion caused by the stresses.

Fiber Reinforced Composites

Technologically, fiber reinforced composites have more importance than particle reinforced composites because fiber reinforced composites are stronger, stiffer than particle reinforced composites. Fiber-reinforced composites are sub-classified on the basis of fiber length. Continuous and Discontinuous fiber. Continuous fiber has greater aspect ratio (l/d) while discontinuous fibers have small aspect ratio. Continuous fiber has certain orientation while discontinuous fibers randomly distributed. Discontinuous fibers are too short to produce a significant improvement in strength. Continuous reinforcements can be arranging in different orientations. It can be aligned unidirectional 0°, ±45°, ±30° helical and in the form of woven cloth. Desired strength and stiffness can be obtained by stacking the sheets of continuous fibers in different orientation with fiber volumes as high as 60 to 70 percent.

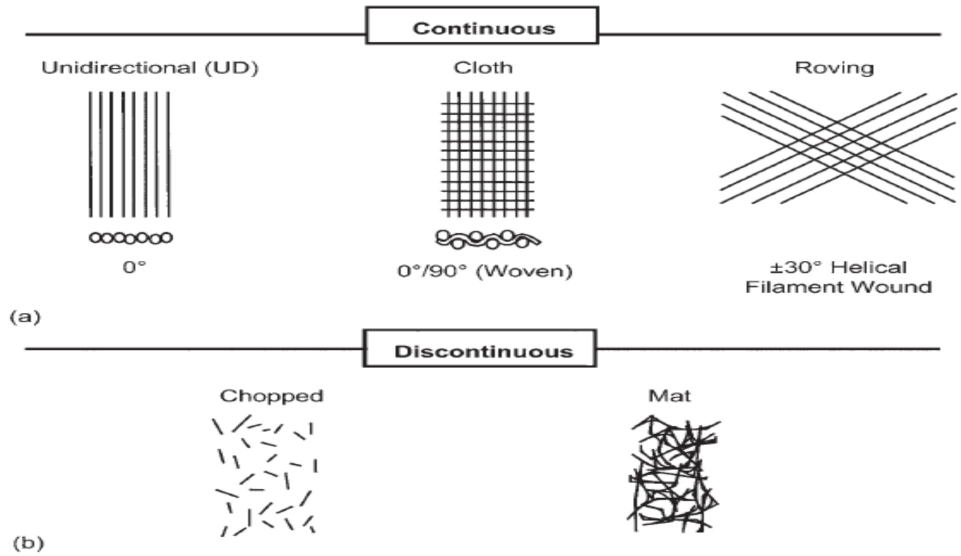

Fig 1.2. Different arrangement of continuous and Discontinuous fibers (Campbell, 2010)

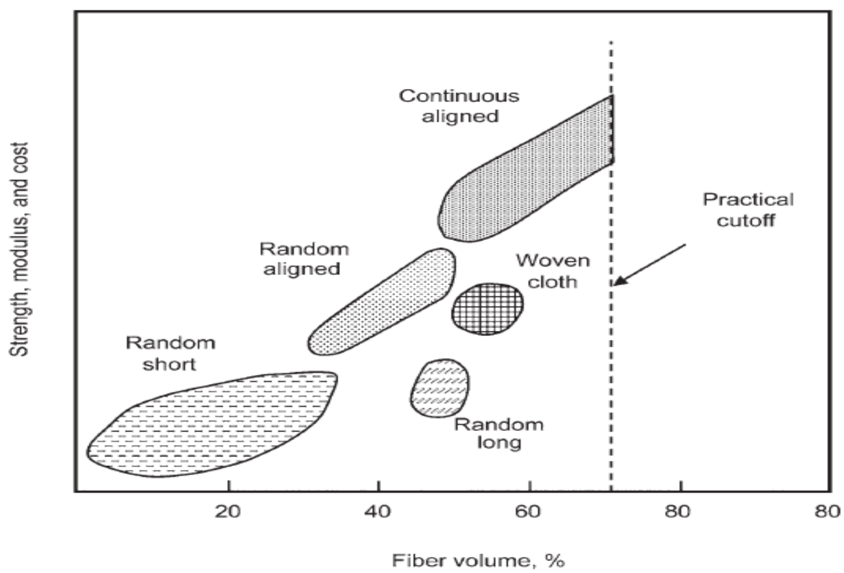

Fig 1.3. Influence of reinforcement arrangement and volume % on composite strength (Campbell, 2010)

Strength and other properties of composite materials depend on the volume fraction, type and orientation of fiber reinforcement. Figure 1.3 shows that continuous-fiber composites have the highest strength and modulus. Volume percentage limit of reinforcement is shown in Fig 1.3, above that limit matrix and reinforcement bond is ineffective. Strength of composite material with discontinuous fibers can be increased if fibers are aligned, but practically it is difficult to maintain alignment. Random short discontinuous fiber composite materials have low strength and modulus. Discontinuous fiber composites are cheaper than continuous fiber composites.

Laminar composites

Two dimensional multiple layers or sheets that are oriented in multiple direction are stacked together to form laminar composites. These layers or sheets are arranged at specific direction to meet the design requirements of structures. When all the layers that are stacked together have same orientation are called Lamina. When the layers that are stacked, arranged at various angles are called laminates. Laminar composites are shown in Fig 1.4 and lamina and laminates are shown in Fig 1.5.

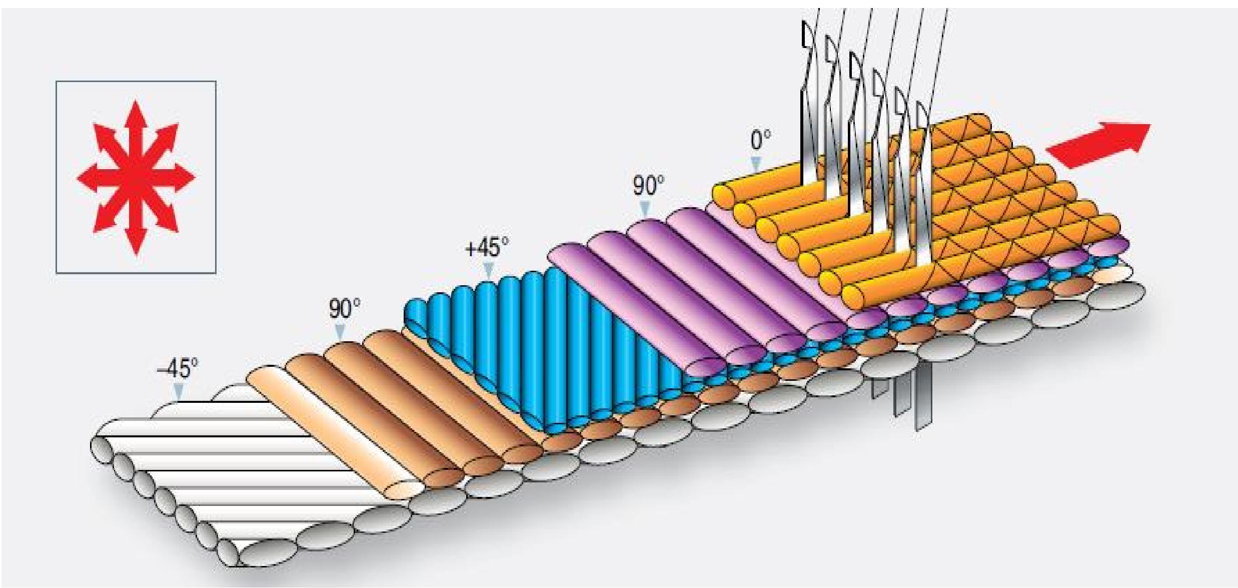

Fig 1.4. Plies orientation at different angles (Federal Aviation Administration , n.d.)

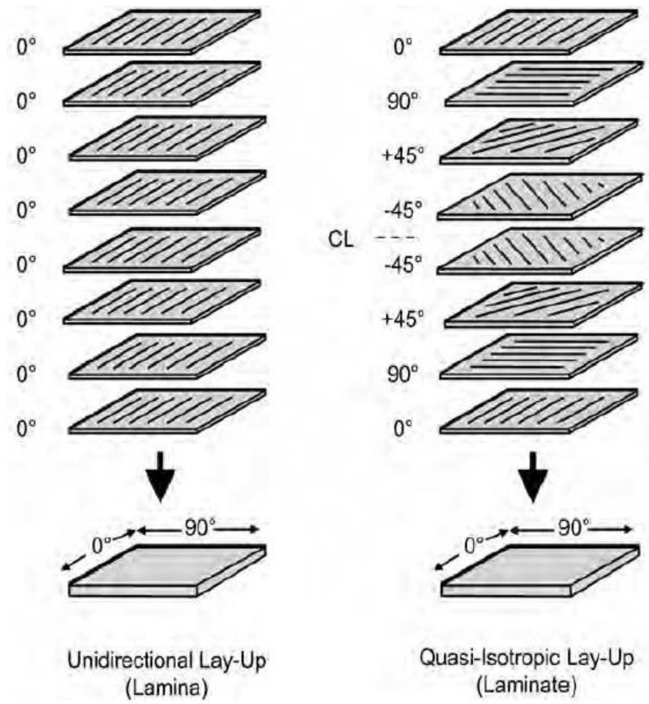

Fig 1.5. Difference between Lamina and laminate lay-ups (Campbell, 2010)

Stress Strain Curves of Matrix and Reinforcement

Polymers are used as matrix phase in Polymer Matrix Composites. There are several polymers, the most widely used polymers are polyester, vinyl ester, epoxy, phenolic, polyimide, polyamide, polypropylene, polyether ether ketone (PEEK), and others (Joseph). Properties of composite materials varies with the use of different type of polymers. Polyesters and vinyl resins and epoxy resins are used in Wind Turbine composite materials. Epoxy resin is expensive than polyester and vinyl resin. Epoxy resin has better mechanical properties than polyester and vinyl resin. Service temperature is determined by matrix, because matrix phase in composite has low melting temperature compared to reinforcement. Matrix phase melts, softens at low temperature compared to reinforcement. Using Matrix alone as structural material has low mechanical properties, such as low strength and low impact resistance. Reinforcement of polymers results into composite materials which has high mechanical properties than the matrix alone (William D. Callister). The resultant polymer composite material have high specific strength, stiffness, fracture resistance and have good abrasion, corrosion , impact and fatigue resistance (Joseph).The stress-strain curve of Fiber, Matrix and resultant composite material is shown in Fig 1.6.

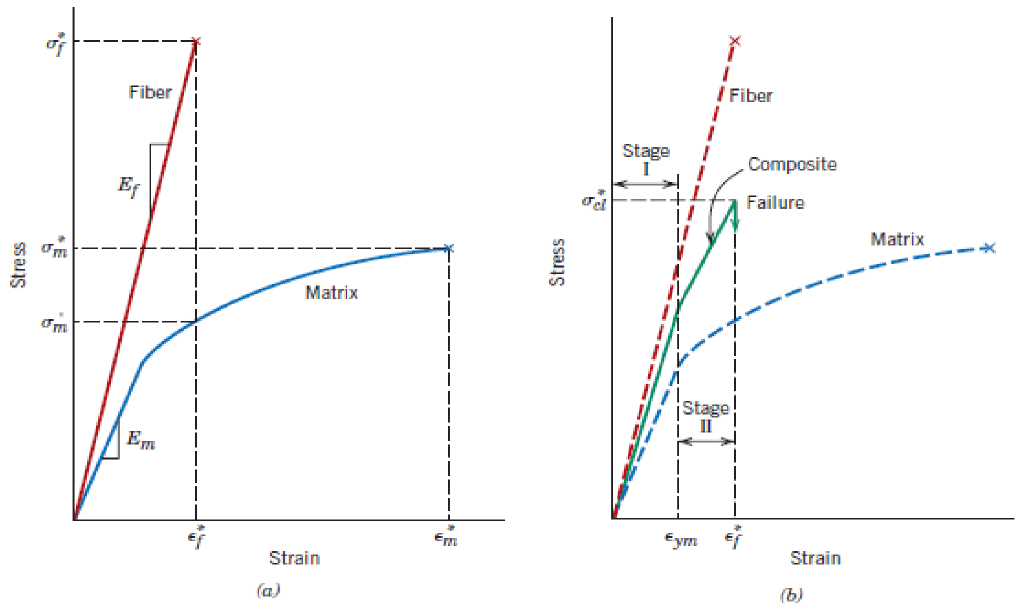

Fig 1.6. Stress strain curves for brittle fiber and ductile matrix materials. (William D. Callister)

Wind Turbine Composites

In the past several, different kind of materials are used to manufacture wind turbine blades. In 1941, an American company S. Morgan-Smith manufactured wind turbine blade from steel. After hundreds of hours of unsteady operation of wind turbine, one of its blade failed (Leon Mishnaevsky Jr. ID, 2017). Steel is heavy and low fatigue resistant compared with other advance materials and cannot be considered good choice for blade construction. Wood is used for long time for the construction of wind turbine blades. Wood is considered interesting because of its low density, still some companies are investing in wood composites for the construction of blades. The material choice for Wind Turbine Materials should be based on some requirements. Material should be stiff to keep structure in shape; it should have low density in order to reduce gravitational loads effect. It should be fatigue resistant and environmental friendly (Theotokoglou, 2017). Advance composite materials have replaced the wooden and steel units because composite materials offer good mechanical, thermal and chemical properties.

Polymer Matrix Composites

Polymer-matrix composites (*PMC*s) as discussed earlier consist of polymer as matrix and fiber as reinforcement medium. Polymer composites has wide range of application, PMCs are inexpensive and easy to fabricate and are classified on the basis of reinforcement, that are glass, carbon, basalt and aramid fiber reinforced composites. Each of them have different mechanical properties.

Glass Fiber–Reinforced Polymer (GFRP) Composites

Glass fiber polymer composites consist of glass fibers, contained within a polymer matrix. GFRP has wide range of applications in electronics, aviation and automobile and wind turbine industry. GFRP has high strength, flexibility and high stiffness. Compared with carbon fiber, glass fiber (GF) have relatively lower strength and rigidity. Because of lower rigidity, it cannot be used in structural parts of airplanes and bridges. There are different types of GF that are shown in table 1.2. E-glass composite is commonly used in Wind Turbine Industry for the construction of rotor blades. It is least expensive compared with S glass fiber which is more expensive and has high strength and modulus. GF is chemically inert and can be used in corrosive environment. Polyester, vinyl ester, phenolic and epoxy resins are used as matrix. The mechanical performance of fiber composite materials depends on the strength and modulus of fiber/matrix and on matrix/fiber interface bonding. Various GF reinforcements such as longitudinal, woven mat, chopped fiber (distinct) and chopped mat have been produced to enhance the mechanical properties of the composites. Chemical composition and mechanical properties are shown in table 1.1 and 1.2 respectively. GF composite materials mechanical properties are shown in table 1.3.

Table 1.1. Chemical-compositions of glass fibers in weight % (TP Sathishkumar, 2014)

Type	(SiO_2)	(Al_2O_3)	Tio_2	B_2o_3	(CaO)	(MgO)	Na_2O	K_2o	Fe_2o_3	Ref.
E-glass	55.0	14.0	0.2	7.0	22.0	1.0	0.5	0.3	–	17
C-glass	64.6	4.1	–	5.0	13.4	3.3	9.6	0.5	–	
S-glass	65.0	25.0	–	–	–	10.0	–	–	–	
A-glass	67.5	3.5	–	1.5	6.5	4.5	13.5	3.0	–	
D-glass	74.0	–	–	22.5	–	–	1.5	2.0	–	
R-glass	60.0	24.0	–	–	9.0	6.0	0.5	0.1	–	
EGR-glass	61.0	13.0	–	–	22.0	3.0	–	0.5	–	
Basalt	52.0	17.2	1.0	–	8.6	5.2	5.0	1.0	5.0	

Table 1.2. Mechanical properties of glass-fiber (TP Sathishkumar, 2014)

Fiber	Density (g/cm^3)	Tensile strength GPa	Young's modulus (GPa)	Elongation (%)	Coefficient of thermal expansion ($10^{-7}/°C$)	Poison's ratio	Refractive index	Ref.
E-glass	2.58	3.445	72.3	4.8	54	0.2	1.558	17
C-glass	2.52	3.310	68.9	4.8	63	–	1.533	
S_2-glass	2.46	4.890	86.9	5.7	16	0.22	1.521	
A-glass	2.44	3.310	68.9	4.8	73	–	1.538	
D-glass	2.11–2.14	2.415	51.7	4.6	25	–	1.465	
R-glass	2.54	4.135	85.5	4.8	33	–	1.546	
EGR-glass	2.72	3.445	80.3	4.8	59	–	1.579	
AR glass	2.70	3.241	73.1	4.4	65	–	1.562	

Table 1.3. Glass-Fiber composite materials strength properties (TP Sathishkumar, 2014)

Type of glass fiber	Resin	Curing agent	V_f	Testing Standard	Tensile Strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength	Interlaminar shear strength (MPa)	Ref.
Woven mat	Polyester	MEKP/Cobalt naphthalene	0.25	ASTM D412 (T)	1.601	80.5	20.0	–	–	41.850 (J)	–	1
Woven mat	Polyester with (3% oligomeric siloxane		0.37	ASTM D-3039 (T), ASTM D 790 (F), ASTM D 2344 (S)	395.8	18000	3.9	399.4	18800	–	44.7	4
Woven mat	Polyester		0.33	ASTM D 638-97 (T),	249	6240	–	–	–	–	–	24
Woven mat	Polyester		–	2810 E6 (T)	189.0	–	–	–	–	–	–	5
Chopped strand	Polyamide66 (PA66)/poly-phenylene sulphide (PPS) blend		0.30	GB/T 16,421–1996 (T), GB/T 16,419–1996 (F), GB/T 16,420 –1996 (I)	–	124	–	159	–	98.2 (kJ/m^2)	–	25
Woven mat [0°/90°]	Isophthalic/neo-pentyl glycol polyester		0.42	PS25C-0118 (T)	200	–	–	–	–	10(J)	–	26
Woven mat (Non-symmetric)	Polyester		–	362 F (BS, 1997) (T)	220	7000	0.055	–	–	–	–	8
Woven	Polyurethanes		0.49	ASTM D3039 (T), ASTM D790M (F), ASTM D2344 (S)	278	18654	–	444	27075	–	27	27
Chopped strand mat	Polyester		0.60	ASTM D638 (T)	250	325	0.022	–	–	–	–	9
Woven mat	Polyester (acid resistant resin)		–	ASTM D 2344 (S)	–	–	–	–	–	–	30	28
Chopped strand mat	Polyester resin		0.015	ASTM E 399 (T)	–	3000	–	16.5	–	–	–	29
Chopped strand + vertical roving	Polyester		–	ASTM D 3039 (T), ASTM D 5379 (I)	103.4719	–	–	–	–	37.926 (J)	–	6
Virgin fiber	Polyester			ASTM D256 (T), ASTM D2240 (I)	64.4	7200	1.8	–	–	645.1 (J/m)	–	30
Glass	Polyester (3 wt% Na-MMT)		0.40	ASTM- D638 (T), ASTM- D790 (F), ASTM- D256 (I)	130.03	–	–	206.15	–	153.50 (KJ/m^2)	–	31
Chopped strand	Epoxy (5.1 V_f flyash)	Hardener	3.98	ASTM standard	–	–	–	–	–	0.0176 (J/mm^2)	–	7
Woven (biaxial stitch)	epoxy		0.57	ASTM D 2355 (S)	–	–	–	–	–	–	18.2	32

(continued)

Type of glass fiber	Resin	Curing agent	V_f	Testing Standard	Tensile Strength (MPa)	Tensile modulus (MPa)	Elongation at break (%)	Flexural strength (MPa)	Flexural modulus (MPa)	Impact strength	Interlaminar shear strength (MPa)	Ref.
Randomly oriented	Epoxy (10 wt% SiC)		0.5	ASTM D 3039-76 (T), ASTM D 256 (I)	179.4	6700	–	297.82	–	1.840(J)	18.99	33
Woven	Epoxy (0.5 wt% MWCNTs)		0.73	ASTM D 2344 (S)	–	–	–	–	–	–	41.46	34
Unidirectional	Epoxy		0.55	ASTM D3039 (T)	784.98	–	0.032	–	–	–	–	35
Woven	Epoxy (6 wt% joc)		0.60	ASTM D 3039 (T)	311	18610	3.8	–	–	–	–	23
Woven + (35 wt% short borosilicate)	Epoxy		–	–	355	43700	1.65	–	–	–	–	36

T: Tensile test; F: Flexural test; I: Impact test; S: Shear test; Joc: Jatropha oil cake; Na-MMT: sodium montmorillonite; MWCNT: Multiwalled carbon nanotube.

Carbon Fiber–Reinforced Polymer (CFRP) Composites

To harness faster and steadier winds, offshore wind turbine installation trend has been started. In order to take advantage of steadier winds and to capture more wind energy, wind turbine rotor diameter needs to be increase which results in heavier blades. Power is proportional to the square of blade length (npower). Mass increase with increasing rotor size is more than the energy extracted from wind.

$$Power = \frac{1}{2} kCp\pi r^2 V^3$$

It is important to minimize the weight of blades and to keep it under control. For light weight blade construction carbon fiber is an option for wind industry because it is lighter, stiffer and fatigue resistant as compared to glass fiber composites. Carbon fiber composites are expensive but are used by the companies Vestas (Aarhus, Denmark) and Siemens Gamesa (Zamudio, Spain), often in structural spar caps of large blades (Leon Mishnaevsky Jr. ID, 2017).

Static Properties of carbon composites

Composite laminate sheet made up of woven bidirectional layers of carbon fiber and epoxy resin. Tensile test was performed according to ISO standards at strain rate of 5 mm/s. Compressive tests were performed to ASTM D 3410/D 3410M at three different strain rates of 0.05 mm/s, 5 mm/s and 50 mm/s. Stress-Strain curves for both tension and compression loads are illustrated in Fig 1.7. In case of tensile test, the curves are linear until brittle failure while in case of compression test the curves shows nonlinear behavior. This non linearity is because of viscoelastic behavior of matrix and also due to specific microstructure of carbon fiber. The other reason of non-linearity in compressive loads is due to misalignment of fibers in laminates. In compression load, misalignment of fiber increases which leads to reduction in specimen stiffness (P.N.B. Reis a, 2008). The experimental results of static strength are given in table 1.4.

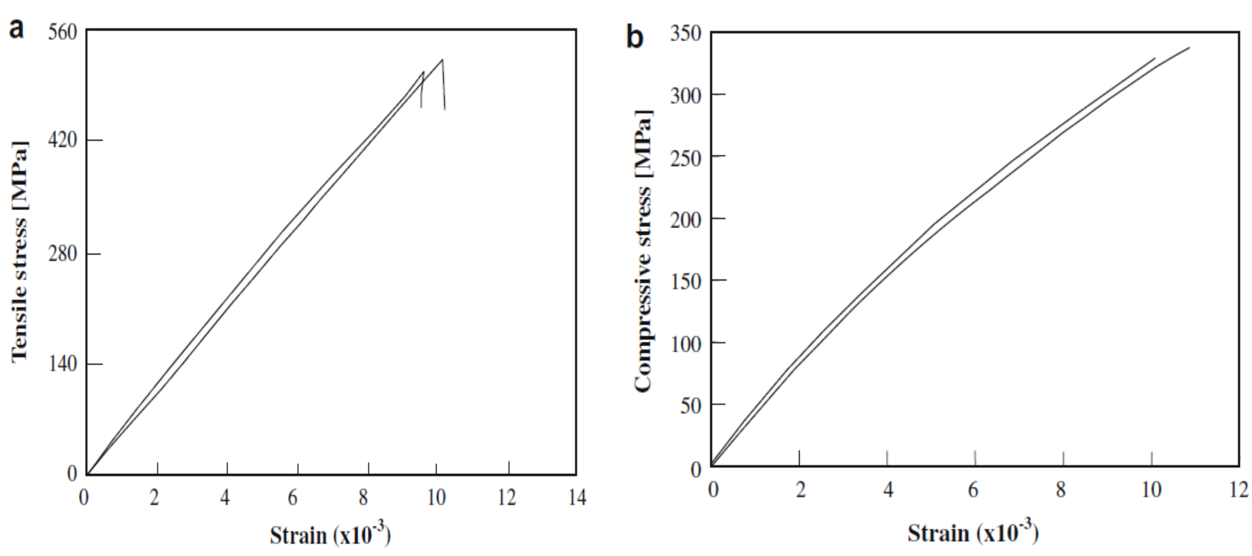

Fig 1.7. Stress Strain plots: (a) tensile test result and (b) compressive tests result (P.N.B. Reis a, 2008)

Table 1.4. Experimental static test results. (P.N.B. Reis a, 2008)

Loading type	Strain rate (mm/s)	σ_{UTS} (MPa)	Average σ_{UTS} (MPa)	Standard deviation (MPa)
Tensile	5	539.2 521.9 568.3 538.6	542.0	19.3
Compressive	0.5	298.0 330.9 321.1 312.4	315.6	13.9
Compressive	5	309.4 313.6 330.8 329.0	320.7	10.8
Compressive	50	322 353.3 342.2 339.5	339.3	12.9

Carbon fiber is expensive and mostly used in high performance applications i.e. in aerospace industry. Carbon fiber composites have high modulus, specific strength and rigidity compared with other fiber composite materials. Mechanical properties taken from MSU/ SNL database and shown in table 1.5 (Bortolotti, 2012), carbon volume percentage is 50% and process used to manufacture specimen is VARTM (Vacuum Assisted Resin Transfer Molding). High stiffness and low density allows thinner blade profile. On account of high specific strength, wind turbine manufacturing industry showed interest in carbon fiber composite materials even it is too expensive. At high temperature, carbon fiber maintains its high strength and not effected by moisture at room temperature. Carbon fiber is creep resistant and have good damping characteristic, low toughness and low ultimate strains. Carbon fiber composites are sensitive to misalignment of fibers that leads to reduction in static compressive and fatigue properties.

