INVESTIGATION OF MECHANICAL PROPERTIES AND FATIGUE PERFORMANCE OF CARBON-GLASS FIBER REINFORCED EPOXY HYBRID COMPOSITES

A Thesis Submitted to
the Graduate School of Engineering and Sciences of
İzmir Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of

MASTER OF SCIENCE

in Mechanical Engineering

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December 2019

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ACKNOWLEDGMENTS

I would like to give my sincere thanks to my advisor, Prof. Metin TANOĞLU for his guidance, support, motivation and encouragement during my thesis.

I would like to thank to my labmates Mustafa AYDIN, Zeynep AY, Osman KARTAV, Yusuf Can UZ and Serkan KANGAL for their help, support and motivation.

I am deeply grateful to my project mate, my dearie friend Ceren TÜRKDOGAN for her contribution, help and motivation.

I am also deeply grateful to Mehmet Deniz GÜNEŞ for his useful comments, invaluable contributions, support and patience during my thesis.

Lastly but most importantly, I offer sincere thanks to my sisters Gizem and Çisem SANDALLI, my father Erol SANDALLI, especially to my mother Seycan SANDALLI and Görkem YILDIZ for their love, support and patience during my graduate education.

ABSTRACT

INVESTIGATION OF MECHANICAL PROPERTIES AND FATIGUE PERFORMANCE OF CARBON-GLASS FIBER REINFORCED EPOXY HYBRID COMPOSITES

Recently, hybrid composites have known as high performance engineering materials and they have been used broadly in engineering applications where high strength to weight ratio, reasonable cost and ease of fabrication are requested. Since these composites offer combination of benefits of different kinds of fibers, their usage is increasing day after day.

The objective of this thesis is to examine the mechanical properties of carbon-glass fiber reinforced epoxy hybrid composites in two different configurations. Also, the fatigue performance under bending tests of these composites were investigated. The hybrid composites were manufactured by using vacuum infusion technique at ambient temperature. To examine the mechanical properties of manufactured composites, a series of mechanical tests such as compression, tensile and three-point bending tests were performed on the samples which were prepared in accordance with the relevant ASTM standards. Load-controlled three-point bending fatigue tests were also carried out to investigate the performance of manufactured composites under fatigue. The fatigue tests were performed at different stress levels varied from 30 percent to 90 percent of average ultimate flexural strength of the samples which were determined from static three-point bending tests. Subsequently stiffness loss and Wöhler curves were constructed using a specific failure criterion.

ÖZET

KARBON-CAM ELYAF TAKVİYELİ EPOKSİ HİBRİT KOMPOZİTLERİN MEKANİK ÖZELLİKLERİNİN VE YORULMA PERFORMANSININ İNCELENMESİ

Son zamanlarda, hibrit kompozitler yüksek performanslı mühendislik malzemeleri olarak bilinmekte ve yüksek dayanım/ağırlık oranı, makul fiyat ve üretim kolaylığı istenilen mühendislik uygulamalarında yaygın olarak kullanılmaktadırlar. Bu kompozitler, farklı tiplerdeki elyafların yararlarının kombinasyonlarını sunduklarından, kullanımları gün geçtikçe artmaktadır.

Bu tezin amacı karbon-cam elyaf takviyeli epoksi hibrit kompozitlerin iki farklı konfigürasyonda mekanik özelliklerinin incelenmesidir. Aynı zamanda, bu kompozitlerin üç-nokta eğme testi altında yorulma performansları incelenmiştir. Hibrit kompozitler ortam sıcaklığında vakum infüzyon tekniğiyle üretilmiştir. Üretilen kompozitlerin mekanik özelliklerini incelemek için ASTM standartlarına uygun olarak hazırlanan numunelerde basma, çekme ve üç nokta bükme gibi bir seri mekanik testler yapılmıştır. Aynı zamanda, kompozitlerin yorulma altındaki performanslarını incelemek için yük kontrollü üç nokta eğme yorulma testleri uygulanmıştır. Yorulma testleri numunelerin ortalama nihai eğilme dayanımlarının yüzde otuzu ile doksanı arasında değişen dayanım seviyelerinde yapıldı. Daha sonra hasar kriterine uygun olarak sertlik kaybı ve Wöhler eğrileri oluşturuldu.

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CHAPTER 1

INTRODUCTION

Fiber-reinforced composite materials are broadly used in most high-performance engineering applications such as aviation, military and automotive due to their outstanding characteristics compared to conventional structural materials for a long time (Prashanth et al. 2017). However, nowadays engineers and scientists are focusing intensively on developing stronger and lighter structural materials in order to follow current technologies for the structures having complex shapes such as wind turbine blades, airplane and automotive structures (Durai Prabhakaran et al. 2013). In accordance with this purpose, development of hybrid composites has become an important subject day after day.

Hybrid composites are formed by combining multiple type of reinforcing materials in a single matrix. With this combination, it may be possible to attain a new composite material having the complementary benefits of its constituents, while alleviating the drawbacks of its constituents (Gururaja and Rao 2012; Pegoretti et al. 2004). These composites offer flexibility to designers with the diversity of fiber/resin systems and they get increasing attention from engineers and scientists due to this offer.

There are many available reinforcement and resin materials to produce a hybrid composite material. However, combination of carbon and glass fibers as reinforcement material in an epoxy matrix is the most preferred system in the literature. Epoxy based carbon/glass fiber reinforced hybrid composites offer a material having characteristics of high strength and elongation with reasonable cost (Wang, Wu, and Li 2018). Due to these useful characteristics they are used in automotive and aviation industry and also in wind turbine blades.

The increasing usage of hybrid composites materials in given engineering applications requires information about their mechanical properties. Therefore, in literature there are studies related with their behavior under tension, compression and bending type of loadings.

Fatigue, the failure occurs under cyclic and repeated loadings, has been extensively studied by many researchers. As a result of those studies, there are many available design data for fatigue of metals, however there is a lack of information about fatigue of fiber-reinforced composites, especially about fiber-