Table 1.5. Unidirectional carbon (50 % volume fraction, VARTM processed) property data from MSU/SNL database (Bortolotti, 2012)

Youngs modulus (GPa)	100
Ultimate tensile strength (MPa)	+1600
Ultimate compressive strength (MPa)	–500 / –700
Ultimate tensile strain (%)	+1.6
Ultimate compressive strain (%)	–0.6 / –1.1

Aramid Fiber–Reinforced Polymer Composites

Aramid fibers have high strength and modulus. There are a number of aramid materials each one has its trade name. The most common among them are Kevlar and Nomex. Tensile strength of aramid fiber is higher than other polymeric fiber material such as glass fiber, but has poor compression strength. Compressive strength comparison of aramid fiber composite with other composites are illustrated in Fig 1.8. This material has outstanding specific strength, has high toughness, high impact, creep and fatigue resistant (William D. Callister). Being an organic fiber, aramid absorb moisture. Tensile strength and modulus decreases with increasing temperature as shown in Fig 1.9 (Campbell, 2010). Aramid fiber shows poor transverse, longitudinal compression and shear strength due to the lack of adhesion to the matrix materials (William D. Callister). Yielding takes place at 0.3 to 0.5 percent that results in kink bands which is related to compressive buckling of aramid fiber. Aramid composites are better in tension-tension and flexural fatigue load as compared to glass fiber composites (Campbell, 2010). Glass, Carbon, Aramid fiber composite material properties are shown in table 1.6. Epoxy is used as matrix material. Fiber Volume fraction is 0.6. (William D. Callister)

Table 1.6. Glass, Carbon, and Aramid Fiber–Reinforced properties. Epoxy as matrix material. Composites Volume Fraction is 60 %. (William D. Callister)

Property	*Glass (E-glass)*	*Carbon (High Strength)*	*Aramid (Kevlar 49)*
Specific gravity	2.1	1.6	1.4
Tensile modulus			
Longitudinal [GPa (10^6 psi)]	45 (6.5)	145 (21)	76 (11)
Transverse [GPa (10^6 psi)]	12 (1.8)	10 (1.5)	5.5 (0.8)
Tensile strength			
Longitudinal [MPa (ksi)]	1020 (150)	1240 (180)	1380 (200)
Transverse [MPa (ksi)]	40 (5.8)	41 (6)	30 (4.3)
Ultimate tensile strain			
Longitudinal	2.3	0.9	1.8
Transverse	0.4	0.4	0.5

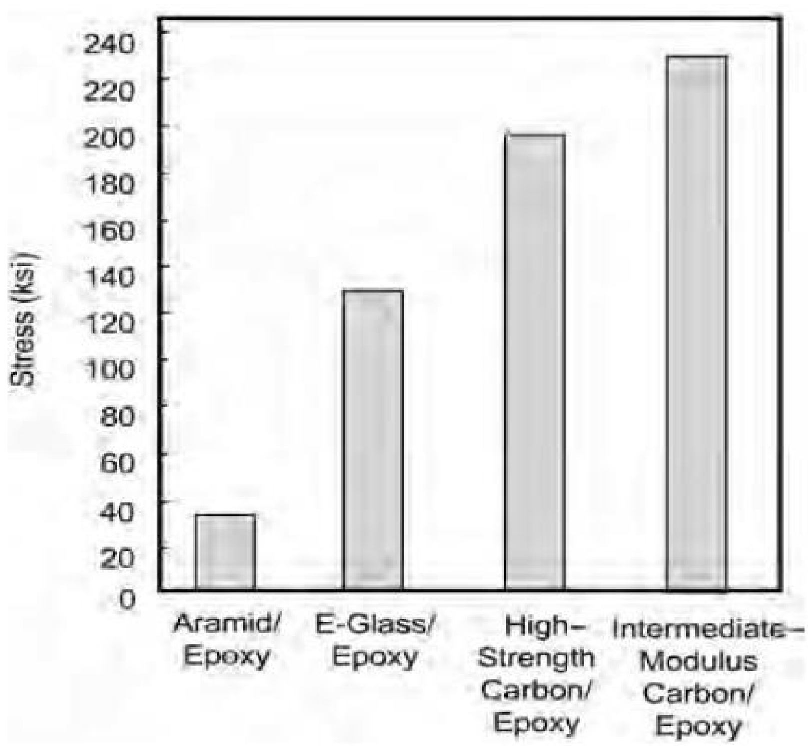

Fig 1.8. Comparison of compressive strengths of UD-composites (Campbell, 2010)

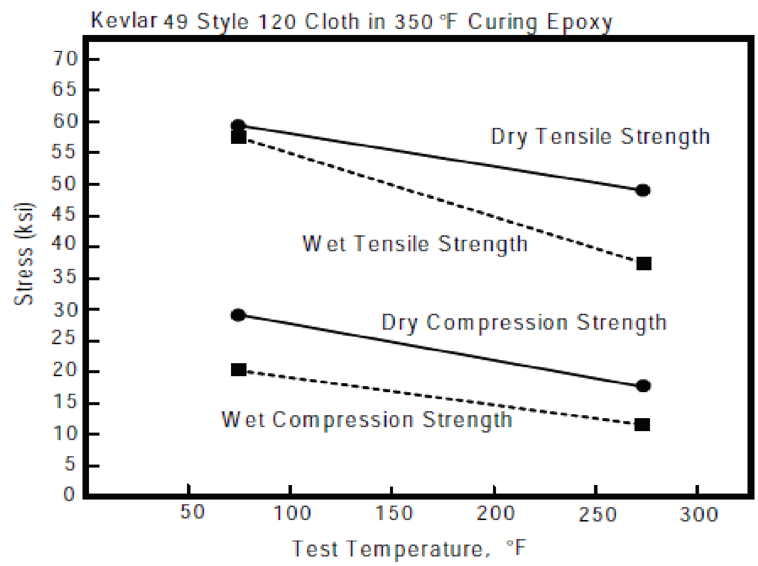

Fig 1.9. Moisture and Temperature influence on Kevlar-epoxy strength (Campbell, 2010)

Basalt Fiber Reinforced Polymer Composite

Modern wind turbine blade size increasing and the reason behind this is to increase the efficiency and energy output of wind turbine and to reduce the cost per kilowatt hour. As discussed earlier in carbon composites, weight of blade increases as the size of blade increase, so material selection is a challenging task. Some of the factors such as light weight, low cost, high fatigue strength, corrosion resistant, recyclability etc. should be taken into account while selecting material for wind turbine blades. Several kind of fiber composites are introduced for rotor blades of wind turbine. Among those materials basalt fiber gained attention due to outstanding mechanical properties and low cost compare with other fiber composites. Basalt/Carbon hybrid is an interesting area in hybrid technologies. Basalt fiber has huge potential to be used in automotive, sporting, boat building and wind turbine industry (A.N. Mengal1, 2014).

UD $[0°]_4$ basalt fiber reinforced (BFR) and glass fiber reinforced (GFR) specimens are fabricated with epoxy as a matrix material and investigated under tensile and bending loads. Results shows that BFR is superior in properties compared with GFR. BFR has high modulus, high tensile and bending strength. The complete test results are reported in (S.M.R. Khalili, 2011). Basalt fiber composites mechanical properties are compared with the glass and carbon fiber composites which are typically used in wind turbine blade construction and the purpose of comparison with glass and carbon composite is to understand the basalt fiber composites potential application in blade construction. Mechanical and thermal properties of basalt fiber are compared with glass fiber and carbon fiber and are described in table 1.7 and 1.8 …. (A.N. Mengal1, 2014)

Table 1.7. Mechanical properties of basalt-fiber, glass-fiber and carbon-fiber (A.N. Mengal1, 2014)

Properties	Basalt fiber	E-glass	S-glass	Carbon fiber
Tensile strength (MPa)	4840	3800	4650	6000
Modulus of elasticity (GPa)	93.1	75.5	86	600
Breaking extension (%)	3.1	4.7	5.6	2.0
Filament diameter (μm)	21	21	21	15
Linear density (g/cm^3)	2.8	2.6	2.5	1.95
Min and Max temperature Range (°C)	-260 -- +700	-50 -- +380	-50 -- +300	-50 -- +700

Table 1.8. Basalt-fiber and glass-fiber thermal properties (A.N. Mengal1, 2014)

Thermal properties	Basalt fiber	Glass fiber
Thermal conductivity (W/m K)	0.031-0.038	0.034-0.04
Thermal expansion coefficient (ppm/°C)	8.0	5.4
Melting temperature (°C)	1280	1120
Maximum operating temperature (°C)	980	650
Sustained operating temperature (°C)	700	480
Minimum operating temperature (°C)	-260	-60

In table it is shown that basalt has good tensile strength and high modulus of elasticity. Density of basalt fiber is practically equal to glass fiber (Pegoretti, 2012). Basalt fiber has high melting and maximum operating temperature compared with glass fiber.

Carbon, glass and two different basalt fiber laminate samples were tested under tensile fatigue loading. Thickness, density, fiber volume fraction and void content of the laminates samples are given in table 1.9. The void content of carbon laminates is low (0.15%) because of the better fiber wettability with epoxy resin matrix. Epoxy-BF200 reinforced composite stiffness is 20% is higher than Epoxy-GF200 is reported while the UTS of Epoxy-BF200 is 30% higher than Epoxy-GF200. S-N tensile fatigue curves are visualized in Fig 1.10. Carbon laminate show low fatigue sensitivity. Epoxy-BF200 because of having high tensile strength also shows better performance in tensile fatigue loading compared with Epoxy-GF200. Due to high void content in Epoxy-BF280, fatigue behavior is affected. (Pegoretti, 2012)

Table 1.9. Carbon, Glass and Basalt epoxy laminates. Φf % (fiber fraction) Φv% (volume fraction) (Pegoretti, 2012)

Sample	Thickness (mm)	Density ($g \cdot cm^{-3}$)	Φ_f (%)	Φ_V (%)
Epoxy-CF200	0.89 ± 0.02	1.51 ± 0.01	63.5	0.15
Epoxy-GF200	0.72 ± 0.02	1.92 ± 0.01	56.3	2.56
Epoxy-BF200	0.68 ± 0.02	1.98 ± 0.02	61.3	2.33
Epoxy-BF280	1.01 ± 0.03	1.86 ± 0.02	54.1	4.13

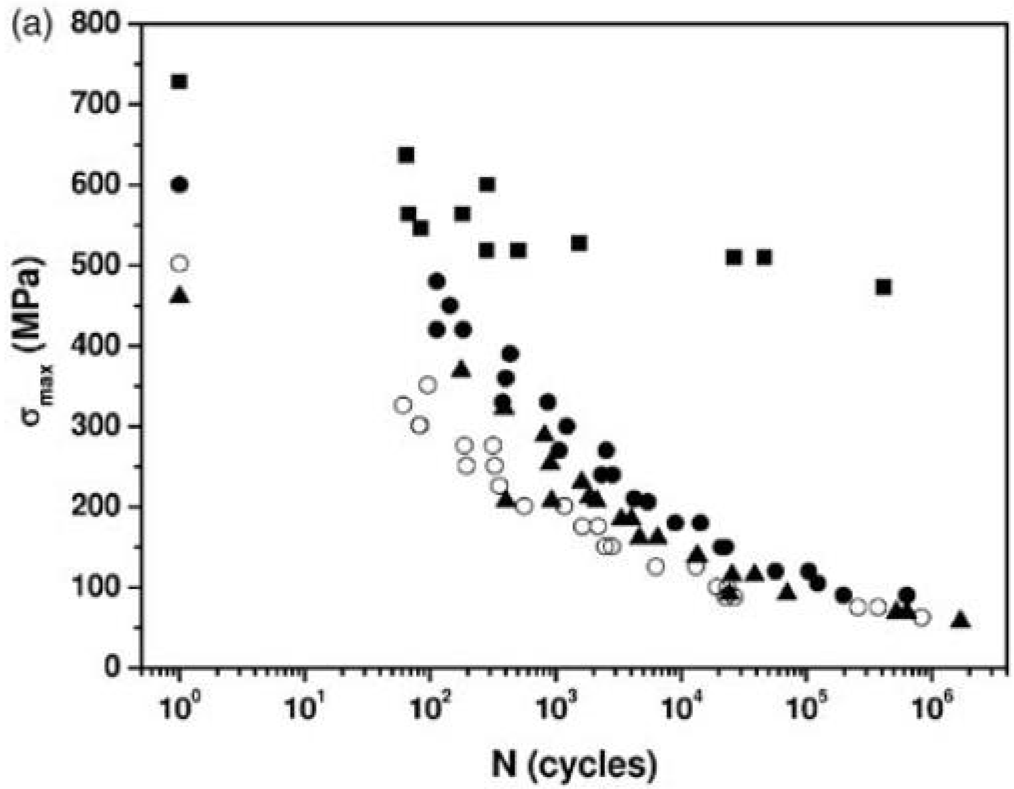

Fig 1.10. Maximum stress – N (cycle) curves from fatigue tests on Epoxy-CF200 (square), Epoxy-GF200 (triangle), Epoxy-BF200 (black dot), Epoxy-BF280 (white dot) (Pegoretti, 2012)

Hybrid Fiber Reinforced composites

Hybrid composites are composed of different kind of fibers in same matrix (William D. Callister). Hybrid composites offer engineers to get the required properties by having many choices of fibers and matrix (Harish1, 2015). Hybrid composites are manufactured in order to improve properties and to overcome the disadvantage of its constituents and to find the cheaper solution (Hatice Taşçı1, 2017). Different kinds of fibers are combined to form hybrid composites but the most common is carbon-glass hybrid composite. As discussed earlier, carbon is expensive material but strong, stiff and lighter. On the other side glass is inexpensive, heavy but less stiff than carbon. Hybrid composites also influence the strain properties. It is reported in (P.W. MANDERS, 1981) that strain limit of carbon/glass epoxy hybrid composite enhance up to 50% and failure strain of the carbon phase increase with decreasing relative proportion of carbon fiber. Hybrid composite is good alternative to pure glass and carbon. Weight can be reduced instead of using pure glass composite and cost can be reduced instead of using pure carbon composite. Fibers in hybrid composites can be aligned in a number of different ways, it can be mixed with each other or layers of single fiber can be constructed and can be stacked with the ply of other fiber to get the required properties. Mechanical properties were found to vary with the arrangement of the reinforcements. (William D. Callister)

Some hybrid composites were developed with varying glass and carbon reinforcement percentage. Epoxy is used as matrix material. Hardness and tensile tests are performed according to ASTM standards. Material, fabrication and specimen preparation information are documented in (Harish1, 2015). Results are shown in Figs 1.11,1.12 and 1.13. Tensile and yield strength increases as the percentage of carbon fiber in hybrid composite increases. The ductility of carbon fiber reinforced composite is higher than the other composites (Harish1, 2015). Compressive failure models are not mature compared to tensile failure models because compressive failure in composites are sensitive to fiber misalignment (Jr., 2017), experimental studies to determine compressive failure envelop shows scatter and different trends due to defects in materials and imperfection in test setups (R. Gutkin a, 2010). Mishnaevsky and Dai predicted that carbon/glass hybrid composites strength reduces by adding carbon fibers because the carbon fiber composites has low compressive strength. (Leon Mishnaevsky Jr., 2013)

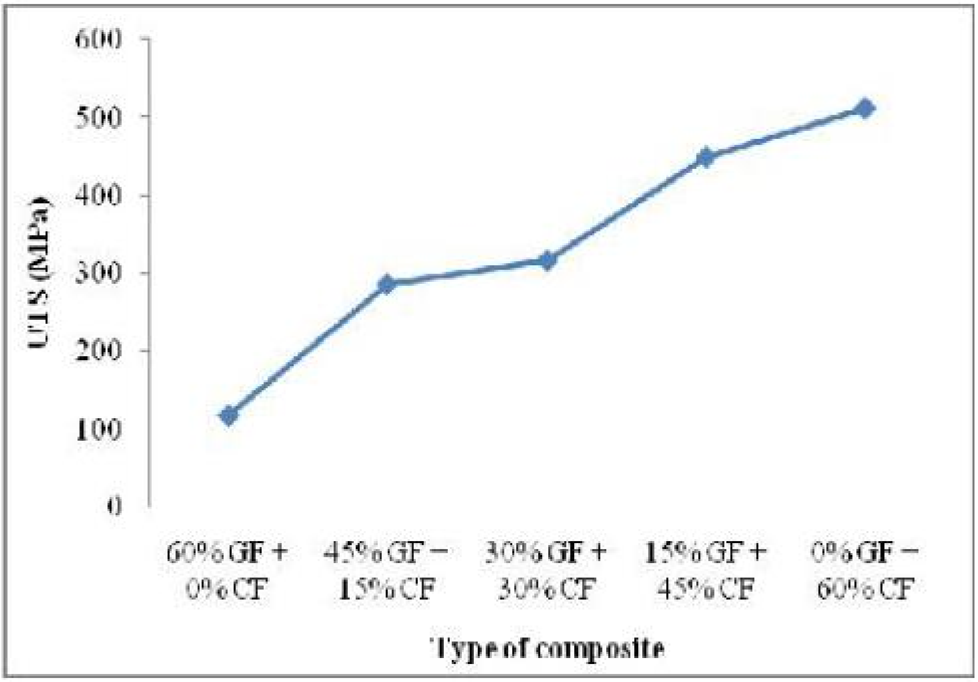

Fig 1.11. Effect of reinforcement on ultimate tensile strength of FRC (Harish1, 2015)

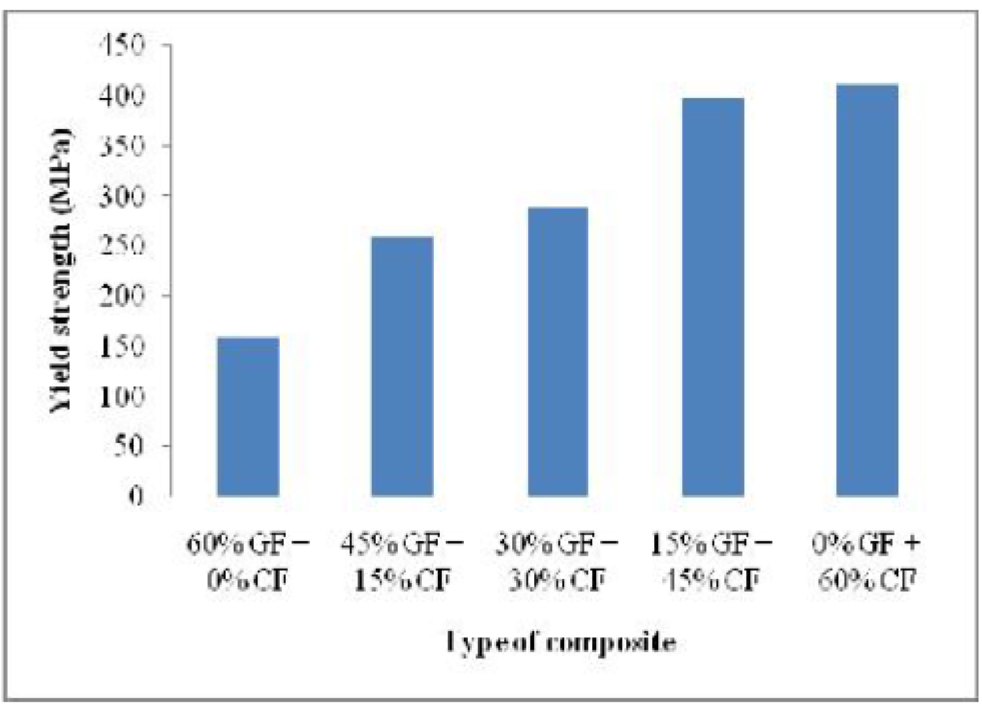

Fig 1.12. Fiber type and volume % effect on Yield strength of FRC (Harish1, 2015)

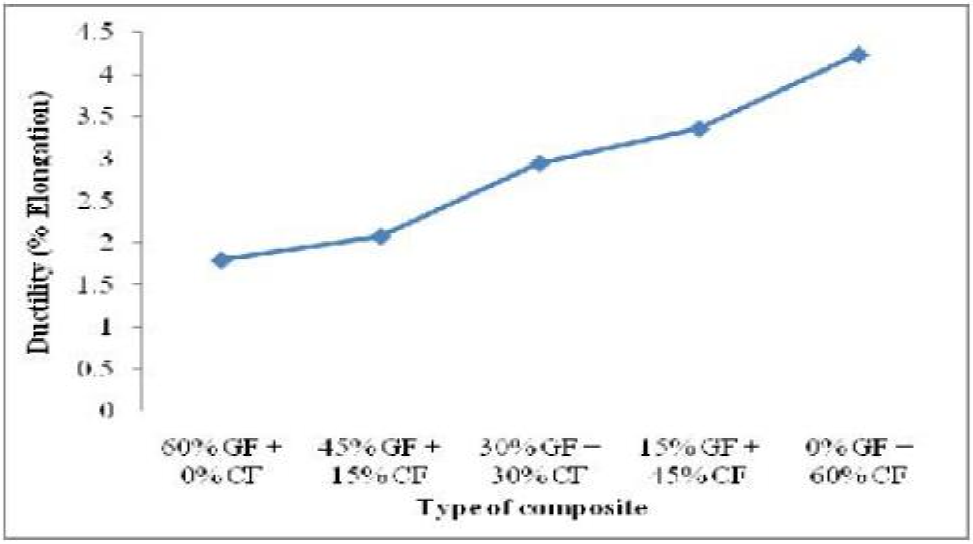

Fig 1.13. Fiber type and volume % effect of on Ductility of FRC (Harish1, 2015)

Natural fibers Composites

Due to increasing cost and high energy demand, developing countries focusing on the cheapest solution to provide low cost energy to remote communities. To provide low cost energy to remote areas, Danish Ministry of foreign affairs initiated joint research project with Nepal government on Development of Wind Energy Technologies in Nepal based of Natural Materials (Leon Mishnaevsky Jr1, 2009).Typically glass fiber and carbon fiber composites are used for wind turbine blades. These composites are non-biodegradable and have high fabrication cost (Ganesh R Kalagia, 2016). Wind turbine industries are looking for light weight, cheap and environmental friendly materials for rotor blade construction. Attempts have been made to replace glass and carbon fiber composites with natural fiber composites which are light, fatigue resistant, cheap and easy to work (Leon Mishnaevsky Jr1, 2009). Along with some advantages, the disadvantages of natural composites are, moisture absorber and have low thermal stability (Leon Mishnaevsky Jr. ID, 2017). Holmes et al. tested bamboo-poplar epoxy laminates and have found that bamboo based composites has the potential to use in wind turbine blades. It is found that bamboo-poplar epoxy laminate has high strength and stiffness. There are a lot of possible approaches to develop laminates from bamboo to use in wind turbines. (John W. Holmes1, 2009)

Tensile Properties

Tensile Testing is performed according to ASTM D3500 standards at fixed loading rate of 1mm/minute. Tensile test results of four specimens taken from same panel are shown in Fig 1.14. Ultimate tensile strength range from 175 MPa to 191 MPa and modulus from 20.5 GPa to 23.0 GPa(3). Strength can be improved by processing thinner slices of bamboo. (John W. Holmes1, 2009)

Compressive properties

Compression tests were performed according to ISO 604 standards at loading rate of 1mm/minute. Stress strain curves of six specimens taken from same panel is shown in Fig 1.15. Compressive strength is between 105 MPa to 118 MPa and modulus from 20.6 GPa to 23.0 GPa. (John W. Holmes1, 2009)

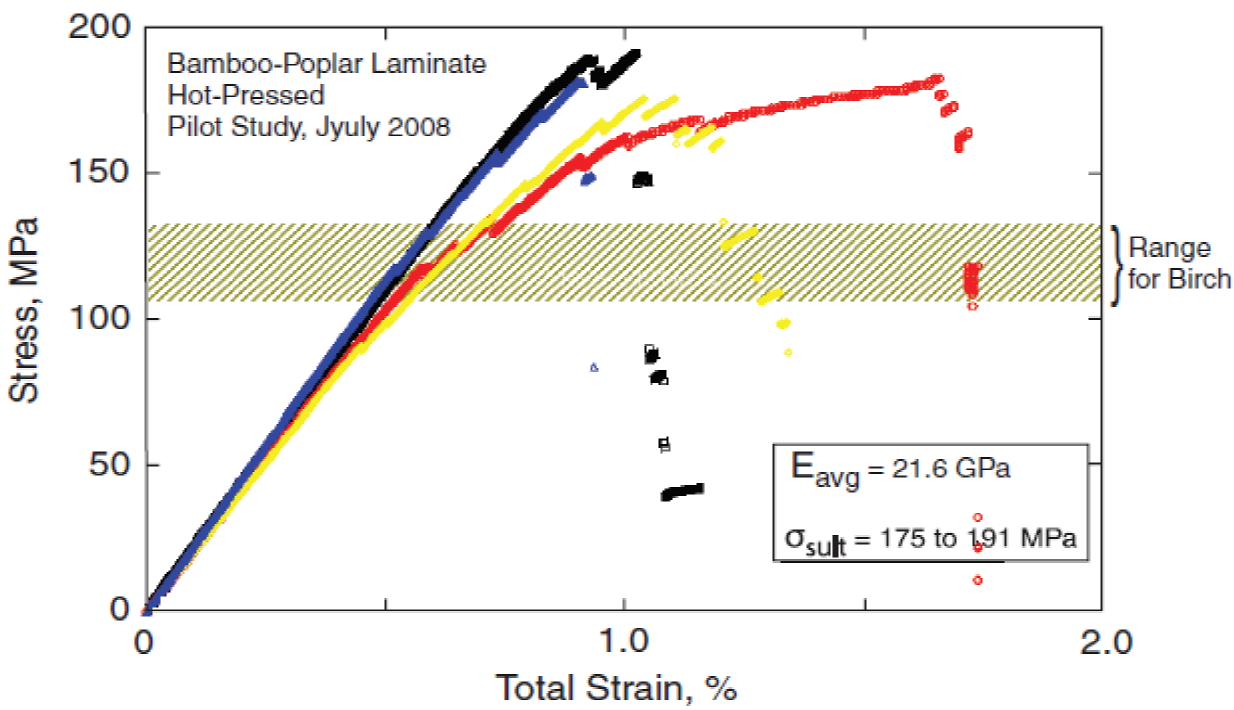

Fig 1.14. Tensile stress strain curves for bamboo-poplar composite. (Tests results at room temperature, displacement rate of 1 mm per minute) (John W. Holmes1, 2009)

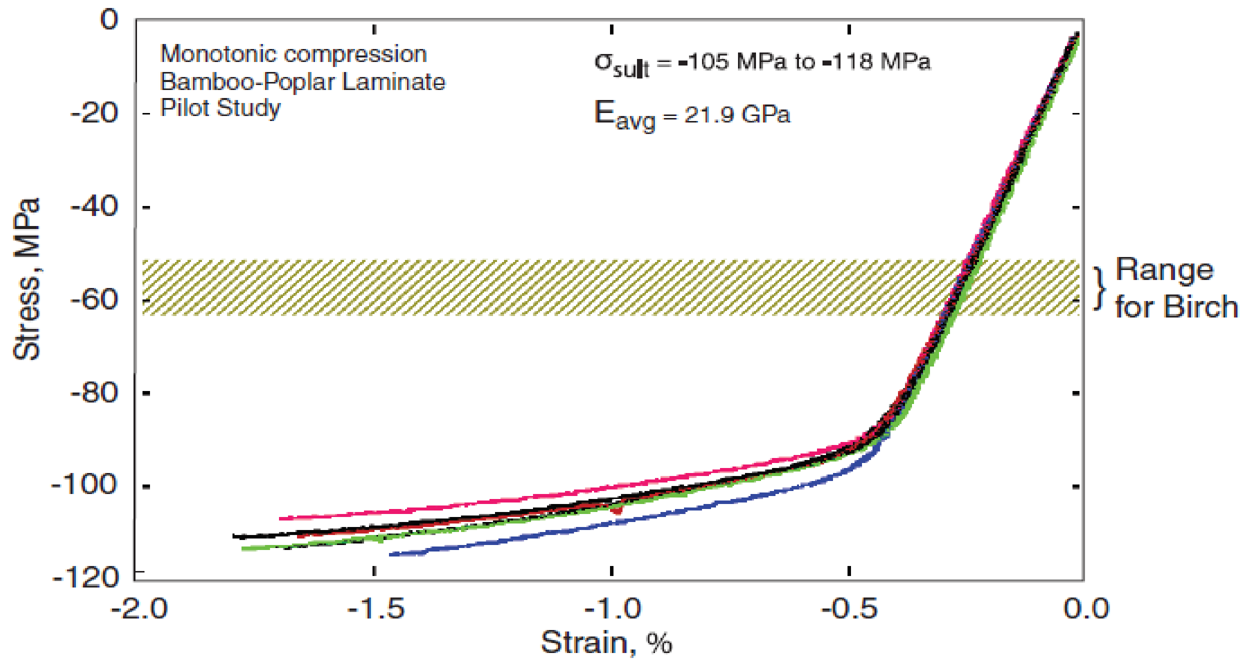

Fig 1.15. Compressive stress strain behavior of bamboo poplar laminate. (Tests results at room temperature, displacement rate of 1 mm per minute) (John W. Holmes1, 2009)

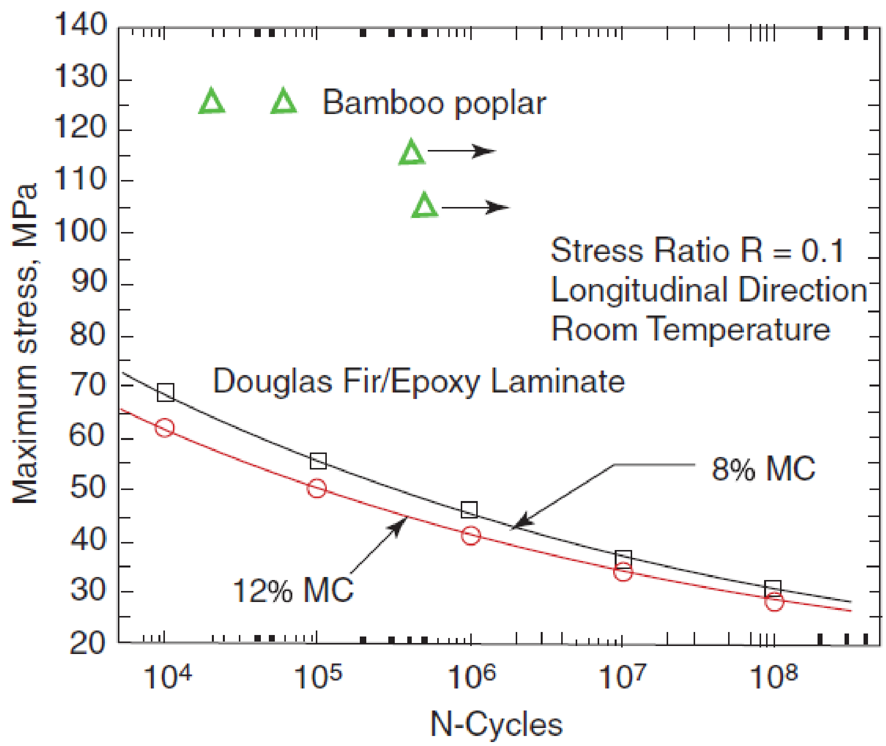

Fig 1.16. S-N curve for bamboo-poplar laminate (tension-tension fatigue test). Fatigue life of bamboo poplar laminate is higher than Douglas Fir/epoxy composites (John W. Holmes1, 2009)

Fatigue Properties

Tensile- tension fatigue tests were performed under load control and at stress ratio R= 0.1 and at loading frequency between 2 Hz and 5 Hz. S-N curve is shown in Fig 1.16. Fatigue life of bamboo-poplar laminates can be improved by improving inter-laminar bonding. Bamboo/poplar showed good fatigue life compared with wood composites. (John W. Holmes1, 2009)

Chapter 2

Specimens' description

Wide range of composite laminates are used to manufacture wind turbine blade, including E glass, WindStrand and Carbon fiber as reinforcement and polyester, vinyl ester, epoxy resin as matrix materials. These materials of wind turbine's interest are tested and results are reported in (John F. Mandell, 2010). Various kind of Resin systems used as matrix material are given in Table 2(a), fabrics detail is shown in Table 2(b), strands used in fabrics are given in table 2(c) and laminate definition in Table 2(d). Laminates are manufactured by different processes such as Resin Transfer Molding (RTM), vacuum assisted RTM, Infusion, SCRIMP infusion and vacuum bag prepreg molding. Static strength test results of two type of laminates multidirectional and Biax are discussed in following sections. Multidirectional laminates contain varying amount of 0° and ±45° plies, whereas biax laminates contain only ±45° biax fabrics.

Table 2.1(a): RTM/Infusion Resins, Cure and post-cure conditions (John F. Mandell, 2010)

Name	Type	Resin	Cure (if not RT) and Post Cure* Temperature, °C
EP-1	Epoxy	Hexion MGS RIMR 135/MGS RIMH 1366	90
EP-2	Epoxy	Vantico TDT 177-155	70
EP-3	Epoxy	SP Systems Prime 20LV	80
EP-4	Epoxy	Huntsman Araldite LY1564/XB3485	60 and 82
EP-5	Epoxy	Hexion MGS L135i/137i	35 and 90
EP-6	Epoxy	Jeffco 1401	60 and 82
EP-7	Epoxy	DOW un-toughened epoxy	90
EP-8	Epoxy	DOW toughened epoxy	90
UP-1	Polyester	U-Pica/Hexion TR-1 with 1.5% MEKP	90
UP-2	Polyester	CoRezyn 63-AX-051 with 1% MEKP	65
UP-3	Polyester	Ashland AROPOL 1101-006 LGT with 1.5% DDM-9 MEKP	65
UP-4	Polyester	CoRezyn 75-AQ-010 with 2.0% MEKP	65
VE-1	Vinyl ester	Ashland Derakane Momentum 411 with 0.1% CoNap, 1% MEKP and 0.02 phr 2,4-Pentanedione	100 65 (mixed mode)
VE-2	Vinyl ester	Ashland Derakane 8084 with 0.3% CoNap and 1.5% MEKP	90
VE-3	Vinyl ester	Ashland Derakane 411-200	NA

Table 2.1(b). Fabric descriptions (John F. Mandell, 2010)

	Manuf.	Designation	Areal Wt. (g/m^2)	Component Strands* Warp Dir.(wt.%)				
				0°	±45°	90°	Mat	Stitch
A	Knytex	D155	527	0	0	99	0	1
B	Saertex	U14EU920-00940-T1300-100000	955	91	0	8	0	1
C	Saertex	S15EU980-01660-T1300-088000	1682	97	0	2	0	1
D	Vectorply	E-LT-5500	1875	92	0	6	0	2
E	Vectorply	E-LM-1810	932	67	0	0	32	1
F	Vectorply	E-LM-3610	1515	80	0	0	20	0
G	Knytex	A260	868	98	0	0	0	2
K	Knytex	DB120	393	0	97	0	0	3
L	Saertex	VU-90079-00830-01270-000000	831	0	97	2	0	1
M	Fiber Glass Ind.	SX-1708	857	0	68	0	30	2
N	Vectorply	E-BX-1700	608	0	99	0	0	1
O	OCV	WindStrand DB1000	1000	5	94	0	0	1
P	Knytex	DB240	837	0	98	0	0	2
R	Saertex (11)	MMWK Triax Glass/carbon/glass	970	69	31	0	0	NA
S	Toray	ACM-13-2 carbon (300-48k-10C yarn)	600	100	0	0	0	NA

Table 2.1(c). Strands used in chosen fabrics (John F. Mandell, 2010)

Fabric (Table 2(b))	Direction (Deg.)	Strand
B	0	NA
C	0	NA
D	0	PPG Hybon 2026 4400 TEX
F	0	PPG Hybon 2026 4400 TEX
L	±45	NA
M	±45, mat	FGI 675/1334
O	0	OCV WindStrand 17-1200 SE2350M2,
S	0	Toray carbon 300-48k-10C

Table 2.1(d). Laminates Description (John F. Mandell, 2010)

Database Laminate Designation	Resin	Fabrics	Layup	V_f (%)	Thickness (mm)	Process	Processed by (if not MSU)
Glass, 0° and ±45° Plies							
DD series	UP-2	A, K	$(0/\pm45/0)_S$	Var.	Var.	VARTM	
QQ1	EP-2	B, L	$(\pm45/0_2)_S$	53	4.09	VARTM	
QQ1I	EP-1	B,L	$(\pm45/0_2)_S$	52	4.10	infusion	
QQ2	EP-2	B, L	$(\pm45/0/\pm45)_S$	52	3.96	VARTM	
QQ4	EP-2	C, M	(±45/0/±45/0/±45)	57	4.03	VARTM	
QQ4I	EP-1	B, L	$(\pm45/0/\pm45)_S$	50	4.59	infusion	
QQ4-L	EP-2	C, M	(±45/0/±45/0/±45)	40	5.70	VARTM	
QQ4-M	EP-3	C, M	(±45/0/±45/0/±45)	46	4.85	VARTM	
SLA	UP-3	D, N	(±45/0/±45/0/±45)	54	4.29	Scrimp	Vectorply
SLB	UP-3	E,N	(±45/0/±45/0/±45)	43	2.69	Scrimp	Vectorply
SLC	UP-3	F,N	(±45/0/±45/0/±45)	51	3.67	Scrimp	Vectorply
TT-TPI-EP	EP-4	D, M	(±45/0/±45/0/±45)	55	4.59	Scrimp	TPI
TT-TPI-VE	VE-3	D, M	(±45/0/±45/0/±45)	55	4.60	Scrimp	TPI
TT	EP-3	D, M	(±45/0/±45/0/±45)	55	4.60	VARTM	
TT	EP-1	D, M	(±45/0/±45/0/±45)	55	4.60	Infused	
TT	UP-1	D, M	(±45/0/±45/0/±45)	52	4.60	Infused	
TT2	EP-1	D,M	(±45/0/0/0/±45)	54	6.60	infused	
TT1A	EP-2	D, L	(±45/0/±45/0/±45)	55	4.37	VARTM	
TT1A	EP-1	D, L	(±45/0/±45/0/±45)	55	4.37	infusion	
TT1A-H	EP-2	D, L	(±45/0/±45/0/±45)	63	3.98	VARTM	
Glass, ±45° plies only							
DH	EP-1	M	$[(RM/-45/45)s]_3$	44	4.57	infusion	
DTR1	UP-1	M	$[(RM/-45/45)s]_3$	44	4.52	infusion	
45D	VE-1	M	$[(RM/-45/45)s]_3$	46	4.12	infusion	
45D2	VE-2	M	$[(RM/-45/45)s]_3$	44	4.41	infusion	
SWA	EP-1	L	$(\pm45)_{3S}$	45	4.20	infusion	
DE2	EP-7	M	$(\pm45)_{3S}$	40	4.93	infusion	
DE4	EP-8	M	$(\pm45)_{3S}$	40	4.85	infusion	
WindStrand Laminates							
WS1	EP-5	O, *	(±45/0*/±45)	61	2.56	infusion	OCV
WS2	EP-5	O, *	$(\pm45/0^*/\pm45)_S$	60	5.19	infusion	OCV
W45	EP-1	O	$(\pm45)_6$	49	4.10	infusion	
Carbon 0° and Glass ±45° Plies							
CGD4E	EP-3	S, K	$(\pm45/0_3/\pm45)$	50	2.61	VARTM	
P2B	**	**	$(\pm45/0_4)s$	55	2.75	vac. bag	
MMWK-C/G-EP	EP-6	R	(0_4)	56	4.30	Scrimp	TPI

Static Properties

Laminates lay-up, fiber volume percentage VF % and ultimate longitudinal tensile and compression strength are given in Table 2.2 and strength in transverse direction are given in table 2.3. Coupons are tested at 0.25mm/s. From table 2.2 it is evident that Carbon Fiber prepreg has high stiffness and strength in longitudinal direction.

Unidirectional layers in laminates are responsible to withstand loads that act along the fiber direction. UD laminates are used in structures which are loaded along the fiber direction. If the structures are not loaded longitudinally along the fiber direction, then biaxial ±45 laminates are used to improve shear resistance and can act as cracks arrester. Multidirectional laminates which are the combination of UD and Biax laminates are used when the structures are loaded in multiple direction. In transverse direction, unidirectional fabric laminates are much weaker. Addition of transverse material in fabric laminate construction effect the transverse properties. The ultimate strain of carbon fiber is the lowest. In static loading, strain performance of glass is good compared to carbon.

Carbon composite compression strength

Carbon fiber reinforced plastic are weak in compression. Fibers in carbon laminates are not perfectly aligned in longitudinal direction. In tensile load along the longitudinal direction tends to align the fibers. Misalignment of fibers decrease with increasing tensile load. While in compression the phenomena are opposite. The misalignment increases with increasing compression load, consequently micro buckling and stiffness reduction occurs. Buckling and kinking are the primary failure mechanisms in compressive loading (P.N.B. Reis a, 2008). CFRP and GFRP have comparable compressive properties (Bortolotti, 2012). Carbon fiber weakness in compression is because of its sensitivity to fiber misalignment and fiber waviness. Carbon fiber strain fall below 1 % due to the presence of small defects, fiber waviness and misalignment. (John F. Mandell, 2010)

Table 2.2: Properties of E-Glass and Carbon prepregs and infused fabrics in longitudinal direction (both in tension and compression) (John F. Mandell, 2010)

Laminate Definition			Longitudinal Direction								Shear
			Elastic Constants				Tension		Compression		
	lay-up	V_F %	E_L GPa	E_T GPa	υ_{LT}	G_{LT} GPa	UTS_L MPa	ε_{max} %	UCS_L MPa	ε_{min} %	τ_{TU} MPa
VARTM Fabric/resin											
Fabric B/EP-3	$[0]_2$	52	38.4	12.0	0.27	----	863	2.71	-583	-1.58	----
Fabric C/EP-3	$[0]_2$	60	45.9	15.8	0.26	----	1233	2.80	-676	-1.65	----
Fabric D/EP-3	$[0]_2$	54	41.8	14.0	0.28	2.63	1151	2.97	-740	-1.79	30
Fabric L/EP-3	$[\pm45]_4$	51	13.8	11.8	----	----	95.4	1.46	-166	-1.44	----
Fabric M/EP-3	$[\pm45]_4$	44	13.6	13.3	----	----	144	2.16	-213	-1.80	----
Prepreg											
NB307-D1 7781 497A Glass	0/90	39	19.2	19.2	0.13	3.95	337	2.21	-497	-2.60	115
NCT307-D1-34-600 Carbon	$[0]_4$	53	123	8.20	0.31	4.71	1979	1.32	-1000	-0.90	103
NCT307-D1-E300 Glass	$[0]_4$	47	35.5	8.33	0.33	4.12	1005	2.83	-788	-2.22	112

Notes: All coupons for this Table were tested at 0.25 mm/s, with a 100 mm gage length. Compression tests used a 13 mm gage length with unsupported edges following ASTM D6641.
E_L - Longitudinal modulus, υ_{LT} - Poisson's ratio, G_{LT} and τ_{TU} - Shear modulus and ultimate shear stress from a simulated shear (±45) ASTM D3518 test. UTS_L - Ultimate longitudinal tensile strength, ε_{MAX} - Ultimate tensile strain, UCS_L - Ultimate longitudinal compressive strength. ε_{MIN} - Ultimate compressive strain.

Table 2.3: Properties of E –Glass, Carbon prepregs and infused fabrics in transverse direction, layups and volume percentage are shown (John F. Mandell, 2010)

Laminate Definition			Transverse Direction			
			Tension		Compression	
	lay-up	V_F %	UTS_T MPa	ε_U %	UCS_T MPa	ε_U %
VARTM Fabrics						
Fabric B/EP-3	$[0]_2$	52	66.7	0.63	-197	-1.40
Fabric C/EP-3	$[0]_2$	60	41.9	0.29	-150	-0.98
Fabric D/EP-3	$[0]_2$	54	59.0	0.46	-202	-1.47
Fabric L/EP-3	$[\pm45]_4$	51	94.7	1.11	-157	-1.50
Fabric M/EP-3	$[\pm45]_4$	44	87.5	1.61	-203	-1.68
Prepreg						
NB307-D1 7781 497A	0/90	39	337	2.21	-497	-2.60
NCT307-D1-34-600 Carbon	$[0]_4$	53	59.9	0.76	-223	-2.72
NCT307-D1-E300 Glass	$[0]_4$	47	51.2	0.74	-168	-2.02

Table 2.4: UD longitudinal elastic modulus comparison for some fabrics and carbon prepreg (fiber volume fraction of 53%). (John F. Mandell, 2010)

Fabric or Prepreg	Fiber	Matrix	0^{o} Ply Modulus, E_L, at $V_f = 53\%$, GPa
Fabric B	E-glass	EP-3	42.5
Fabric D	E-glass	EP-3	41.6
NCT307-D1-34-600	Carbon	Epoxy	123
WS1, 0^{o} plies	WindStrand	EP-1	48.3

Strain Rate Effect

Tensile strength and percentage difference in strength of Glass fiber, WindStrand and Carbon fiber laminates at two different displacement rates are shown in Table 2.5. (John F. Mandell D. D., 2010). There are different kind of failure modes in composite materials, fiber dominated and matrix dominated failure modes are major kinds of failure modes. Unidirectional laminates or the laminates that are dominant with 0° layers, will exhibit the fiber dominated failure mode. UD laminates strength is independent of the rate/frequency of loading. While matrix dominated failure mode is rate/frequency dependent due to viscous behavior of matrix (Ellyin, 1994). Strength increases with high loading rates. Tensile and compressive tests have been performed at varying strain rates on number of laminates. Tests results are shown in Fig 2.1 and 2.2. Both tensile and compressive properties are rate sensitive. Laminates with 0° and ±45 plies show steeper normalized slope compared with laminates containing only ±45. (John F. Mandell D. D., 2002)

Tensile and Compressive Stress Strain Curves

The tensile and compressive stress-strain curves of multidirectional (TT) laminate is compared with the unidirectional (D) 0° and biax (M) ±45° fabric laminates in axial direction. Mechanical properties of laminates depend on the orientation, number of plies and content of fiber. In Figs 2.3 and 2.4 it is shown that unidirectional fabric laminates are stiffer compared to multidirectional and biax. Multidirectional fabric laminates are stiffer than biax because of the presence of unidirectional plies. Multidirectional laminate is slightly nonlinear because of the presence of nonlinear

±45° plies. Biax plies non linearity is because of the matrix cracking well before fiber failure. In fact, some studies reveal that the nonlinear elastic behavior, in both tension and compression ranges, is due to viscoelastic behavior of the matrix.

Table 2.5: Effect of displacement on means strengths of different kind of laminates (static and fatigue displacement rates in the axial direction). (John F. Mandell D. D., 2002)

Laminate	Tensile Strength, 13 mm/s (MPa)	Tensile Strength, 0.02 mm/s (MPa)	% Difference
QQ1	869	691	-21
DD16	632	549	-13
WS1	865	754	-13
TT-TPI-EP	837	732	-13
P2B	1546	1516	-2
DH	224	164	-27
DTR1	214	210	-2
45D	238	197	-17
45D2	207	167	-19
SWA	174	124	-29
WS1	223	157	-30

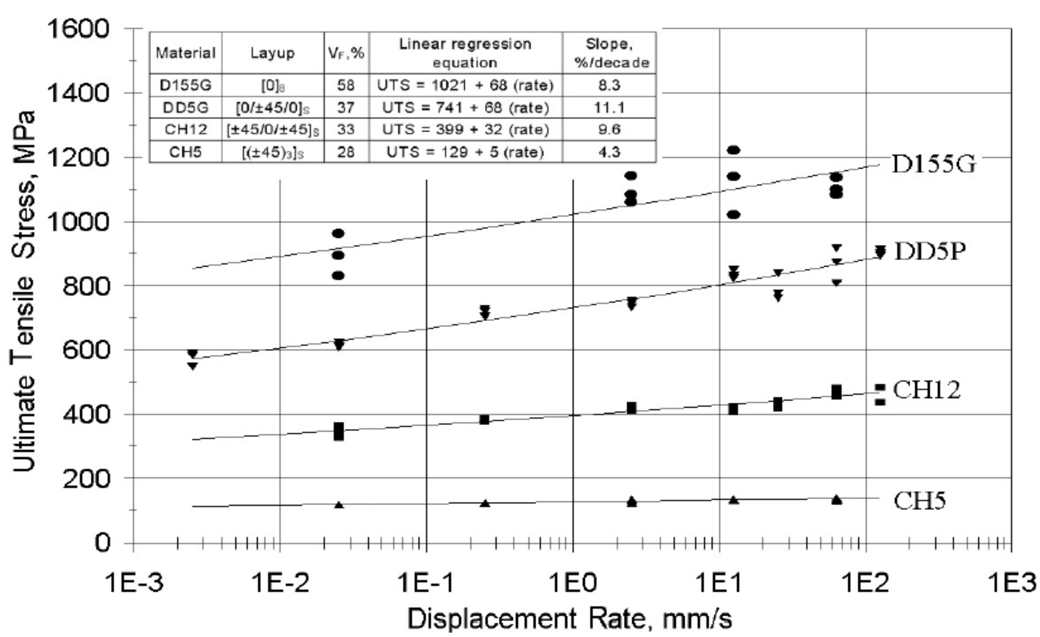

Fig 2.1. Ultimate Tensile Strength versus Displacement Rate for some laminates with different volume percentage (John F. Mandell D. D., 2002)

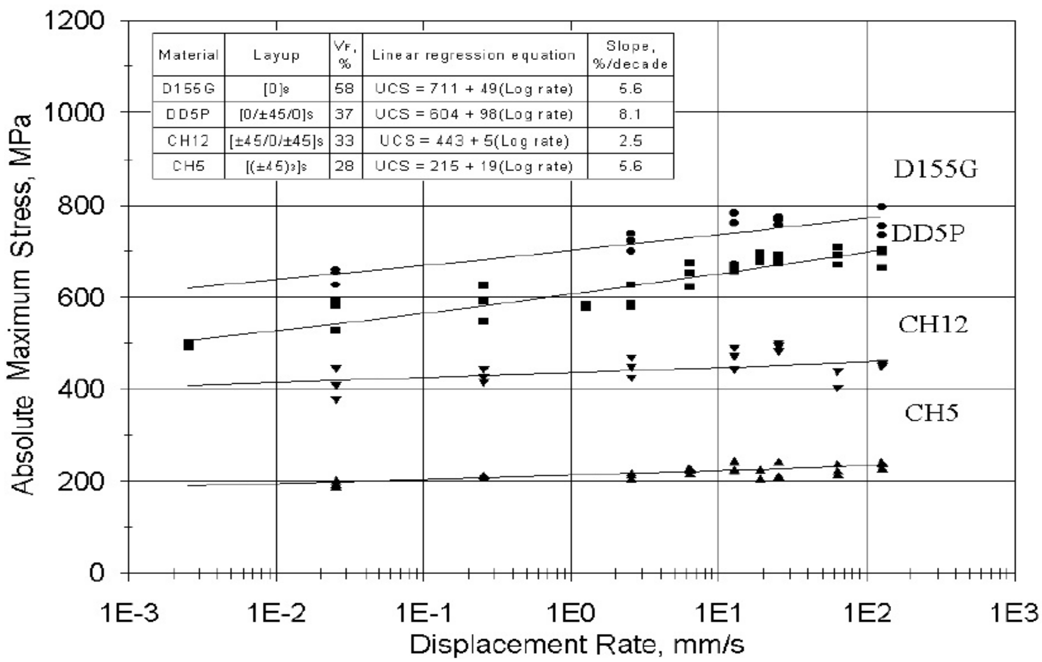

Fig 2.2.UCS (Ultimate Compressive Strength) versus Displacement Rate (different volume %) (John F. Mandell D. D., 2002)

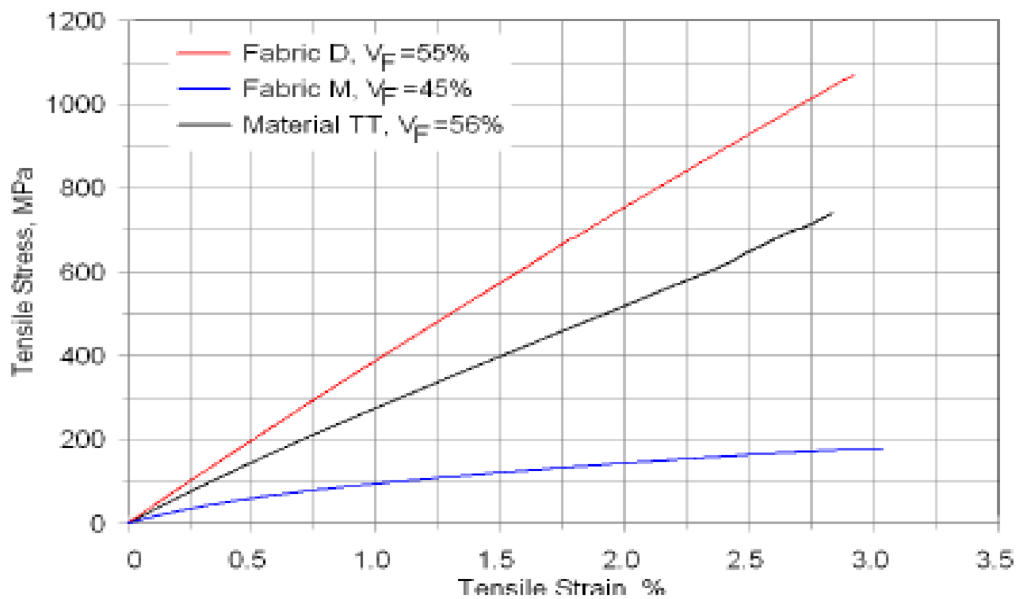

Fig 2.3. Tensile Stress strain curve in axial direction with matrix material (epoxy EP-1), compassion of 0° and ±45° plies (John F. Mandell D. D., 2010)

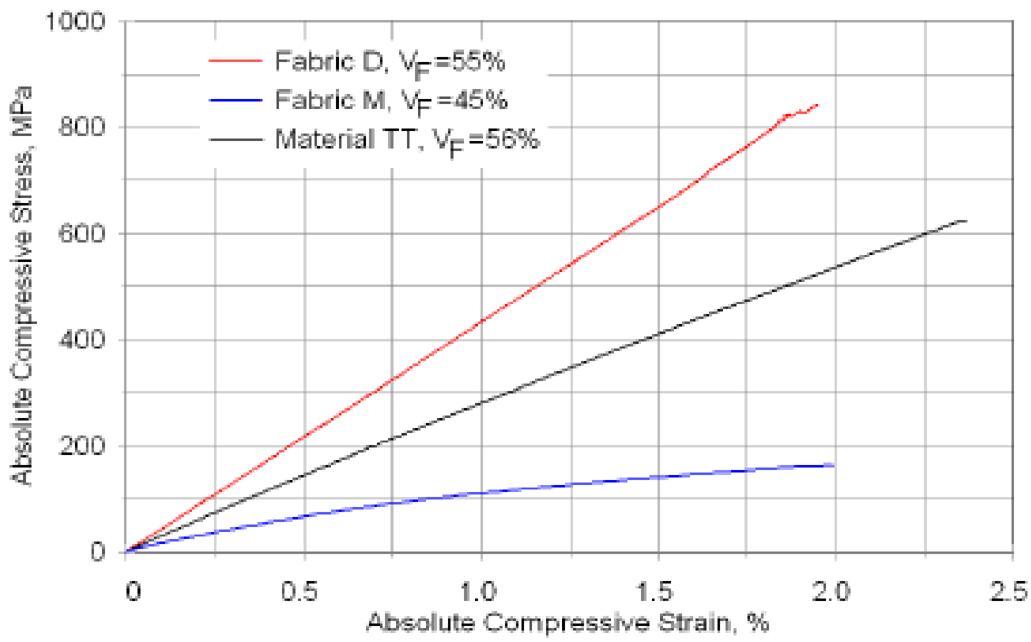

Fig 2.4. Compressive stress strain curve in axial direction with matrix material (epoxy EP-1), comparison of 0° and ±45° plies (John F. Mandell D. D., 2010)

Transverse Stress Strain Curves

Unidirectional laminates show low mechanical properties when loaded in transverse direction. To improve strength properties in transverse direction, mat or transverse material is added during fabric construction. Unidirectional fabric (D) laminates transverse tensile stress strain curves are compared in Fig 2.5. Two different resins, epoxy EP-1 and polyester UP-3 are used as matrix in unidirectional D fabric laminates. Laminates with epoxy resin shows good results compared with polyester. The knee point strain at which the transverse cracking occurs is higher for laminate with epoxy resin. In Fig 2.6, longitudinal tensile and transverse stress strain curve for two different multidirectional laminates QQ1 and QQ4 are illustrated.

Tensile and compressive stress strain curve for different kind of biaxial laminates (±45°) L, M and O are shown in fig 2.7. The difference in stress strain curves is because of difference in fabric construction, content and direction. For such kind of biaxial fabric laminates, resin has limited effect (John F. Mandell D. D., 2010). The nonlinear behavior of stress strain curves is because of the accumulation of matrix cracking. In biaxial laminates ±45° when loaded in tension and compression, cracks occur in matrix and these cracks grows along the fiber direction. Increasing cracks in matrix reduce the overall stiffness, producing a knee in the stress-strain curve. (John F. Mandell D. D., 2002)

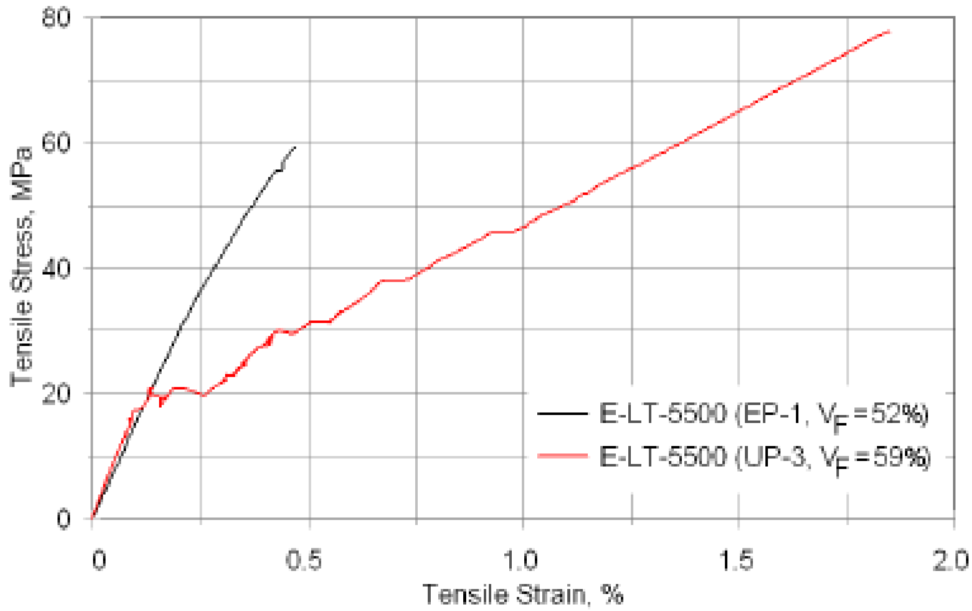

Fig 2.5. Transverse tensile stress strain curves for unidirectional fabric D laminates with epoxy EP- 1 and polyester UP-3 (John F. Mandell D. D., 2010)

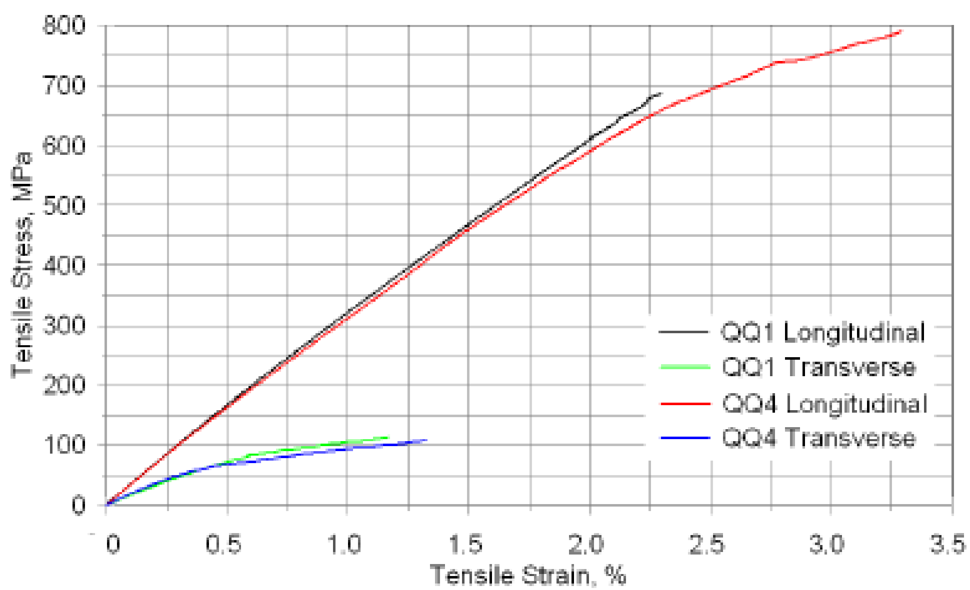

Figure 2.6. Axial and transverse tensile stress-strain curves for multidirectional laminates QQ1 and QQ4. (John F. Mandell D. D., 2010)

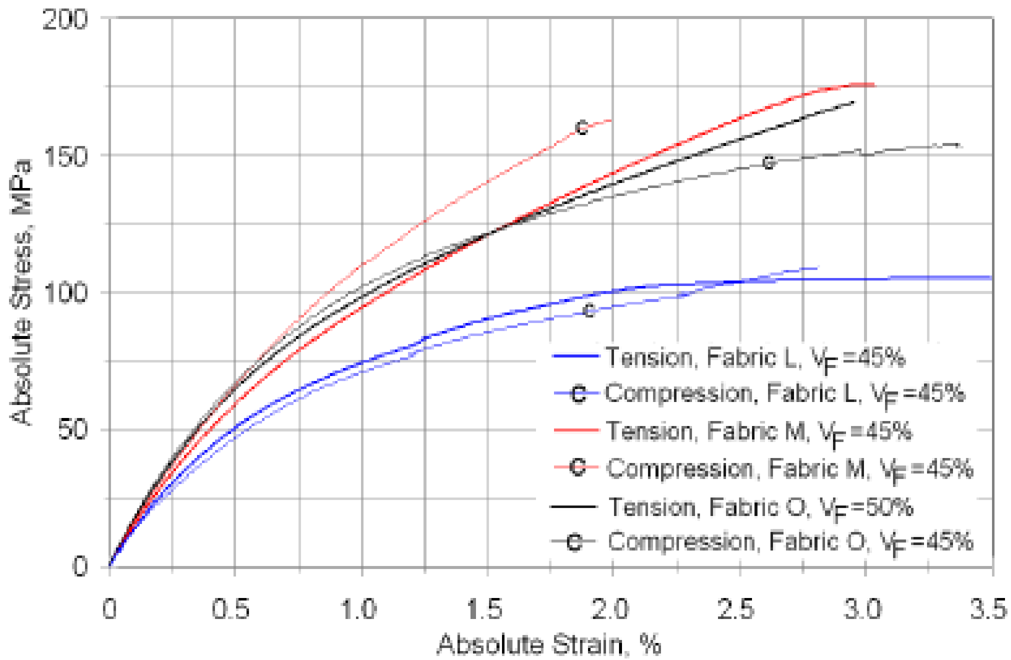

Figure 2.7. Tensile and compressive stress-strain curves for biax fabrics; L, M, and O in the warp direction, epoxy EP-1. (John F. Mandell D. D., 2010)

Static Properties in Three Directions

Typically glass composite materials are used in the construction of wind turbine blades. Static strength properties of composite materials are widely investigated in-plane direction, but properties through thickness of test specimens and in three directions are not common. UD reinforcing fabrics contain warp-direction aligned strands stitched to a backing with organic yarn; the backing may be transverse glass strands (fabric D) or a combination of transverse and random mat glass strands (fabric H), or just mat. Fabric D details are already in mentioned in Table 2(b), while fabric H details are reported in (Daniel D. Samborsky1, 2012). Infused UD 93mm thick fabric laminates is constructed and shear and normal test coupons are machined in different directions. Coupon orientation indices are shown in Fig 2.8. Laminates elastic constants, strength and strain in different directions are listed in table 2.7 and 2.8. Properties of the resin material which is used in laminate construction is shown in Fig 2.6. Detailed strength properties for each coupon orientation and stress direction are given in (John F. Mandell1, 2015). Strength properties in z direction are weaker than longitudinal fiber direction. The z-direction tensile strength is lower than the in-plane transverse tension strength due the fabric backing strands in transverse direction (Daniel D. Samborsky1, 2012). Z-direction compression strength and transverse compression strength is more or less similar.

Table 2.6. Resin Properties (John F. Mandell1, 2015)

Neat Resin Properties	
Tensile Modulus (GPa)	3.53
Poisson's Ratio'	0.347
Compression Modulus (GPa)	2.98
Shear Modulus (GPa)	0.990
0.2% Offset Tensile Yield Stress (MPa)	41.0
Ultimate Tensile Strength (MPa)	76.3
Ultimate Tensile Strain (%)	4.20
0.2% Offset Compressive Yield Stress (MPa)	-64.7
Ultimate Compressive Strength (MPa)	-91.0
Ultimate Compressive Strain (%)	-5.38
0.2% Offset Shear Stress (MPa)	26.1
Shear Stress at 5% Strain (MPa)	37.7

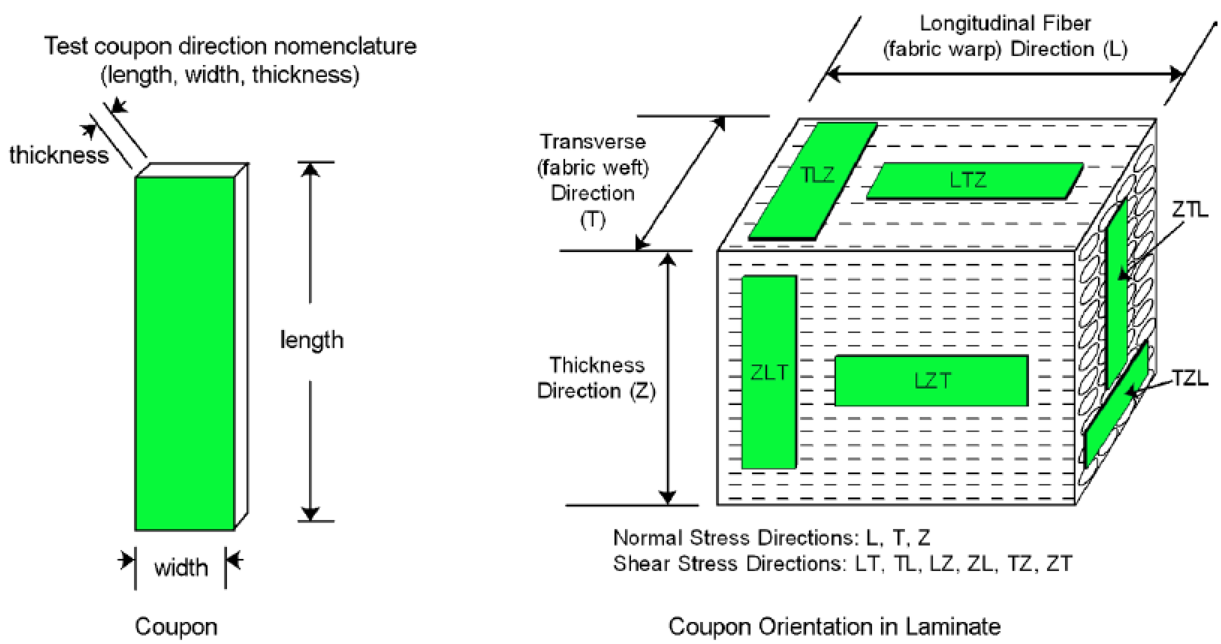

Figure 2.8. Tested coupon oriented in different direction and location in thick-laminate. (John F. Mandell1, 2015)

Table 2.7. Average 3D elastic-modulus for thick-UD glass fabric-epoxy laminate and for neat resin. (John F. Mandell1, 2015)

LAMINATE ELASTIC CONSTANTS[1]	V_F = 56.8 – 58.2%
Tensile Modulus E_L (GPa)	44.6
Tensile Modulus E_T (GPa)	17.0
Tensile Modulus E_Z (GPa)	16.7
Compressive Modulus E_L (GPa)	42.8
Compressive Modulus E_T (GPa)	16.0
Compressive Modulus E_Z (GPa)	14.2
Poisson Ratio ν_{LT}	0.262
Poisson Ratio ν_{LZ}	0.264
Poisson Ratio ν_{TL}	0.079
Poisson Ratio ν_{TZ}	0.350
Poisson Ratio ν_{ZL}	0.090
Poisson Ratio ν_{ZT}	0.353
Shear Modulus G_{LT} (GPa)	3.49
Shear Modulus G_{LZ} (GPa)	3.77
Shear Modulus G_{TL} (GPa)	3.04
Shear Modulus G_{TZ} (GPa)	3.46
Shear Modulus G_{ZL} (GPa)	3.22
Shear Modulus G_{ZT} (GPa)	3.50

[1]Tensile and compressive moduli and Poisson's ratios determined from best fit line between 0.1% and 0.3% strain; shear moduli calculated from best fit line between 0.2% and 0.6% shear strain.

Table 2.8. Average 3D strength properties for thick UD glass fabric-epoxy laminate in different stress direction and for neat resin. (John F. Mandell1, 2015)

LAMINATE STRENGTH PROPERTIES	STRESS DIRECTION	STRENGTH (MPa)	ULTIMATE STRAIN (%)
Tension	L	1240	3.00
Tension[1]	T	43.9	0.28
Tension	Z	31.3	0.21
Compression	L	-774	-1.83
Compression	T	-179	-1.16
Compression	Z	-185	-1.44
Shear[2]	LT	55.8	5.00
Shear[2]	LZ	54.4	5.00
Shear	TL	52.0	4.60
Shear[2]	TZ	45.6	5.00
Shear	ZL	33.9	1.10
Shear	ZT	28.4	0.81

[1]Transverse tension properties given for first cracking (knee) stress
[2]Shear values given for 5% strain following ASTM D5379

Chapter 3

Fatigue

General Overview of Fatigue

The cyclic loads that acts on a component which varies with time, the damage or crack caused by such cyclic loads is called fatigue. According to ASTM, the process of progressive localized permanent structural change occurring in a material subjected to conditions that produce fluctuating stresses and strains at some point or points and that may culminate in cracks or complete fracture after a sufficient number of fluctuations. (ASTM international, n.d.)

Fatigue in Composite Materials

Composite materials are considered insensitive to fatigue damage. There are some reasons that obliged researchers to consider fatigue damage in fiber reinforced composites during design processes. Due to good mechanical properties, composite materials are used for critical structures that must bear fatigue loads during operation, e.g. Wind turbine blades and airplane structural parts that are prone to high alternating loads, are fatigue sensitive. In unidirectional composite materials fatigue failure is sudden, understanding and prediction of fatigue life of UD composites are important (Vassilopoulos, 2011). In comparison with metallic material, the damage mechanism is complex in composite materials (BAKIS, 1990) . Composite materials are inhomogeneous and anisotropic. In composite materials, damage does not always occur due to the propagation of single crack as it happens in metallic materials. A large number of micro damage events occur over the large surface of material due to heterogeneity of material because matrix and reinforcement have different properties (Thomas Jolliveta, 2013). In composites, damage may occur independently due to fiber breakage, matrix cracking, fiber-matrix de-bonding, delamination and transverse play cracking or sometimes interactively of these micro-damages. (Harris, 2003)

Stiffness Reduction by cyclic loading

Composite materials sustain damage at low stress level and in early life, because the damage in composite materials is distributed throughout the stressed area. Failure is not immediate but reduction of stiffness occurs with time. With the passage of time under cyclic loading, the damages accumulate in some region and residual load bearing capacity falls to the level of maximum stress of alternating load cycle and as a result failure occurs, as shown in Fig 3.1. (Harris, 2003)

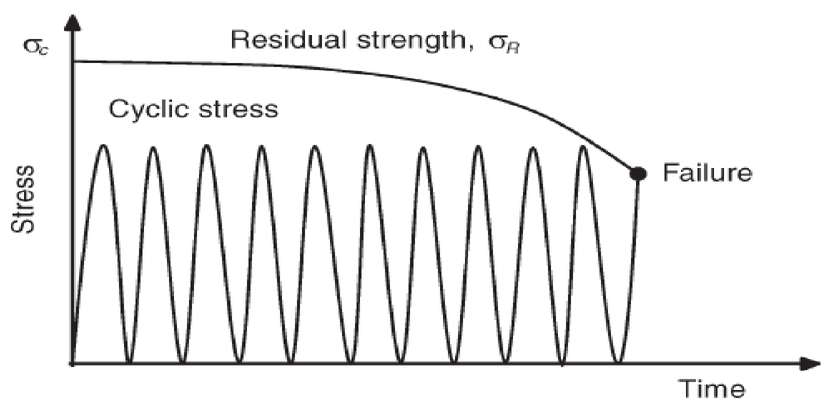

Fig 3.1. Composites strength reduction with time

To demonstrate stiffness reduction, strain and stress control tests are performed. In strain controlled test, strain limit is kept constant, as damage develops, stiffness of the composite material reduces and less load is required to reach controlled stain level as shown in Fig 3.2. In load controlled test, load level is kept constant, as fatigue damage develops, stiffness reduces and strain level changes and increase as shown in Fig3.3. (BAKIS, 1990)

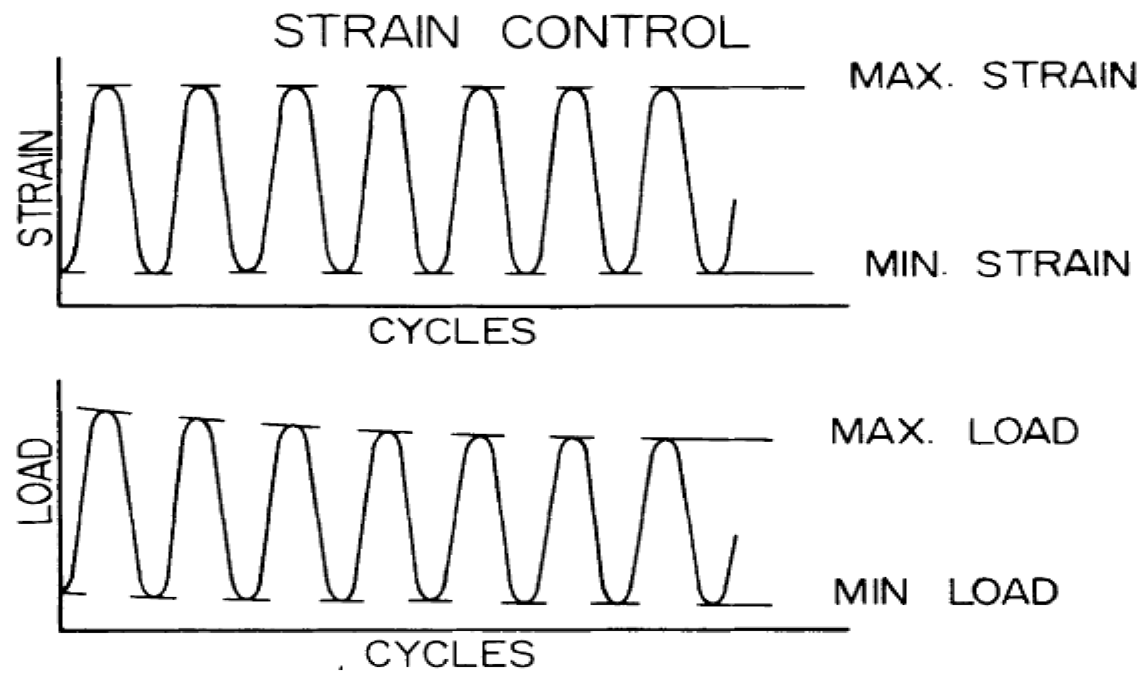

Fig 3.2. Strain-controlled testing, (above) constant maximum-minimum load, (below) decrease in load with cycles (BAKIS, 1990)

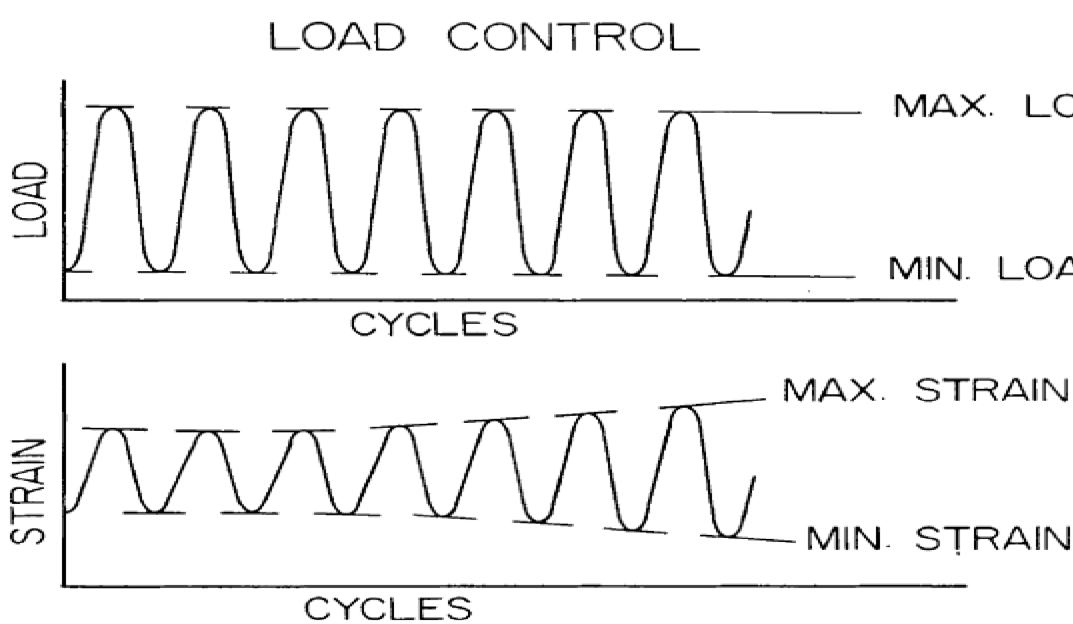

Fig 3.3. Load-controlled testing, (above) constant maximum-minimum load, (below) increase in strain with cycle (BAKIS, 1990)

Cyclic loads on Wind Turbine blades and Fatigue life prediction

Wind turbine blades are composed of many structural components which are made up of different composite laminates and bonded together by adhesives. From past few decades, wide range of experimental programs have been conducted to analyze the fatigue behavior of FRP composite materials for wind turbine blades. Fatigue life prediction of rotor blades is challenging task because of inherent defects of composite materials. Defects such as voids, fiber misalignment in plies, wrinkles, waviness that are produced during construction can become a cause of damage initiation which can result in matrix cracking, fiber breakage, de-bonding and interface cracking. These failure modes occur independently and also interactively and could cause catastrophic failure. For reliable fatigue life prediction, it is important to consider the effect of each of failure mode. It is difficult to predict the fatigue behavior of composite materials under all loading conditions. Standard experiments are performed in the laboratories and models are established to predict the fatigue life of materials and structures (VASSILOPOULOS, 2013). Due to the complex failure mechanism phenomenological and mathematical models have been developed for fatigue analysis and fatigue life prediction of materials and structures. Phenomenological method relies on derived S-N curves. (R. P. L. NIJSSEN, 2013)

Rotor blades are the most critical part of wind turbine because blades are subjected to a high number of alternating loads due to stochastic nature of wind during service life of 20 years. Number of load cycles estimated are 10^8 or 10^9 (Nijssen, 2006). Fatigue analysis of wind turbine blade composites are important to get the required design service life. To achieve this goal, a large number of fatigue tests have been performed on composite material specimens. In many applications the load cycles applied to a component in service vary both in magnitude and time history. These load–time histories are captured electronically. The captured load cycle is then used to control a suitable test facility, such as a servo-hydraulic test machine. It is also possible to apply a strain or displacement history rather than a load (stress) history in the same manner. However, the majority of laboratory fatigue studies are conducted under the conditions of constant frequency and constant amplitude profile (i.e. between constant maximum and minimum loads).(Harris, 2003)

SN Formulation

Some of the fatigue terminologies are given below. A fatigue load is generally represented by sinusoid. The sinusoid was characterized by the maximum load and by the R-value, which is the ratio between minimum and maximum load (Bortolotti, 2012). Fatigue test results are characterized by general terms S and N as shown in Fig 3.4. S is a general term used for stress, strain, or displacement. N represents the number of cycles to failure. Both stress and strain are used to represent fatigue properties. In stress and strain controlled fatigue test, stress and strain are used along y axis. Flat and steep S-N curves are indicated in Fig 3.4(right). Flat curves represent good fatigue properties. S-N curves are derived at constant R values. For composite laminates, the S-N curves are usually derived under given loading conditions in order to model the constant amplitude fatigue behavior of the examined materials (VASSILOPOULOS, 2013). SN curves are formulated in log-log, lin-log form. Log-log (1) and lin-log (2) formulation are given below. (Nijssen, 2006)

$\boldsymbol{log\,N = a + b.logS}$ or $\boldsymbol{logN = c + d.S}$ **(1)**

$\boldsymbol{N = CS^{b}}$ **(2)**

Where

N = number of cycles to failure

S = maximum absolute Stress or Strain

a-d = constants which depend on fatigue stress state

C = 10^{a}

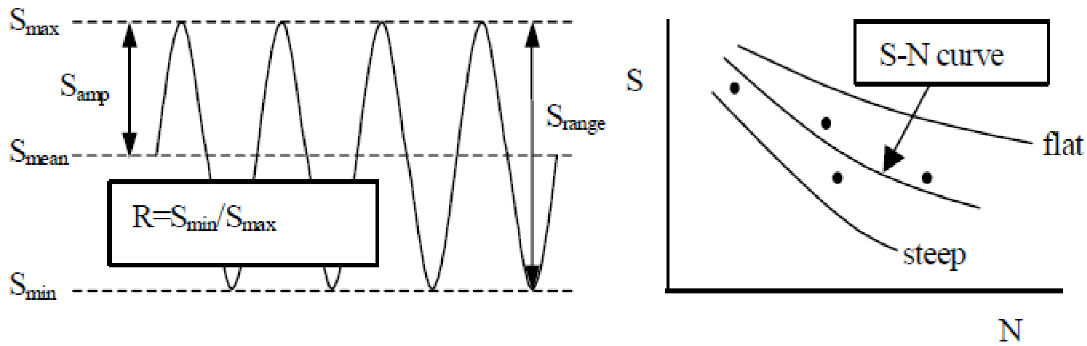

Fig 3.4 Fatigue terminologies (left), general SN-curve to predict fatigue behavior of materials (right) (Nijssen, 2006)

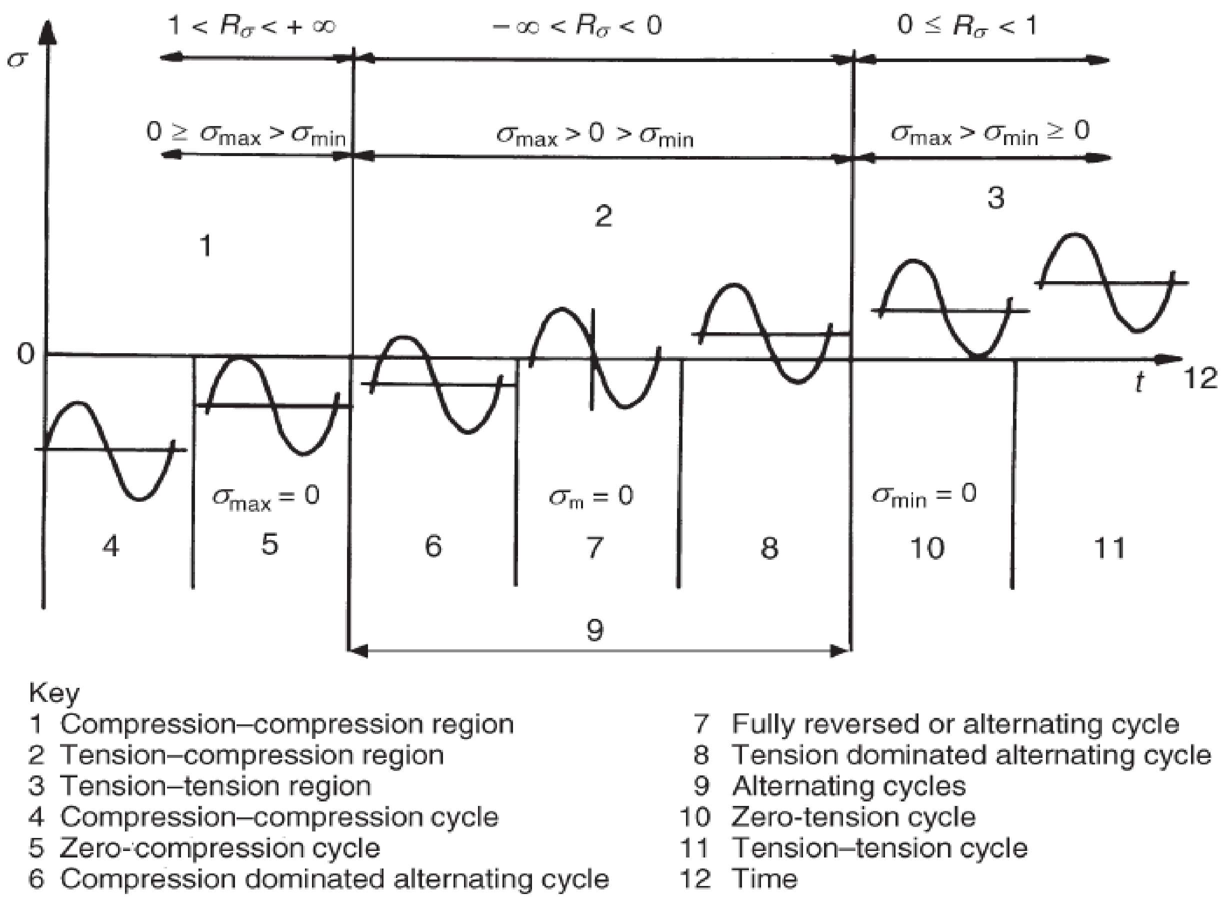

Fig 3.5.Various types of cycles visualized for stress (σ) (Harris, 2003)

Constant Life Diagram, CLD

SN curves are determined at constant R value to model constant amplitude of fatigue behavior of material. In reality structure experience irregular loading patterns. In case of wind turbine blades which operate in open air are subjected to irregular loads due to stochastic nature of wind. It is not easy to model the fatigue behavior of composite material which are loaded in different loading pattern, e.g. in tension-tension, tension-compression and compression-compression. The effect of the different mean stress levels of the various loading cases is very critical for the fatigue life of any composite material. It is not easy to interpolate between different loading domains in order to model the behavior of the material under new loadings and so constant life diagrams (CLD) were established to address this problem (VASSILOPOULOS, 2013). S-N data which is experimentally obtained by doing constant amplitude tests on specimens can also be represented on constant life diagram. CLD is a useful tool to show the fatigue behavior of a material. SN curves are projected on mean and alternating stress plane and is shown in fig (R. P. L. NIJSSEN, 2013). Constant life lines on CLD are function of mean cyclic stress and cyclic stress amplitude. Constant life lines connect points based at different R values but with the same number of cycles to failure. Typical CLD is shown in fig 3.6. In composites, the CLD is typically not symmetric (Nijssen, 2006).

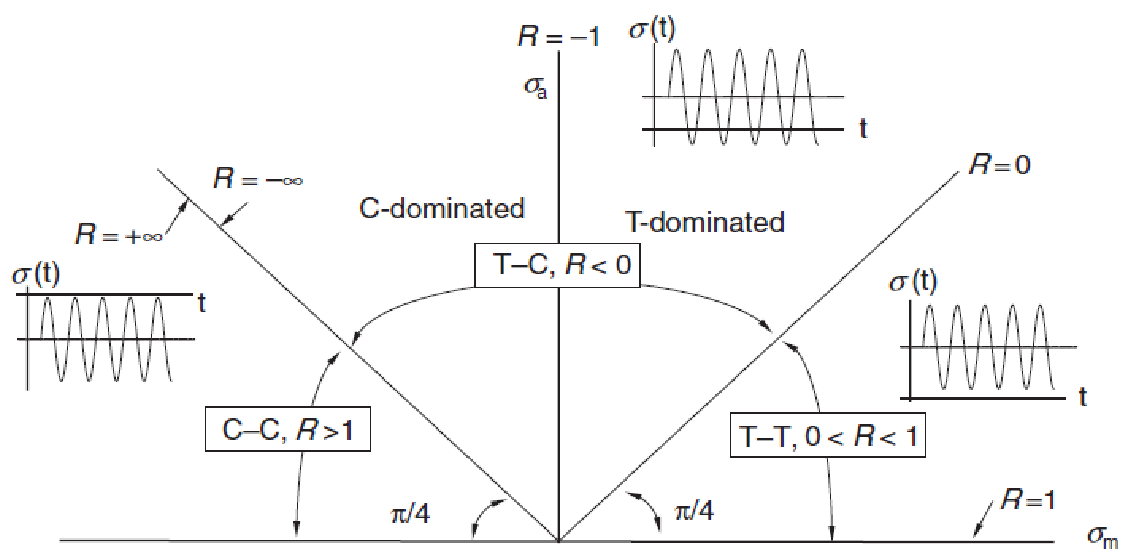

Fig 3.6. Interpretation for $\sigma_m - \sigma_a$ plane, CLD-diagram (VASSILOPOULOS, 2013)

Phenomenological Approach to predict the Fatigue Life

Phenomenological methodology which predict the fatigue life of material that leads to the calculation of Miner's damage coefficient. Phenomenological/classic fatigue life methodology is a sequential method; a number of sub problems should be solved to get the final results. The graphical representation of phenomenological life prediction scheme is illustrated in Fig 3.7.The basic steps needs to be followed to get the end result are given below (VASSILOPOULOS, 2013)

1. Load cycle counting
2. Modeling of the experimental constant amplitude fatigue behavior (SN curve at single R value)
3. Interpretation of fatigue behavior for assessment of the mean stress effect (CLD construction)
4. Adoption of the fatigue failure criterion
5. Damage summation which is carried out according to the linear Palmgren-Miner rule.

Fatigue Limit in Composite Material

Attempts have been made to predict the fatigue life of composite materials. In metallic material, one assume fatigue limit because under certain load, slippage of internal crystal structure takes place, below that load, no fatigue occurs. On the other side, composite material cannot be treated as virgin metallic material, rather it acts as a structure, and absence of fatigue limit makes sense in composite materials. In composite materials, the damage could occur during processing due to residual stresses and due to thermal expansion coefficient difference of composite constituents (Nijssen, 2006), (Kiasat, 2000) . Talreja explained damage mechanism of unidirectional, off axis and angled polymeric laminates and their resulting fatigue behavior and fatigue limit. He theorized the fatigue limit of off-axis and angled laminates and reported that fatigue limit of off axis and angled laminates would be

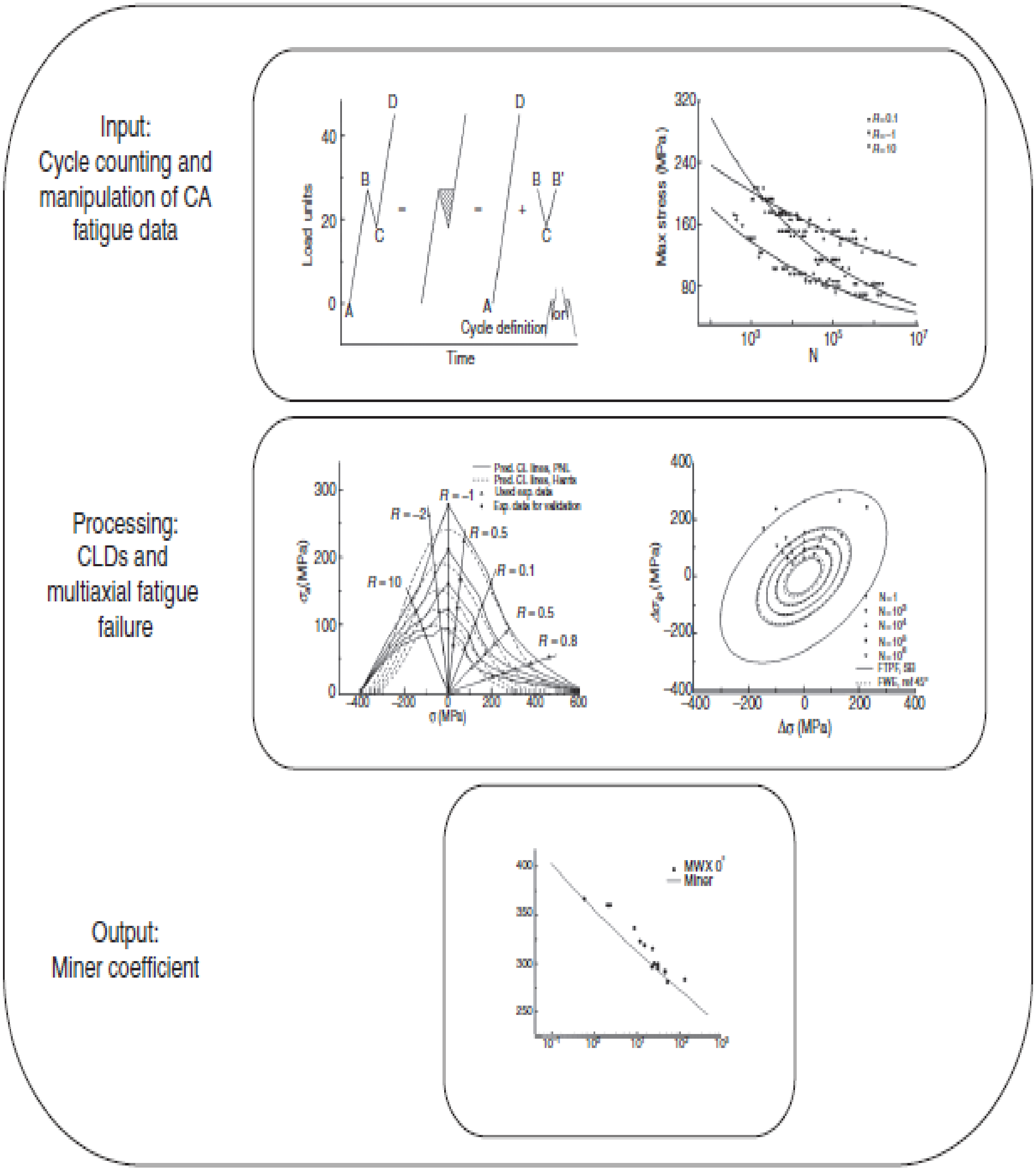

Fig 3.7. Graphical presentation of phenomenological fatigue-life prediction scheme. (VASSILOPOULOS, 2013)

determined by the fatigue limit of matrix material. Limiting strain in fatigue for matrix cracking, transverse fiber de-bonding and delamination in 90° plies are 0.6%, 0.1% and 0.46% respectively (Talreja). According to Bach for unidirectional laminate, stain limit is 0.3% and 0.2% at stress ratio R=0.1 and R=-1 respectively. While for angled laminates, fatigue limit expected at stain level of 0.1%. No indication of fatigue limit for 0° /±45° GFRP. A suggestion is given by Bach that fatigue limit would be in very high cycle range i.e. at 10^9 cycle. From the past research work it is found that the fatigue limit for fiber reinforced composite materials is uncertain and it is suggested that every load cycle can damage the composite structure. (BACH, 1992)

Fatigue Strength Comparison for Several Potential Wind Turbine Blade Laminates

Fatigue tests have been performed on number of composite material laminates appropriate for wind turbine blades. These composite materials laminates include E glass, WindStrand glass Carbon and hybrid fibers, all with same matrix material except DD16. In these tests epoxy resin is used as matrix material. Fatigue test results of some of the laminates namely DD16 (E glass/polyester), MD2 (E glass/epoxy), QQ1 (E glass/epoxy), P2P (Hybrid, carbon/glass) that are fabricated by MSU, OPTIMAT are presented here. SN5-0291(E glass/epoxy), WS1 (WindStrand Glass) are fabricated by TPI (supplied by Global Energy Concepts/BSDS program) and Owens Corning respectively. Description of the above mentioned fiber laminates are given in (Daniel D. Samborsky, 2009) and more details can be found in OPTIMAT and DOE/MSU Databases (Samborsky, 1997). Test methods and test geometries have been described in detail in (Daniel D. Samborsky, 2009). Static tests were run under ASTM test standards. Fatigue tests were performed under load control and at constant amplitude. Test frequency were kept in between 1-10 Hz range in order to avoid heating effect. Static and Fatigue results are given below.

Static Properties of Materials

The laminates given below in table 3.1 differ in lay-up and 0° ply content. Strength and modulus increase with higher percentage of 0° ply content in laminates. P2B has clear advantage in term of strength because of higher carbon fiber % of 0° plies and also because of higher stiffness of carbon fiber. P2B laminates has low ultimate strain value.

Table 3.1. Static-strength & modulus Results, obtained at the fatigue rate, 13mm/s (Daniel D. Samborsky, 2009)

Material and Direction	Tensile Strength (MPa)	Compressive Strength (MPa)	Ultimate Strains (Tensile / Compressive) %	Elastic Modulus (GPa)	0^{O} Ply Modulus, E_L (GPa)
DD16 (Axial)	632 (539)	-402 (-358)	2.9 / -2.3	18.3	----
QQ1 (Axial)	869 (758)	-690 (-596)	2.6 / -2.1	33.0	42.5
QQ1T (Transverse)	149 (128)	-274 (-233)	0.87 / -2.1	17.0	---
P2B (Axial)	1546 (1301)	-1070 (-914)	1.4 / -1.0	101	123
P2BT (Transverse)	79.4 (72.0)	-240 (-219)	0.89 / -2.6	8.85	---
SN5-0291 (Axial)	837 (605)	----	3.0 / --	29.4	41.6
WS1 (Axial)	865 (692)	---	2.7 / --	32.6	48.3

Tensile Fatigue Results

P2B hybrid carbon/glass and QQ1 E glass fatigue test results at different R values are given in (Daniel D. Samborsky, 2009). It is found that P2B has high fatigue resistance compared with QQ1.Tensile fatigue resistance results at stress ratio R = 0.1 for three glass/epoxy laminates (QQ1, WS1 and SN5-0291) of current interest for wind turbine blades are shown in Fig 3.8, fiber content range from 53 to 64 % by volume. Maximum tensile stress and strain of above mentioned glass fiber laminates are compared. All three glass laminates differ each other in terms of 0° ply content and fiber percentage. QQ1 has poor tensile fatigue resistance in given fiber content range as compared with WS1 and SN5-0291. Maximum strain limit of WSI and SN5-0291 is high than QQ1. At 10^6 cycle WSI and SN5-0291 can withstand twice the maximum strain as can QQ1 Fig 3.9.

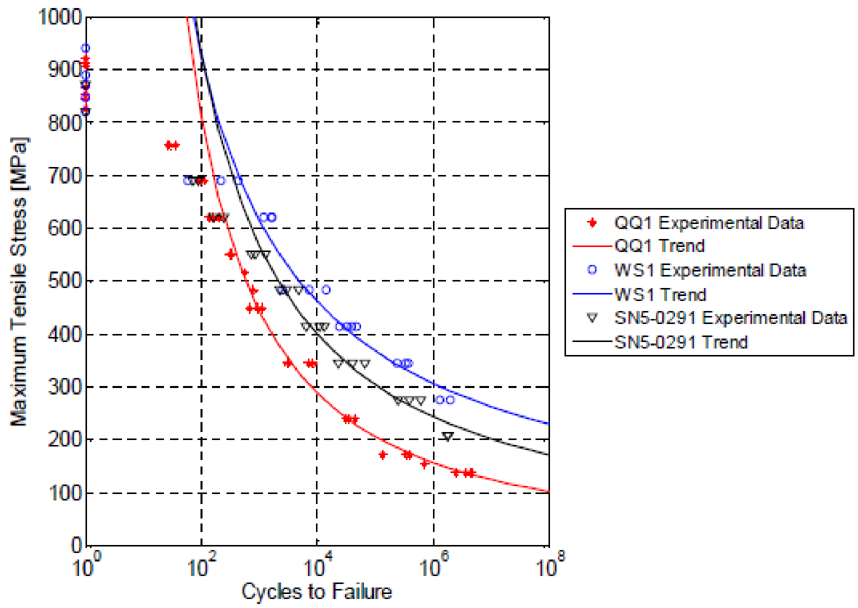

Fig 3.8. Tensile Fatigue Comparison of E-Glass-Epoxy materials QQ1, SN5-0291, and Windstrand-Epoxy material WS1, at stress ratio (R = 0.1) (Daniel D. Samborsky, 2009)

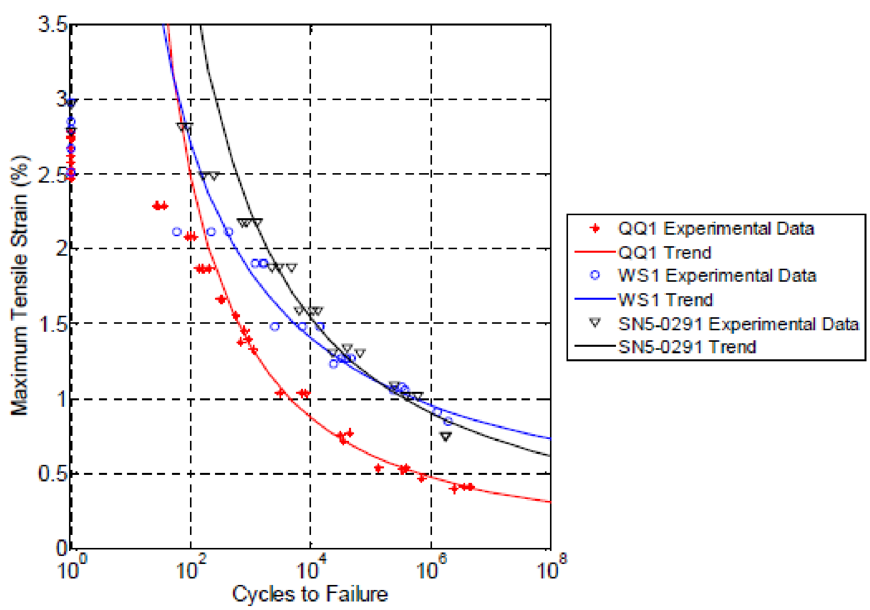

Fig 3.9. Tensile Fatigue Comparison of E-Glass-Epoxy materials QQ1, SN5-0291, and Windstrand-Epoxy Material WS1, stress ratio (R = 0.1). (Daniel D. Samborsky, 2009)

CLD Diagrams

Mean axial stress and strain CLD’s for QQ1 and P2B are compared and shown in Fig 3.10. Carbon hybrid P2B is high in strength than QQ1 but in case of strain, the order is reversed. Carbon hybrid strain limit is less compared with QQ1. It is reported in (Daniel D. Samborsky, 2009) that strength in transverse direction is small for 0° dominated laminates. P2B has 80% 0° plies, so it is weaker than QQ1 which has 64% 0° and more ±45 plies in transverse direction.

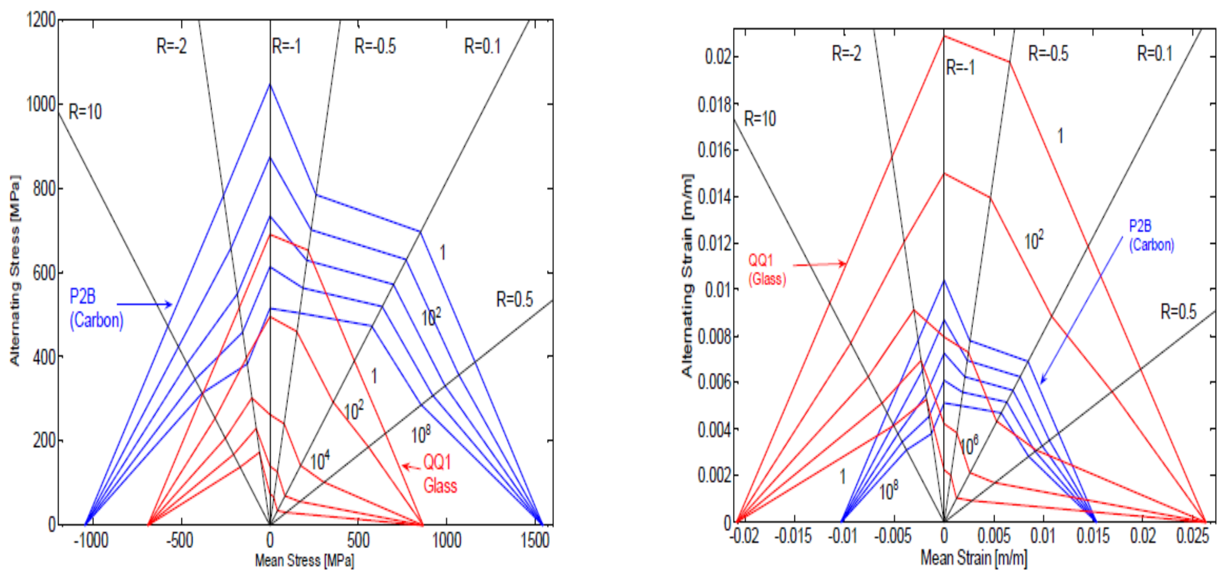

Fig 3.10. Comparison of Materials QQ1 (E-Glass) and P2B (Carbon-dominated) in axial-direction, Stress Constant-Life-Diagram (left). Strain Constant-Life-Diagram, (right). (Daniel D. Samborsky, 2009)

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Effect of Resin on Tensile Fatigue Properties

Resin type has influence on the properties of composite materials. Tensile fatigue test is performed on TT multidirectional glass laminates having layup (±45/0/±45/0/±45) and fiber volume percentage of 52%. Two different resin type epoxy EP-1 and polyester UP-1 are used as a matrix material in TT glass laminates. Tensile fatigue stress and strain results are shown in Fig 3.11. Which shows epoxy has clear advantage over polyester for above mentioned laminate layup. Vinyl ester is also tested and it is found that vinyl ester performance is better than polyester.

Performance order of the matrices for tensile fatigue of MD laminate is epoxy>vinyl ester>polyester. For biax fabric laminates, resin effect is limited for tensile fatigue loading. While toughened epoxy EP-8 shows improve fatigue strain (J. F. MANDELL, 2013), (John F. Mandell D. D., 2010). Fatigue stress, strain vs log cycles curves are shown in Fig 3.12.

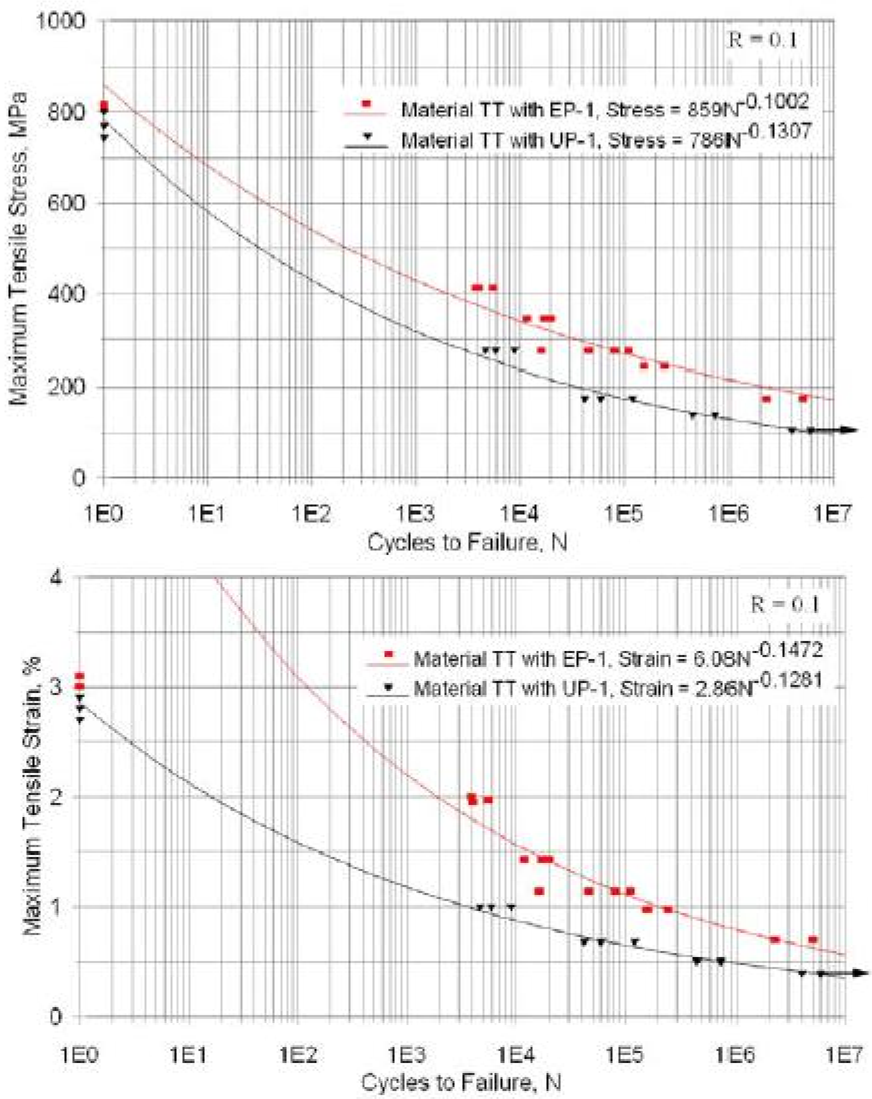

Fig 3.11. Stress (top), strain (bottom) vs. log cycles data for (±45°/0°/±45°/0°/±45°) MD (multidirectional) infused laminates containing fabrics D, M, TT-EP-1 (epoxy, Vf = 52%), TT-UP-1 (polyester, Vf = 52%), stress ratio (R = 0.1) (John F. Mandell D. D., 2010)

Effect of Stress Ratio R on Fatigue Properties of WTB materials

DD16 laminate as described before in section…. was tested at 13 R values, full dataset is available in (John F. Mandell1 D. D., 2009). SN curves of DD16 in axial direction is given in (John F. Mandell D. D., 2010),QQ1 (E glass) , P2B (carbon/glass hybrid) tested at 6 R values shown in Fig 3.13. The higher cycle tensile fatigue domain appears particularly sensitive (John F. Mandell1 D. D., 2009). It is found that laminate at reverse loading R = -1, has short lifetime at particular stress value. P2P at R= 0.1 and 0.5 has high fatigue strain. In compression (R= -1, -0.5, -2), P2B has low fatigue strain limit Fig 3.14.

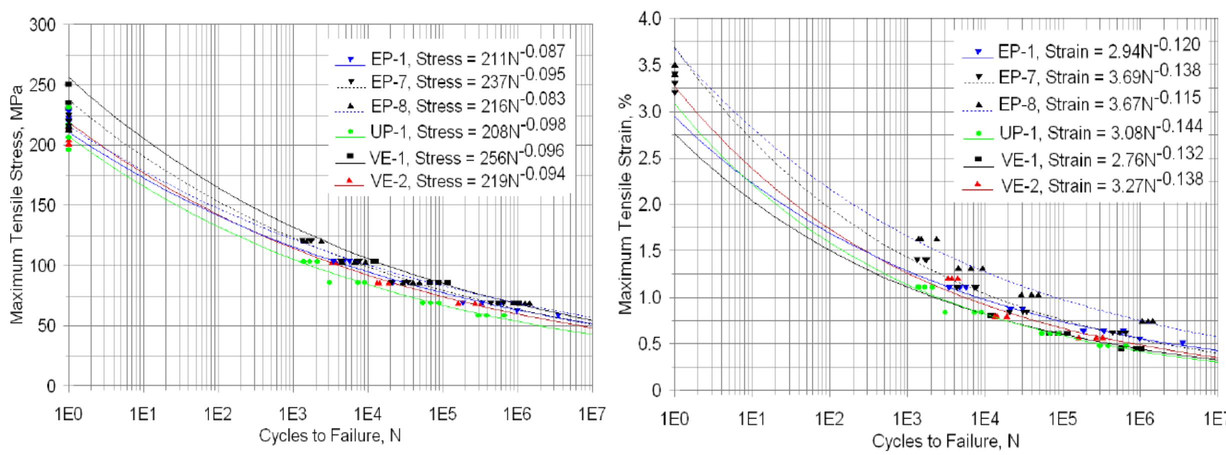

Fig 3.12. Stress (left) & strain (right) vs. log cycles data for fabric M ±45 laminates with various resins, at stress ratio (R = 0.1). (John F. Mandell D. D., 2010)

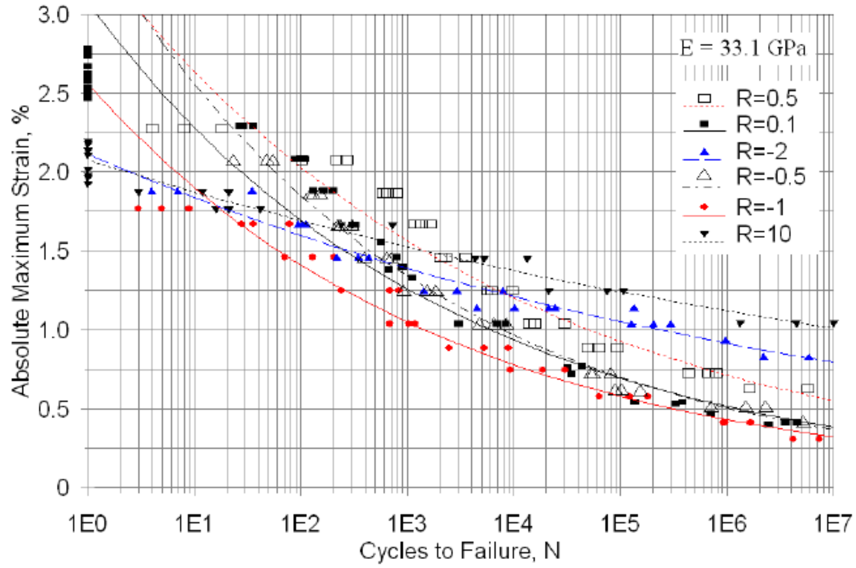

Fig 3.13. **Effect of different loading-conditions (stress ratio, R-value) on fatigue strain vs. fatigue life for E-glass-epoxy laminate QQ1 in the axial-direction.** (John F. Mandell D. D., 2010)

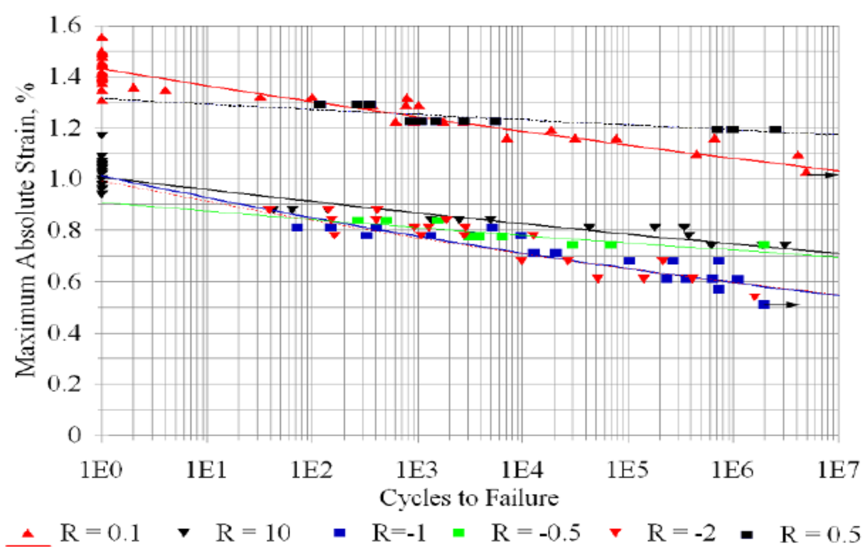

Fig 3.14. Effect of different loading-conditions (stress ratio, R-value) on fatigue strain vs. fatigue life for hybrid laminate P2B, in axial-direction. (John F. Mandell D. D., 2010)

Effect of fiber type on Fatigue Strength

Mechanical properties of composite materials depend on many factors, one factor of them is the type of fiber. Different fibers have different strength and stiffness (FC Campbell book). Four different laminates, QQ1 (glass), TT-TPI-EP (glass), Wind Strand^{TM} WSI, and P2P (carbon prepreg hybrid) are tested in tension (R =0.1) and compression (R= 10) fatigue load. Epoxy Resin is used as a matrix material in all laminates. Fiber contents among laminates is slightly different. Tensile and compression fatigue stress strain curves of the above materials are compared and visualized in Fig 3.15 and 3.16. P2B hybrid showed much higher fatigue resistance in tension (R=0.1) compared with other laminates. QQ1 (glass) is less fatigue resistant. WS1 showed better performance than other two glass laminates. QQ1 showed lower tensile strain limit. WS1 and TT-TPI-EP have higher tensile strain limit at low cycle. P2B is superior in terms of tensile strain at higher cycles, while in compression fatigue load P2B showed lower failure strain limit. (John F. Mandell D. D., 2010)

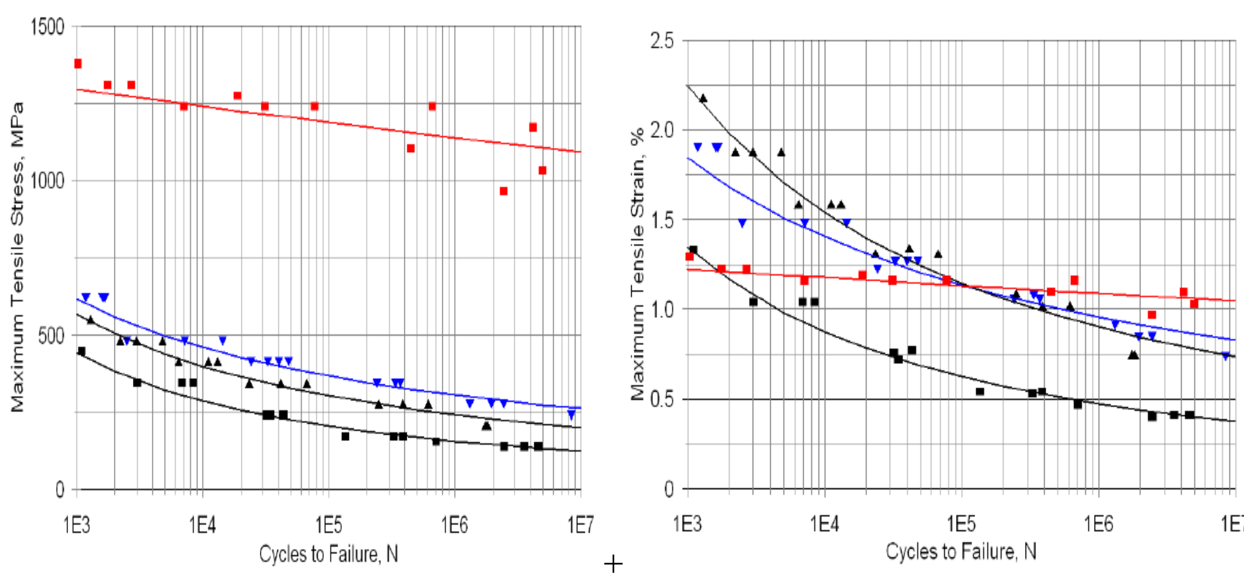

Fig 3.15. Tensile-fatigue comparison of MD (multidirectional) laminates based on E-glass (QQ1 and TT-TPI-EP), WindStrand^{TM} (WS1) and carbon (P2B) fibers at similar fiber contents, in terms of stress (left) and strain (right), epoxy-resins, at stress ratio (R = 0.1). (John F. Mandell D. D., 2010)

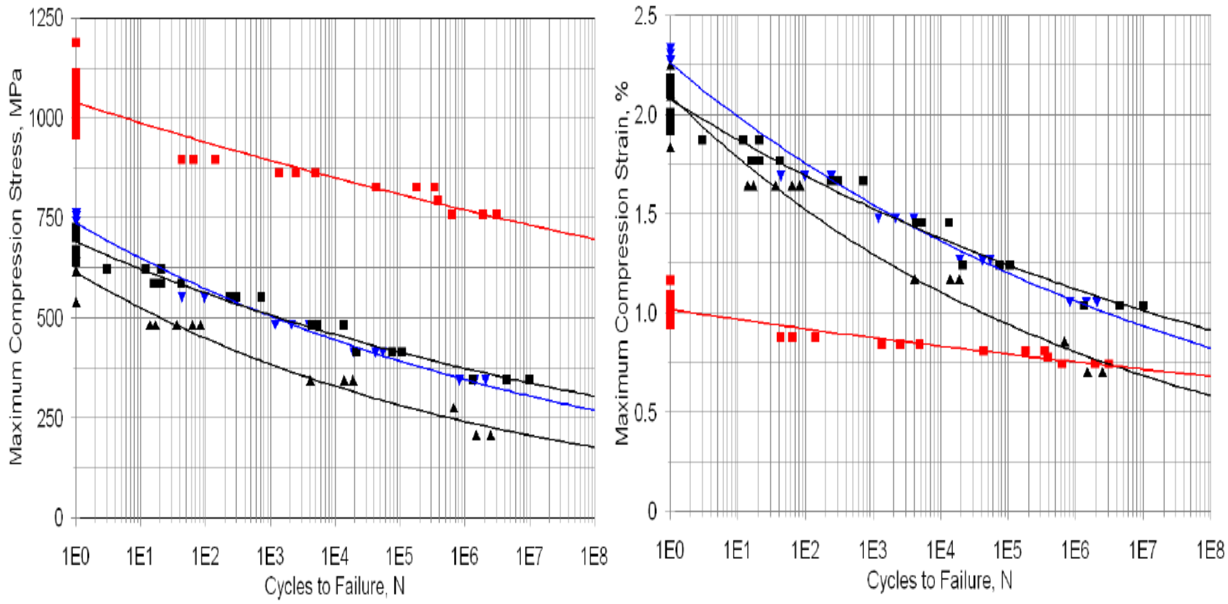

Fig 3.16. Compressive fatigue comparison of MD laminates based on E-glass (QQ1 and TT-TPI-EP), WindStrand™ (WS1) and carbon (P2B) fibers at similar fiber contents, in terms of stress (left) and strain (right), epoxy-resins, at stress ratio (R = 10). (John F. Mandell D. D., 2010)

■ P2B, VF=55% ■ QQ1, VF=53% ▲ TT-TPI-EP, VF=55% ▼ WS1, VF=61%

Chapter 4

Wind Turbine Design

Loads on wind turbine blades

Wind turbine are vulnerable to nature's forces and experience strong loads throughout their entire service life. Wind turbine needs to be design to withstand extreme environmental condition. Special attention is required to design rotor blades in order to efficiently convert kinetic energy of the incoming wind into mechanical energy. Appropriate material should be used to withstand the loads for their entire service life. Different forces and moments are acting on the rotor blade during operation. Wind loads are the main load which are acting on rotor blades. The aero-foil design generates lift and drag force which are transformed into driving and thrust force, Fig 4.1. Rotor blades rotate in gravitational field, which creates inertia forces and moments. Wind loads generate flap-wise and edge-wise bending, Fig 4.2. Gravitational loads mainly generate edge-wise bending loads. Shear resultant of edge-wise and flap-wise loading cause torsional loading. (SÖKER, 2013)

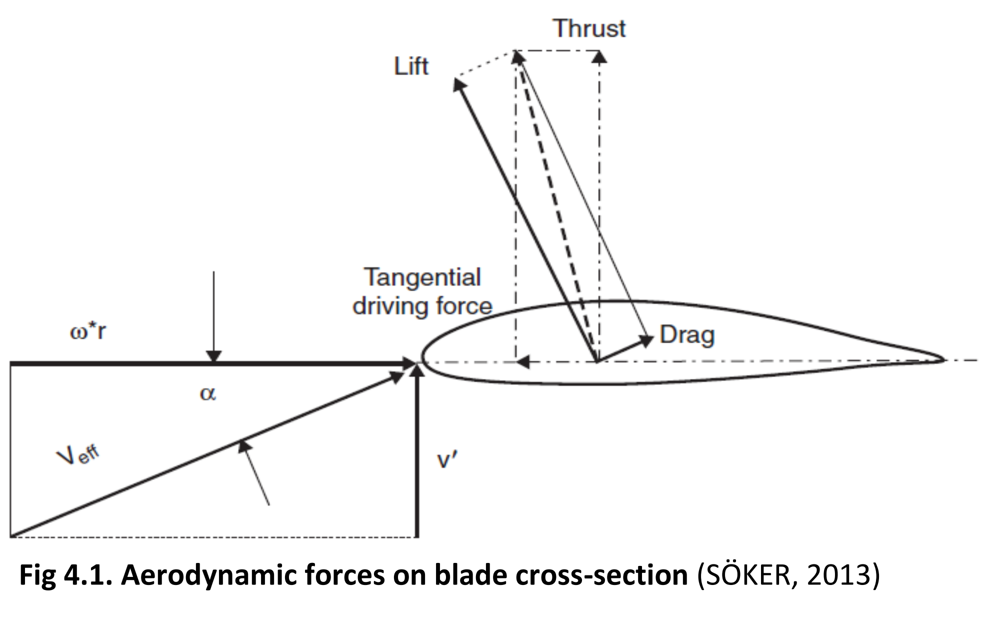

Fig 4.1. Aerodynamic forces on blade cross-section (SÖKER, 2013)

These external loads which are acting on the rotor blade, create internal loads in term of stress and strain in blade structures. These internal loads can deform the shape of the blade structure. Rotor tip deflection must be taken into consideration during designing because rotor blade can collide with the tower if the deflection is high. The blade should be stiff enough to have low rotor tip deflection. The magnitude and orientation of internal loads are of main concern for the designer as to design a blade that withstand the external loads. The advantage of fiber reinforced composite is that it can be oriented in the direction of external force, so that maximum stiffness can be achieved. Due to stochastic nature of wind, these external forces acting on rotor blades varies continuously. The alternating nature of loads cause fatigue damage in structure. (SÖKER, 2013)

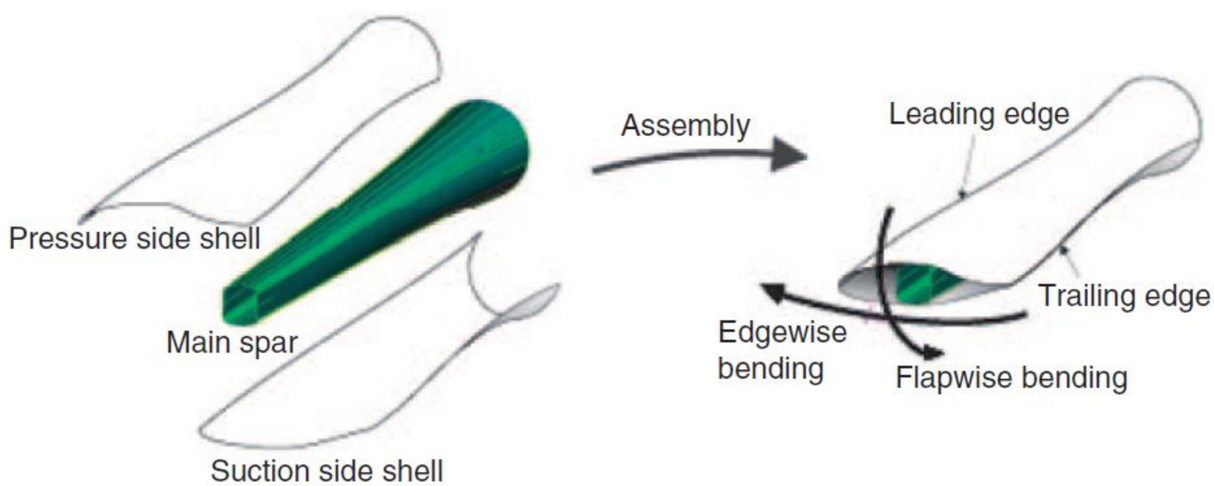

Fig 4.2. Wind-turbine-blade components, flap-wise and edgewise loads (Thomsen, 2009)

While designing wind turbine blades four basic structural requirements should be taken into consideration (a) Enough spar stiffness to withstand flap wise bending load and low tip deflection. (b) Sufficient structural strength to sustain in unusual extreme loading condition. (c) At least 20-years fatigue life of structure (d) various structural requirements related to the high mass of the WTB. (Theotokoglou, 2017). Wind turbine blade is beam like structure mainly composed of spar and pressure side shell and suction side shell as shown in Fig 4.2, both faces of shell are joined together by adhesives. Conventionally epoxy is used as an adhesives (Theotokoglou, 2017).

Stiffness is provided to the shell by shear web, attached with spar caps as integrated structure (box spar) or as internal stiffeners bonded with spar caps by adhesives (Leon Mishnaevsky Jr. ID, 2017). Manufacturers are using different design concepts for the construction of blades. Spar, webs and shells can be manufactured in single construction process. Wind Turbine blade structural parts can also be manufactured separately and then combined by bonding process. Different concepts of blades are shown in Fig 4.3 and 4.4. Different manufacturers use different manufacturing process but generally VARTM is used for wind turbine blade construction (Thomsen, 2009)

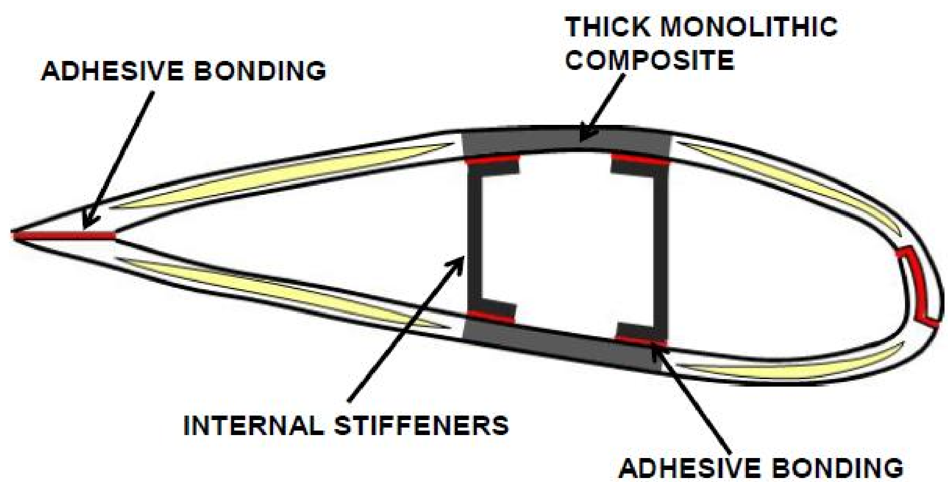

Fig 4.3. Blade components, internal stiffeners (Aymerich, 2012)

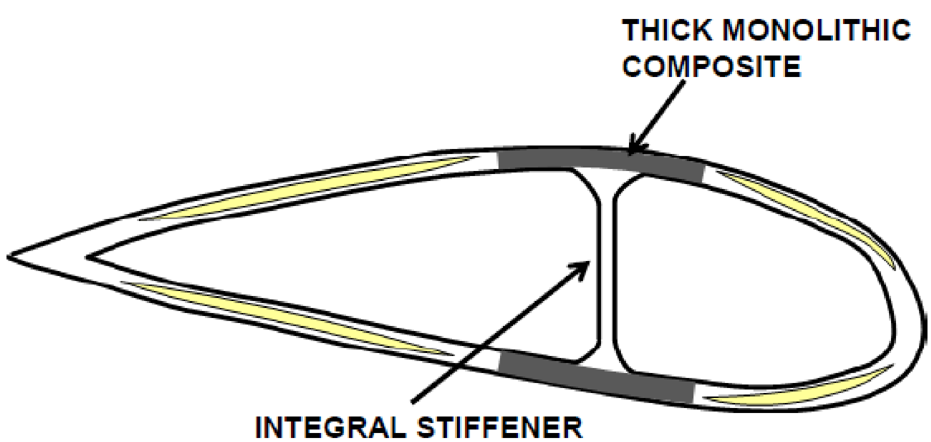

Fig 4.4. Blade component, integral stiffener (Aymerich, 2012)

The main purpose of airfoil shells is to give aerodynamic shape to the blade (Bortolotti, 2012). The airfoil shells are made up of multi-axial laminates and sandwich structure to resist buckling, torsion and to reduce weight of blade (Nijssen, 2006). Different spar construction is shown in Fig 4.3 and 4.4. Spar cap perform as a beam and bear the flap-wise bending moment. Pressure side of spar is under tension-tension load while suction side of spar is under compression-compression load (Leon Mishnaevsky Jr. ID, 2017). Spars are made up of monolithic composites. For some large wind turbines, hybrid composites are used in spars to obtain the required stiffness. Edge-wise loads are carried by leading and trailing edges of blade profile. To resist edgewise loads unidirectional fiber reinforcement is used in leading and trailing edges. Internal stiffener is also called shear webs which bear flap-wise shear loads. (Bortolotti, 2012)

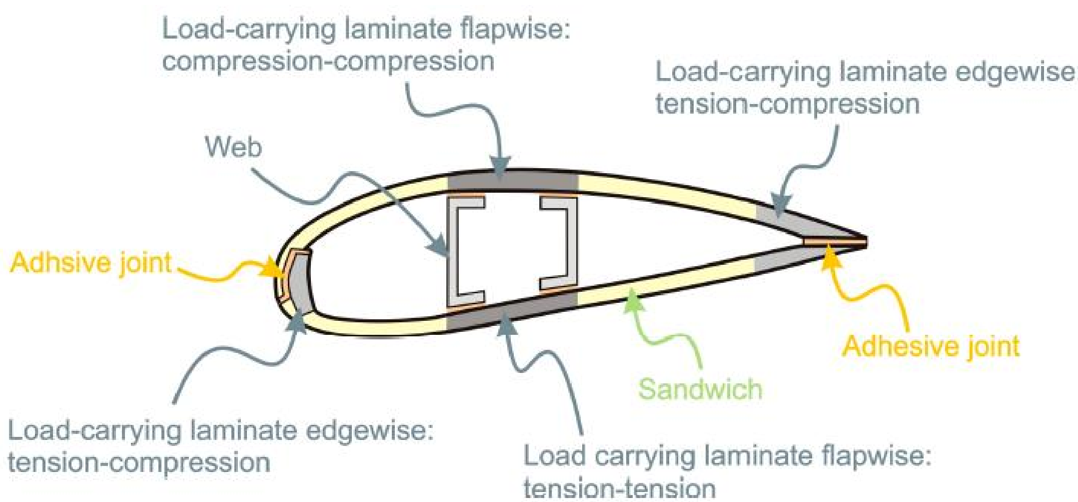

Fig 4.5. Wind Turbine blade sectional scheme (Leon Mishnaevsky Jr. ID, 2017)

Composite layups in Blade structure

UD and biaxial fiber laminates are normally use in wind turbine blade structure. UD 0 ° fiber laminates are used along the span of rotor blades. UD 0° plies are used to provide resistance against bending loads while ± 45° plies laminates are used to resist torsion and buckling (Kevin Coxa, 2012). UD 0° plies are used to provide bending stiffness to lower and upper flanges of spar. Biaxial layups are also used in spar caps to provide buckling resistance (Thomsen, 2009). Shear webs are made up of composite sandwich. Face sheets laminates of shear webs are oriented ±45 with internal polymeric core. Shear webs layup design is like +45glass/core/+45glass (Kevin Coxa, 2012). Using sandwich composites reduce the weight and increase in-plane shear buckling (Thomsen, 2009), (Aymerich, 2012)). Sandwich structure has an issue, these structures are more susceptible to delamination failure because of weak interfaces between the adjacent material with different strength and stiffness properties and are sensitive to inter-laminar shear (Thomsen, 2009).Finite element model of spar is analyzed with single skin and sandwich flanges. The result shows weight reduction of 22.3% and increase of buckling load capacity is observed (C. BERGGREEN, 2007). Airfoil shell is also constructed from sandwich panels. Tri-axial laminates ±45/0/±45 are used in airfoil skins with polymeric or balsa core to resist buckling (Bortolotti, 2012). 0° glass fiber ply in airfoil shell skin is used to reduce stress concentration due to ply drops in airfoil skin (Kevin Coxa, 2012).

Use of carbon-hybrids composites in spars-webs comparison with Glass fiber reinforced composite

Carbon use in wind industry is rare because of high cost of carbon fabrics. Studies have been done on the use of carbon fiber into large wind turbines and it is found that replacement of 0 glass fiber plies with carbon in spar flanges enhance spar stiffness, increase buckling resistance, lowering tip deflection and reduce blade weight (C. BERGGREEN, 2007). Finite element model of blade is developed, geometrical parameters of model are given in (Theotokoglou, 2017).CFRP and GFRP composite materials are compared, result shows significant reduction in displacement in case of carbon fiber. Displacement comparison between GFRP and CFRP composite material is shown in table 4.1.

Table 4.1. Displacement comparison between GFRP & CFRP material systems. (Theotokoglou, 2017)

	Glass/epoxy	Carbon/epoxy	Percentage difference (%)
Area A (mm)	−5.688	−1.484	−73.9
Area C (mm)	3.192	0.870	−72.7

Chapter 5

Factors Effecting Laminate Properties

Laminates thickness effect on static and fatigue properties

Thickness effect of laminates on static and fatigue properties of wind turbine composite materials are studied in (R. P. L. Nijssen, 2014), (Lahuerta Calahorra, 2017). Some parameters that can cause the difference in static and fatigue properties of thin and thick laminates are self-heating of laminates when loaded dynamically, scaling effect of coupons, geometric design influence and lastly effect of the manufacturing process.

When dynamic load acts on composite materials, self-heating takes place that results in temperature rise of material. Temperature change takes place through the thickness of composite laminate that effect the mechanical properties and as result premature failure occurs (Lahuerta, 2014) In order to evaluate the heating effect, 30mm thick coupon is tested at two different frequencies and at different loading condition and results are shown in Fig 5.2, it is found that the fatigue life of thick laminates reduced because of the coupon surface heating. Temperature rise of 15 to 20 ° C is recorded while the core temperature of coupons was higher than maximum service temperature. S-N curves of 20mm thick coupon at two different frequencies are shown on the right side of Fig 5.2. Fatigue life decrease with increasing frequency and heating (R. P. L. Nijssen, 2014).

The second factor that cause the difference in static and fatigue properties between thin and thick laminates is the scaling effect, to study this effect, three unidirectional compression coupons of 4, 10 and 20mm of thickness are tested in static and fatigue condition and other three factors are minimized. The test result of scaling geometry shows no reduction in ultimate strength but fatigue life decrease with increasing thickness (F. Lahuerta, 2014). Lamina properties varies through the thickness of laminates. Variability of properties of laminae through thickness is because of manufacturing process. To analyze this effect, sub-laminates are extracted from 60mm infused thick plates, and tested in static (1mm/min) and fatigue condition. Properties through thickness of laminate varies because the curing cycle temperature is different at different thickness position. Static compression stresses through thickness of laminates are shown in Fig 5.4, stresses are high in the middle layers. The S-N curves of middle layer shows different behavior than the outer layer.

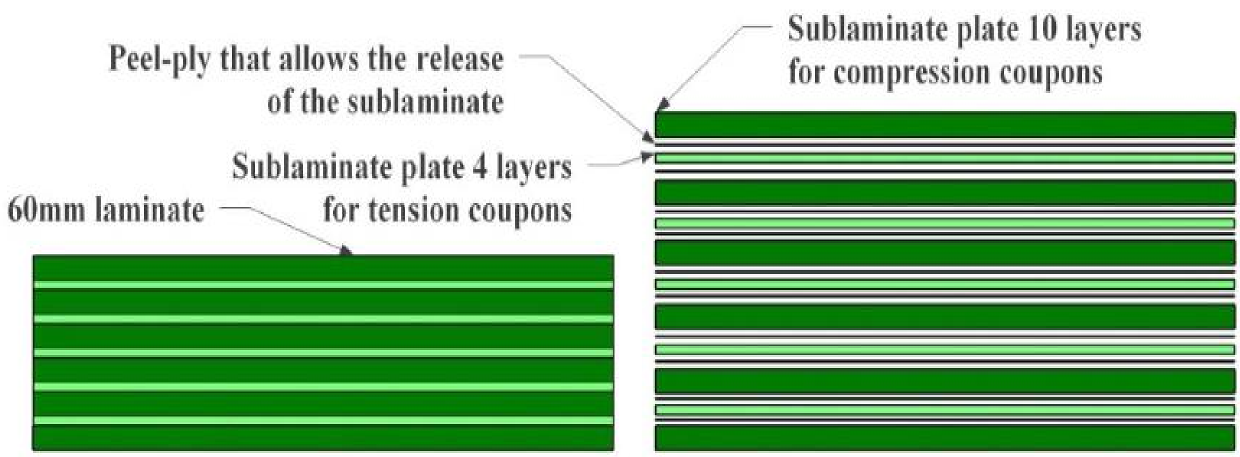

Fig 5.1. Sub-laminates plates extraction from a 60mm infused plate (R. P. L. Nijssen, 2014)

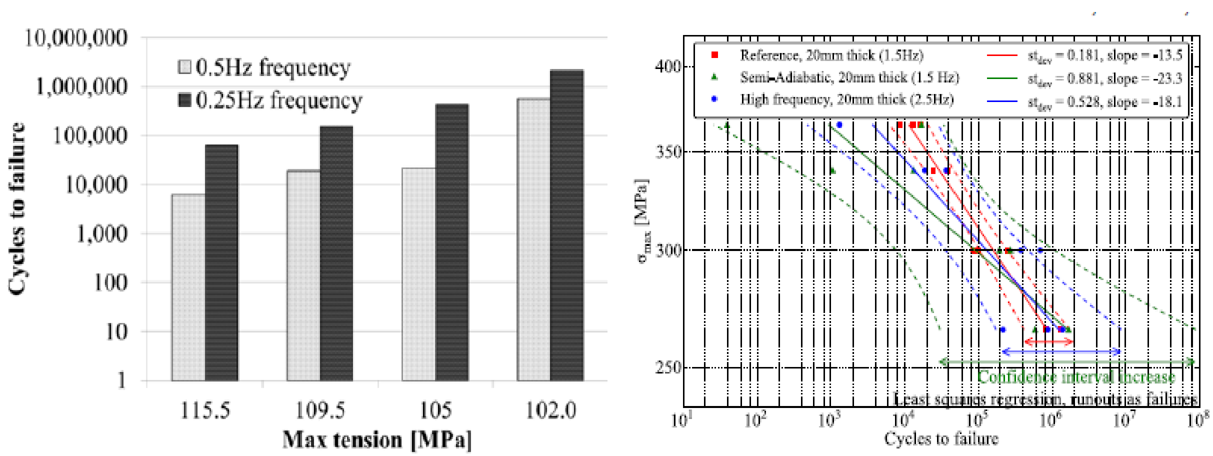

Fig 5.2. Self-heating fatigue tests. Left, fatigue life of transverse direction (90°) compression coupons 30mm thick tested ad 0.5 and 0.25Hz. Right, S-N curves of 20mm thick compression end-loading coupons. (R. P. L. Nijssen, 2014)

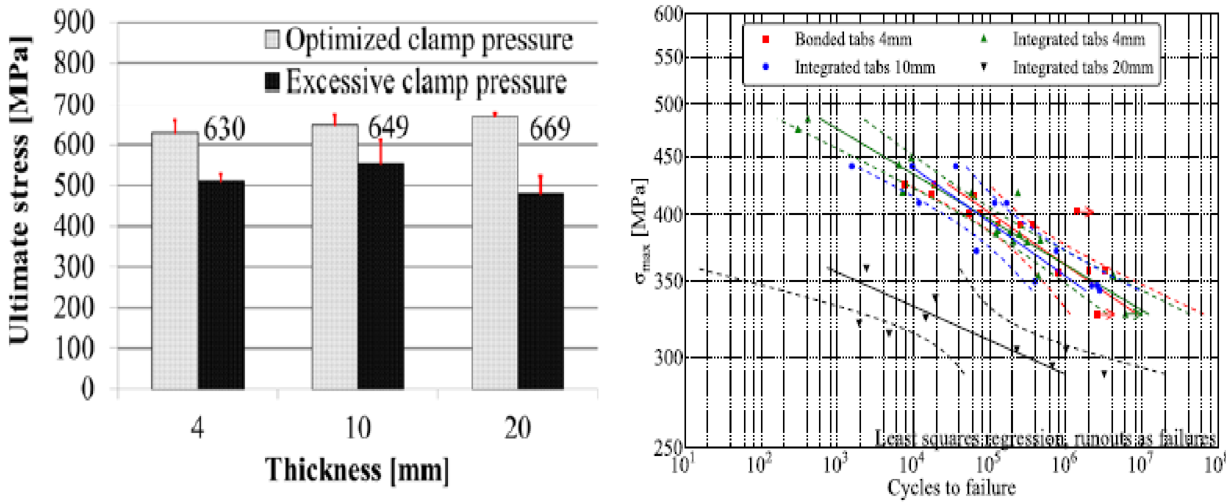

Fig 5.3. Left, static compression tests for 4, 10 and 20mm thick coupons, showing close compression ultimate stresses. Right, S-N curves for 4, 10 and 20mm coupons, showing a decrease in fatigue life. (R. P. L. Nijssen, 2014)

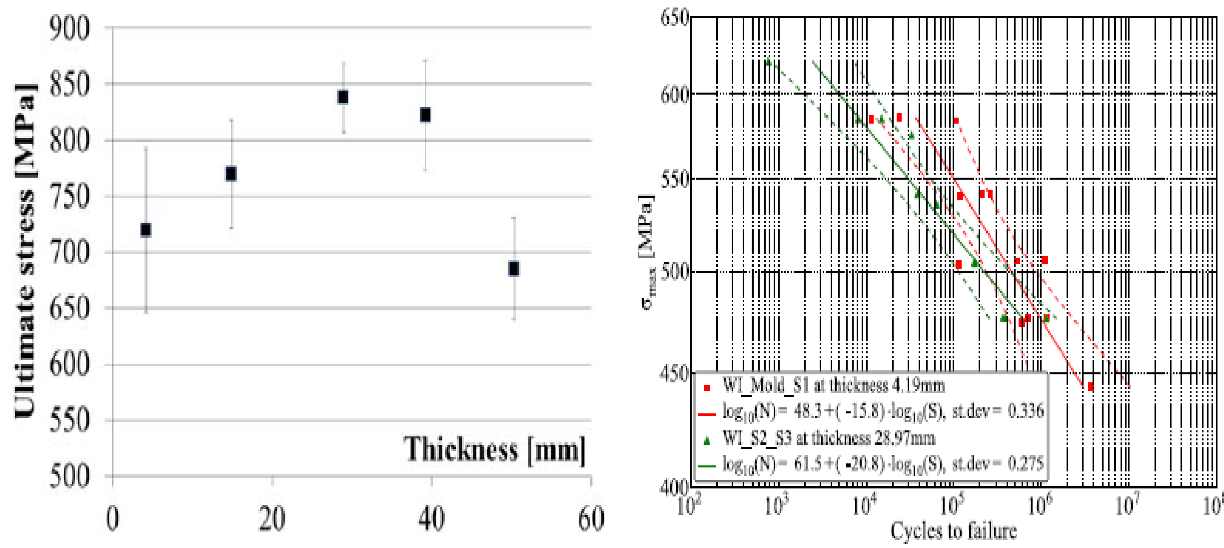

Fig 5.4. Manufacturing process. Left, static compression ultimate stresses through the thickness. Right, sub-laminate S-N curves at thickness position 4mm (mold-side) and 29mm (middle-plate). (R. P. L. Nijssen, 2014)

Effect of low and high temperature on static and fatigue properties of laminates

Among other challenges in wind industry, one of the challenge is to harvest wind energy resource from northernmost regions, some of the regions in northern part of Europe have high wind energy potential. Researches have been done on the performance of wind turbine blade materials in harsh environment. Investing on wind turbine to operate in northern region's harsh environment is risky. Wind turbine blades are the most critical and expensive part of wind plant. Blades are more susceptible to harsh environment and may undergo accelerated failure. Different kinds of loads are acting on wind turbine blades as discussed in chapter 4. Upper surface of the blades undergo compression stresses and lower surface is loaded in tension as shown in Fig 4.5. Unidirectional and biaxial ±45° pattern of lamina are used in wind turbine blade structure to sustain the loads. Biaxial ±45° laminate failure is matrix dominated failure as already discussed in introductory chapter 1. Matrix properties are affected by moisture and temperature so do the properties of composite materials (Laurent Cormier1, 2016).

Researches have been done on number of composite materials in the past. Shen and Springer have tested Thornel 300/Fiberite 1034 graphite epoxy composites at 200K to 380K and concluded to have negligible effects on tensile strength. Slight reduction in strength is observed as the temperature increase (SPRINGER, 1977), (SPRINGER C.-H. S., 1976). Cormier and Joncas have reported that at -40°C, unidirectional E glass epoxy tensile and shear strength increases because matrix material shrinks and become stiff at low temperature. Compressive thermal stress which is generated due to matrix shrinkage contribute in strengthening of composite materials. Literature review on the effects of cold temperature on the mechanical properties of composite materials are reported in (Joncas, 2010). As a part of European Upwind project, tensile and reversed fatigue tests at -40°C have been performed on unidirectional E-glass epoxy composite material by Nijssen and Cormier (Laurent Cormier, 2012) and reported negative to negligible influence on tensile and reversed fatigue performance. Wind Energy strategic network (WESNet) that works to develop innovative solutions to the technical issues that Canadian Wind Sector is confronting. Some of the materials have been tested in WESNet and parts of the results are presented.

Static properties

Static tensile, compressive test results and tensile and fully reversed fatigue results of biaxial glass-epoxy laminates (±45) are presented here. Reinforcement and Matrix material description is given in (Laurent Cormier1, 2016). Tensile properties at 23 and -40°C are shown in table 5.1. Tensile strength and Modulus of the biaxial laminates increased at -40°C. The increase in mechanical properties is due to improvement of matrix properties. Shear and compressive properties at -40°C are shown in tables 5.2 and 5.3. Both shear and compressive properties increase at lower temperature. Stitching fabrics helps in preventing laminates from buckling (Laurent Cormier1, 2016). The current results shows the improvement of mechanical properties at low temperature which are in contradiction with the results obtained by Shen and Springer (Laurent Cormier1, 2016), (SPRINGER, 1977), (SPRINGER C.-H. S., 1976). It is stated that one of the cause of contradiction in results is fiber volume fraction vf. UD glass-epoxy composite material (vf=55%) was tested under tension and compression at 60°C, both tensile and compressive strength is reduced (Laurent Cormier, 2012). More details regarding material description, test standards and test results are reported in (Laurent Cormier, 2012).

Table 5.1.Tensile-strength properties (Laurent Cormier1, 2016)

T °C	Property –	S_x^+ MPa	$\sigma_{S_x^+}$ MPa	E_x^+ GPa	$\sigma_{E_x^+}$ GPa
23	Mean	130	4.38	11.8	0.444
	95% bounds	[127, 133]	[3.01, 7.99]	[11.5, 12.1]	[0.306, 0.811]
−40	Mean	173	6.34	14.2	0.861
	95% bounds	[165, 181]	[3.80, 18.31]	[13.2, 15.3]	[0.516, 2.49]

Table 5.2. Shear-strength properties (Laurent Cormier1, 2016)

T °C	Property –	S_{12} MPa	$\sigma_{S_{12}}$ MPa	G_{12} GPa	$\sigma_{G_{12}}$ GPa
23	Mean	65.1	2.20	3.45	0.150
	95% bounds	[63.5, 66.7]	[1.51, 4.01]	[3.34, 3.56]	[0.103, 0.275]
−40	Mean	86.5	3.17	4.38	0.275
	95% bounds	[82.6, 90.5]	[1.90, 9.15]	[4.04, 4.72]	[0.165, 0.795]

Table 5.3. Compressive-strength properties (Laurent Cormier1, 2016)

T °C	Property –	$S_{\bar{x}}$ MPa	$\sigma_{S_{\bar{x}}}$ MPa	$E_{\bar{x}}$ GPa	$\sigma_{E_{\bar{x}}}$ GPa
23	Mean	130	3.43	12.3	0.236
	95% bounds	[126, 134]	[2.14, 8.42]	[12.1, 12.5]	[0.148, 0.580]
−40	Mean	177	7.68	14.6	0.453
	95% bounds	[169, 185]	[4.79, 18.9]	[14.9, 15.0]	[0.283, 1.11]

Tensile Fatigue Properties R=0.1

Tensile fatigue test results at stress ratio R=0.1 and at two different temperatures -40°C and 23°C are shown in Fig 5.5. The difference in slope at two different temperatures is less. Fatigue life at -40°C is improved as compared with fatigue life at 23°C. Change in temperature effect the mechanical properties of composite materials. When laminates are loaded at room temperature, matrix cracks occur at multiple sites along the fiber direction, these cracks interact with each other and cracks grows and spread out throughout the ply, consequently leading to specimen failure. At -40°C, lower crack density is observed. At lower temperature, both matrix tensile and shear strength properties are likely to be improved, delaying the cracks initiation along the fiber direction. Reduction in interaction between cracks at lower temperature (-40°C) leads to less scatter of fatigue results. Compliant and stiff nature of matrix material influence the strength properties of composite materials. Optimal strength could be obtained at an intermediate matrix compliance (Laurent Cormier1, 2016).

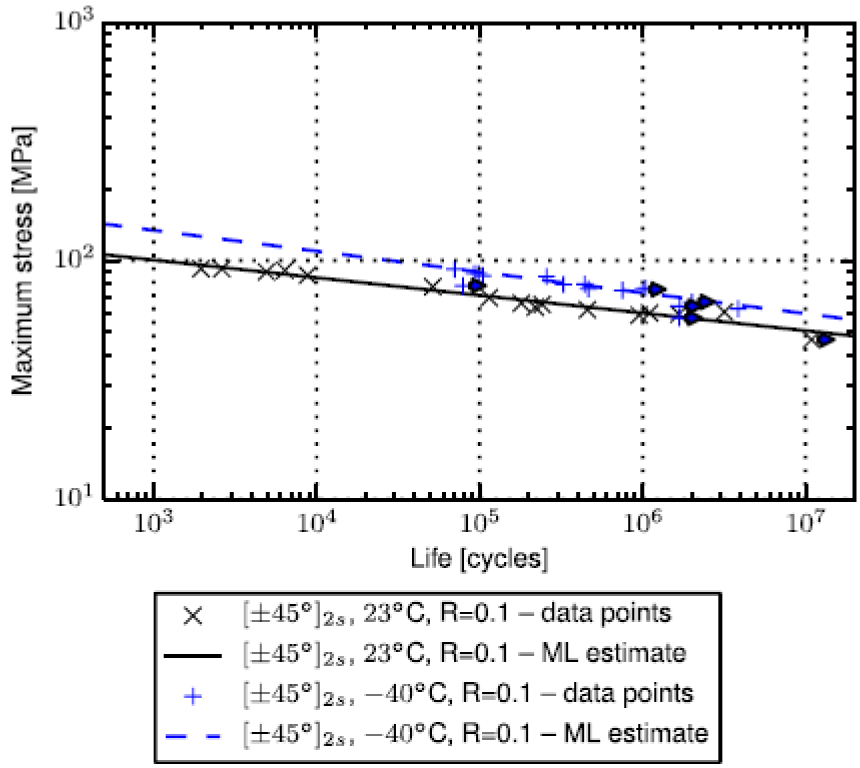

Fig 5.5. S-N curves for $[\pm 45°]_{2s}$ glass–epoxy at 23°C & -40°C temperature, at stress ratio of 0.1 (solid arrows indicate run-outs). (Laurent Cormier1, 2016)

Fully reversed fatigue R = -1

Fatigue strength of glass-epoxy is intensely affected by changing the temperature from 23°C to -40°C under fully reversed loading condition. Comparing with 23°C, fatigue life improved of about one decade at -40°C (Laurent Cormier1, 2016), (Laurent Cormier, 2012)). It is reported that at lower temperature (-40°C) two phenomenon can occur that increase the strength of material. (a) Ply stiffness rises at lower temperature, so high stress is required to break the matrix. (b) The inter-laminar shear strength increase that lessen the delamination growth (Laurent Cormier1, 2016). S-N curves at R=-1 is visualized in Fig 5.6. Comparing the R = 0.1 loading, at R= -1 loading condition, failure occurs earlier.

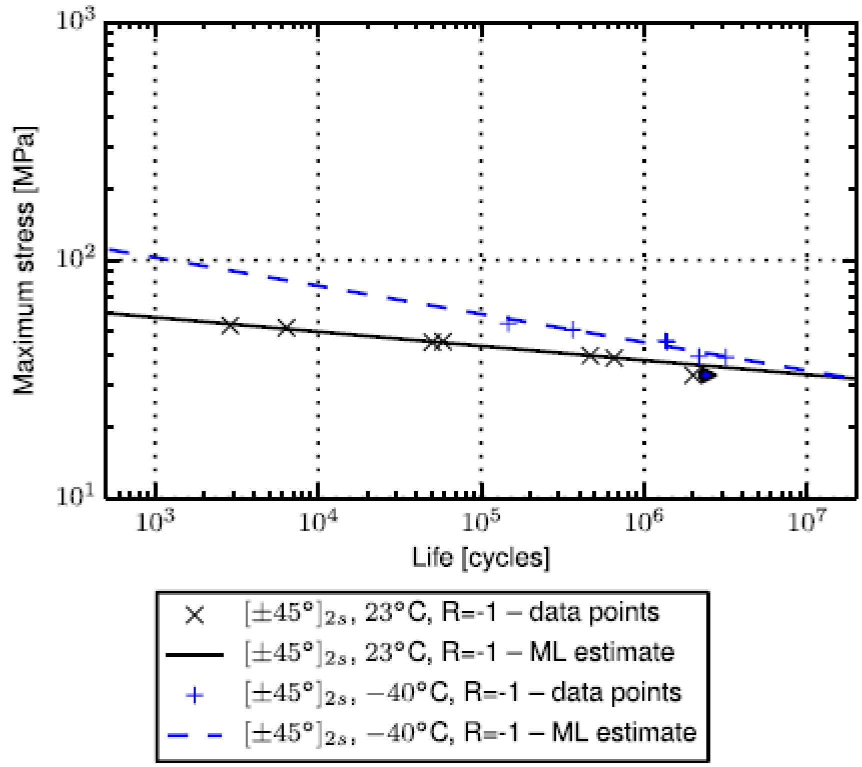

Fig 5.6. S-N curves for [±45°]$_{2s}$ glass–epoxy at 23°C & -40°C temperature, at stress ratio of -1 (solid arrows indicate run-outs). (Laurent Cormier1, 2016)

Effect of waviness on static and fatigue compressive properties

Low cost materials and processes are used for the production of wind turbine blades which results in imperfections and weaknesses in strength properties. Different types of flaws in wind turbine composite materials are investigated and documented in DOE/ MSU database (J.F. Mandell and D.D. Samborsky, 2002). Among those flaws and imperfections in wind turbine spar caps, one is waviness which mainly effects the compressive properties of laminates and also cause reduction in tensile strength and fatigue resistance (Daniel D. Samborsky1 D. A., 2015). More attention is given to the waviness of prepreg laminates. Waviness in laminates reduce the compressive strength because of two reasons: (1) the waviness in laminate structure intensifies the fiber, strand or layer buckling failure mode and (2) due to waviness, misalignment of fiber, strands and layers occurs producing matrix dominated failure in plies which are align in longitudinal direction (0°). It should be noted that fiber dominated failure occurs in plies which are oriented in longitudinal direction but in-plane waviness in laminates change the fiber dominated failure mode to matrix dominates failure mode in compression. (J.F. Mandell)

Static compressive properties

Wave geometry of in-plane and out of plane waviness is characterized by parameters that are wavelength (λ), wave amplitude (δ), severity (δ/λ) and off-axis orientation (ɵ). In-plane and out of plane waviness are shown in Fig 5.7 (right) (Wang, 2001).Waviness characterization is shown in Fig 5.7 (left). Schematic of laminate is shown in Fig 5.8 with three of the four 0° plies contain waviness. Compressive strength varies with number of 0° ply with waviness in laminates. Compressive strength as a function of 0° ply fraction with in-plane waviness in laminates and for three wave severities is shown in Fig 5.9. 25% single 0° surface layer, 50% is for the two internal 0° layers and 75% three layers' case is illustrated in Fig 5.9. It is evident from the figure that with increasing severity and 0° plies fraction, compressive strength gradually decreases. Ply drops and ply joints cause reduction of compressive strength (J.F. Mandell). At higher wave angles, compressive and tensile properties were reported to be similar (Daniel D. Samborsky1 D. A., 2015). Toughness effect on waviness of two different resins, Vinyl ester and polyester is investigated and results are shown in Fig 5.10. Compressive strength improves with tougher resin (J.F. Mandell).

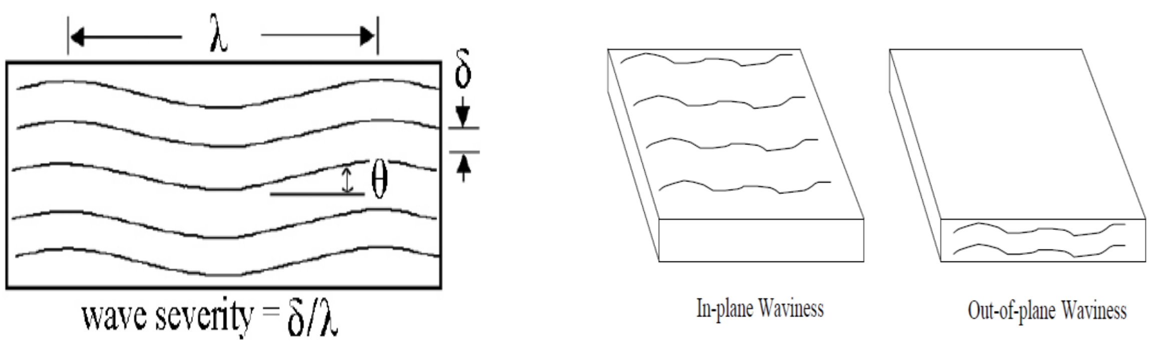

Fig 5.7. Waviness Characterization (left) (J.F. Mandell)**, in-plane and out-of-plane waviness (right)** (Wang, 2001)

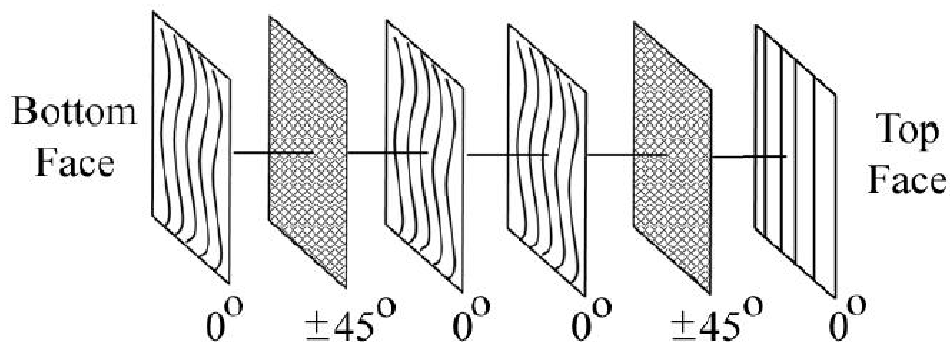

Fig 5.8. Laminate Configuration with Three Layers of In-Plane Waviness (J.F. Mandell)

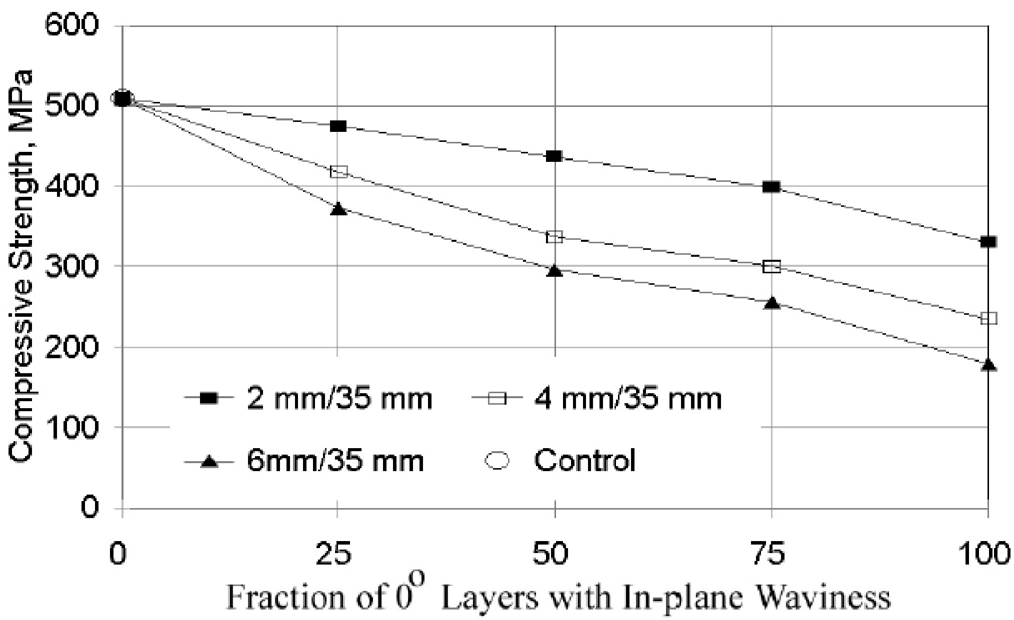

Fig 5.9. Effects of Multi-layer In-plane Waviness on Compressive-Strength for various wave parameters δ/λ. (J.F. Mandell)

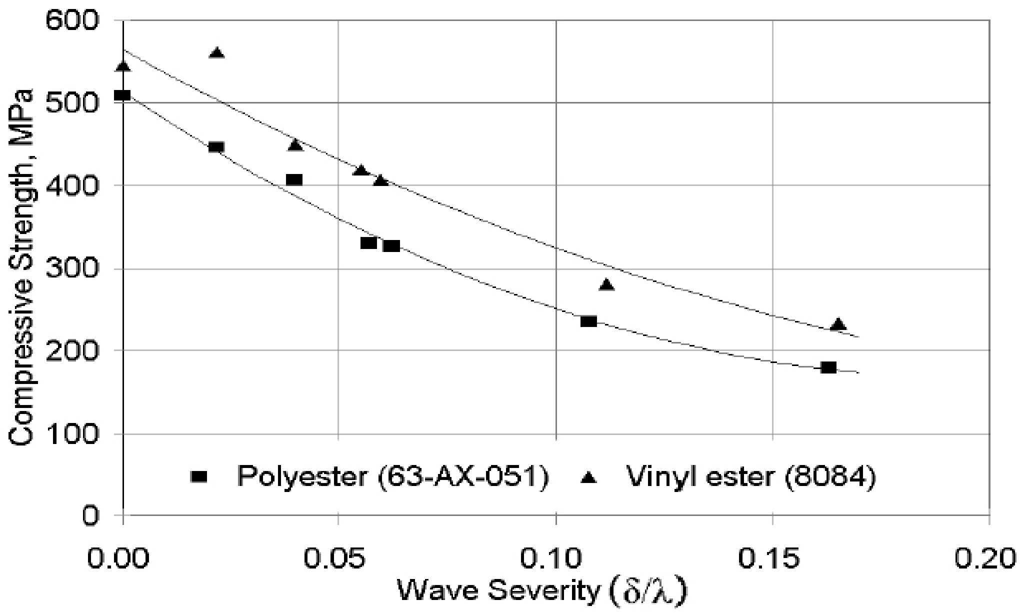

Fig 5.10. Resin toughness effect on Compressive-Strength of Laminates at varying wave severity. (J.F. Mandell)

Fatigue strength in waviness

Fatigue test results for glass/polyester laminates are shown in fig 5.11. It is evident that intense strength reduction takes place at waviness angles range between 10° to 30° .The strength values at some waviness angle ϴ and laminates which are arranged at the same angle ±ϴ found similar, which shows that waviness effect is nearly equal to the effect of fiber orientation. (Daniel D. Samborsky1 D. A., 2015)

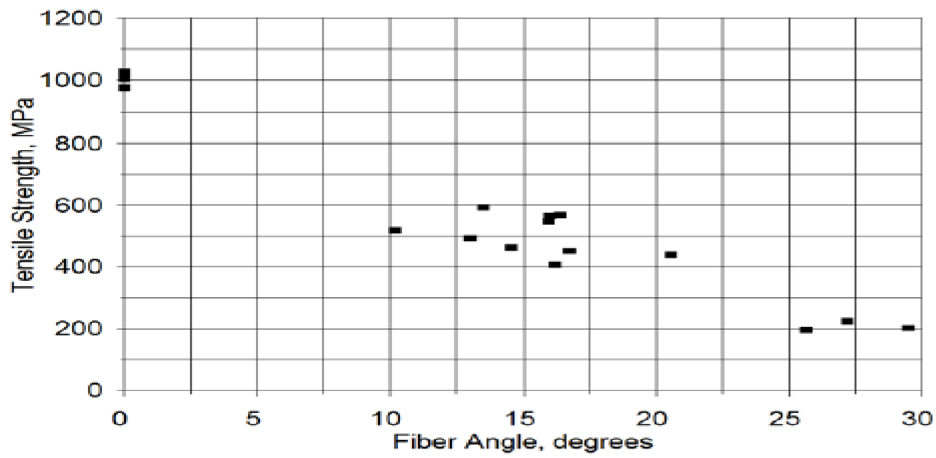

Fig 5.11. Static tensile-strength vs average waviness-angle for UD glass-epoxy laminates. (Daniel D. Samborsky1 D. A., 2015)

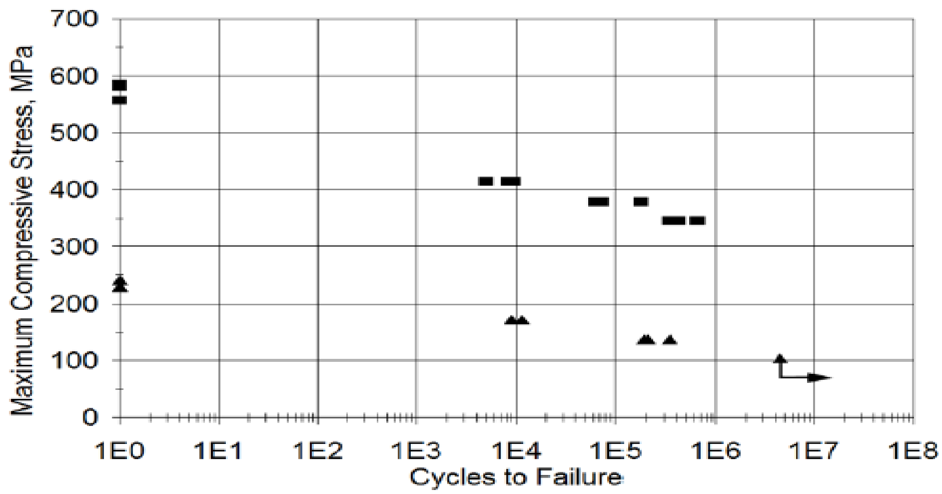

Fig 5.12. Compressive-fatigue S-N data for (0/±45/0)s glass-polyester laminates with (triangles) and without (squares) waviness flaws in the 0° plies (approximate wave angle 17°). (Daniel D. Samborsky1 D. A., 2015)

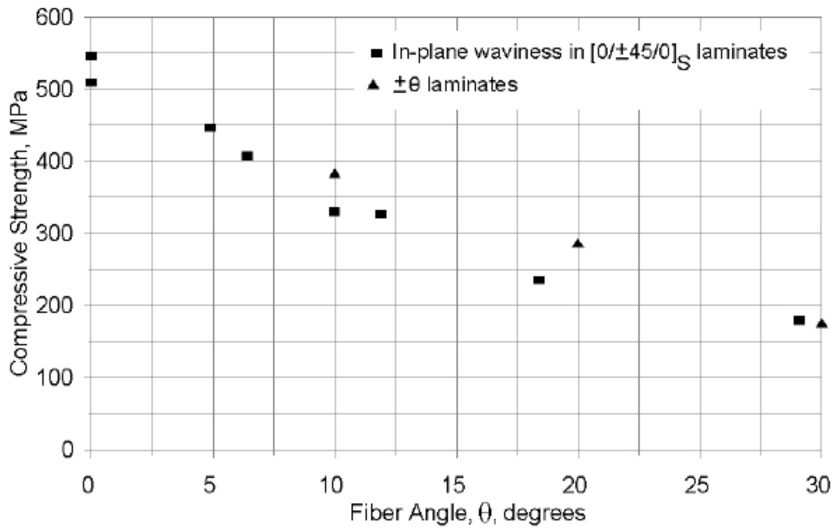

Fig 5.13. Comparison of compressive strength of 0° plies and off axis laminates vs misalignment angle. All 0° plies with waviness.(J.F. Mandell)

Two laminates DD11 and DD5P with through-thickness and in-plane waviness respectively with severity of 4mm/35mm and one laminate DD5P without waviness were tested. For all laminates polyester is used as a matrix material (Wang, 2001). D155 fabric is used as reinforcement in DD5P laminates. Woven A130 fabric is used as reinforcement in DD11. Compressive fatigue test results are shown in Fig 5.14 for the above mentioned laminates. Laminate with four 0° plies without waviness is stronger under both static and fatigue loading compared with other two laminates with waviness in all four 0° plies. Static and fatigue strength reduction in laminates DD11 and DD5P is because of waviness.

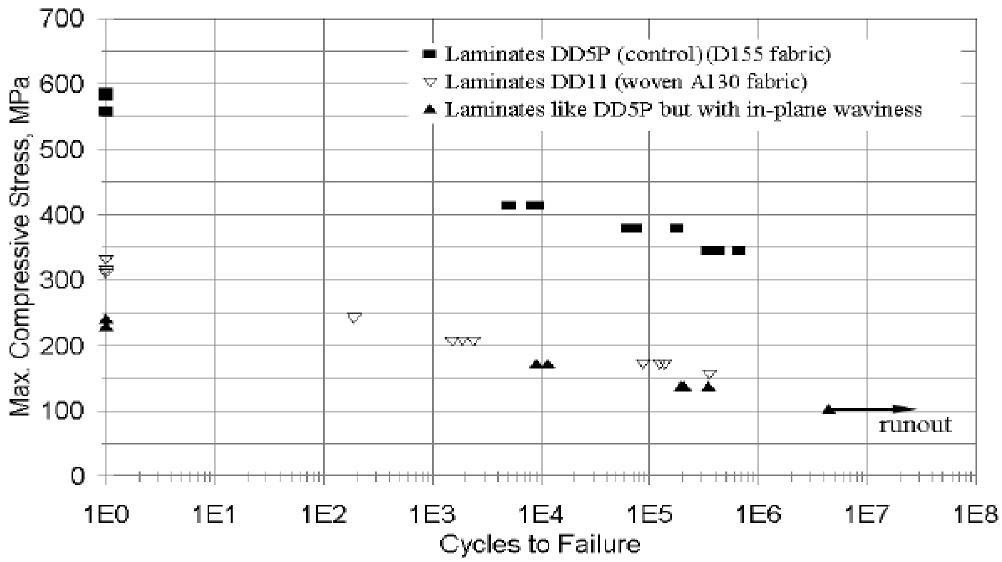

Fig 5.14. Compressive stress vs cycles to failure for Laminates with 4-Layers In-Plane (4 mm-35mm) Waviness and through thickness (DD11) Waviness compared with Control- Laminate DD5P, at stress ratio (R = 10) (J.F. Mandell)

Conclusion

Glass composite material is normally used in wind turbine blades. Turbines are getting larger; weight of the rotor blade also increases which increase gravitational loads. Glass composites has high density and not considered suitable for large wind turbines. Carbon fiber composites, which has high strength and stiffness can be used in the construction of blade. Carbon composites are expensive and has low compressive strength. It can be used in the main component of blade i.e. spars to reduce blade tip deflection and to reduce blade weight. Basalt fiber composite which has good mechanical and thermal properties can replace glass fiber composite material. Adding Nano-reinforcement in matrix material can improve the fatigue resistance, shear, tensile and compressive strength and also fracture toughness of composite material. It also improves the damping ratio and delamination resistance of turbine blades. Fiber waviness in laminates which cause strength reduction could be address through the use of automated fabric placement process.

References

A.N. Mengal1, a. S. (2014). Basalt Carbon Hybrid Composite for Wind Turbine Rotor Blades: A short review.

ASTM international. (n.d.). Retrieved from https://www.astm.org/DATABASE.CART/HISTORICAL/E1823-96R02.htm.

Aymerich, F. (2012). *Composite materials for wind turbine blades: issues and challanges.* Retrieved from http://people.unica.it/francescoaymerich/files/2013/11/Composite-Materials-for-Wind-Turbine-Blades.pdf.

BACH, P. (1992). Fatgue properties of glass and glass/carbon polyester composites for wind turbine.

BAKIS, W. W. (1990). Fatigue Behavior of Composite Laminates.

Bortolotti, P. (2012). *Carbon Glass Hybrid Materials for Wind Turbine Rotor Blades.*

C. BERGGREEN, 1. K. (2007). Application and Analysis of Sandwich elements in the primary structure of large wind turbine blades .

Campbell, F. (2010). *Structural Composite Materials.*

Daniel D. Samborsky, T. J. (2009). Comparison of Tensile Fatigue Resistance and Constant life diagrams for several potential wind turbine blade laminates.

Daniel D. Samborsky1, D. A. (2015). Fatigue Resistance of Wind Blade Laminates Containing In-Plane waviness flaws.

Daniel D. Samborsky1, J. F. (2012). The SNL/MSU/DOE Fatigue of Composite Materials database: Recent Trends.

Ellyin, D. K. (1994). Rate/frequency-dependent behaviour of fiber glass/epoxy laminates in tensile and cyclic loading .

F. Lahuerta, T. W. (2014). STATIC AND FATIGUE PERFORMANCE OF THICK LAMINATES test design and experimental compression results.

Federal Aviation Administration . (n.d.). Retrieved from https://www.faa.gov/regulations_policies/handbooks_manuals/aircraft/amt_airframe_handbook/media/ama_Ch07.pdf .

Ganesh R Kalagia, R. P. (2016). Experimental Study on Mechanical Properties of Natural Fiber rienforced polymer composite materials for wind turbine blades.

Harish1, T. D. (2015). Mechanical properties of carbon/glass fiber reinforced epoxy hybrid polymer composites.

Harris, B. (2003). *Fatigue in composites.*

Hatice Taşçı1, A. A. (2017). Development of carbon-glass fiber reinforced hybrid composites by vacuum infusion technique.

J. F. MANDELL, D. D. (2013). Effects of resin and reinforcement variation on fatigue resistance of wind turbine blades.

J.F. Mandell and D.D. Samborsky. (2002). MSU/DOE Wind Turbine Blade Composite Material Fatigue Database, Sandia National Laboratories, Albuquerque, NM, 87185.

J.F. Mandell, D. S. (n.d.). Effects of fiber waviness on composites for wind Turbine blades.

John F. Mandell, D. D. (2002). *Fatigue of composite materials and substructure for wind turbine blades.*

John F. Mandell, D. D. (2010). *Analysis of SNL/MSU/DOE Fatigue Database trends for wind turbine blade materials .*

John F. Mandell, D. D. (2010). Analysis of SNL/MSU/DOE Fatigue database trends for wind turbine blades.

John F. Mandell1, D. D. (2009). Testing and Analysis of Low Cost Composite Materials Under Spectrum Loading and High Cycle Fatigue Conditions.

John F. Mandell1, D. D. (2015). Analysis of SNL/MSU/DOE Fatigue Database Trends for Wind Turbine Blade Materials, 2010-2015.

John W. Holmes1, P. B. (2009). Development of a Bamboo-Based Composite as a sustainable green material for wind turbine blades.

Joncas, L. C. (2010). Effects of Cold Temperature, Moisture and freeze thaw cycles on the mechanical properties of unidirectional fiber glass epoxy composites.

Joseph, J. P. (n.d.). Advances in Polymer Composites: Macro- and microcomposites. In *Polymer composites.*

Jr., L. M. (2017). Perspective for Fibre-Hybrid Composites in Wind Energy Applications.

Kevin Coxa, A. E. (2012). Structural design and analysis of a 10MW wind turbine blade.

Kiasat, M. (2000). *Curing Shrinkage and Residual Stresses in Viscoelastic Thermosetting Resins and Composites.*

Lahuerta Calahorra, F. (2017). Thickness effect in composite laminates in static and fatigue loading.

Lahuerta, F. (2014). Self-heating forecasting for thick laminate specimens in fatigue.

Laurent Cormier, R. P. (2012). Temperature and Frequency Effects on the Fatigue properties of unidirectional glass fiber epoxy composites.

Laurent Cormier1, S. J. (2016). Effects of low temperature on the mechanical properties of glass fiber epoxy composites: static tension, compression R=0.1 and R=1 fatigue of +-˙45° laminates.

Leon Mishnaevsky Jr. ID, K. B. (2017). Materials for Wind Turbine Blades: An Overview.

Leon Mishnaevsky Jr., G. D. (2013). Hybrid carbon/glass fiber composites: Micromechanical analysis of structure damage resistance relationship.

Leon Mishnaevsky Jr1, P. F. (2009). Strength and Reliability of Wood for the Components of low cost wind turbine: computational and experimental analysis and application.

Nijssen, R. (2006). *Fatigue Life Prediction and Strength degradation of Wind Turbine Rotor Blade composites.*

npower, R. (n.d.). *Wind Turbine Power Calculations.* The Royal Acadmey of Engineering.

P.N.B. Reis a, J. F. (2008). *Fatigue life evaluation for carbon-epoxy laminate composites under constant and variable block loading.*

P.W. MANDERS, M. G. (1981). The strength of hybrid glass/carbon fibre composites.

Pegoretti, A. D. (2012). Fatigue resistance of basalt fibers-reinforced laminates. *Composite Materials*.

R. Gutkin a, S. P. (2010). Micro-mechanical modelling of shear-driven fibre compressive failure and of fiber kinking for failure envolpe generation in CFRP laminates.

R. P. L. Nijssen, F. L. (2014). Effect of laminate thickness on the static and fatigue properties of wind turbine composites.

R. P. L. NIJSSEN, P. B. (2013). Fatigue as a design driver for composite wind turbine blades.

S.M.R. Khalili, V. D. (2011). Mechanical behavior of basalt fiber-reinforced and basalt fiber metal laminate composites under tensile and bending loads. *Reinforced Plastics and Composites*.

Samborsky, J. F. (1997). *DOE/MSU Composite Material Fatigue Database: Test Methods, Materials, and Analysis 1997.*

SÖKER, H. (2013). Loads on wind turbine blades.

SPRINGER, C.-H. S. (1976). Effects of Moisture and Temperature on the tensile strength of composite materials.

SPRINGER, C.-H. S. (1977). Enviornmental effects on elastic moduli of composite materials .

Talreja, R. (n.d.). Fatigue of Composite Materials: Damage Mechanisms and Fatigue-Life Diagrams. *1981*.

Theotokoglou, G. B. (2017). Cross-section analysis of wind turbine blades: comparison of failure between glass and carbon.

Thomas Jolliveta, C. P. (2013). Damage of composite materials.

Thomsen, O. T. (2009). Sandwich Materials for Wind Turbine Blades -- Present and Future. *Sandwich Structures and Materials*.

TP Sathishkumar, S. S. (2014). Glass fiber-reinforced polymer composites - a review. *Reinforced Plastics and Composites*.

Vassilopoulos, A. P. (2011). Introduction to the Fatigue of Fiber-Reinforced Polymer Composites.

VASSILOPOULOS, A. P. (2013). Fatigue life prediction of wind turbine blade composite material.

Wang, L. (2001). *Effects of in-plane fiber waviness on the static and fatigue strength of fiberglass.*

William D. Callister, J. D. (n.d.). *Material Science and Engineering, An Intorduction* (8th ed.). USA.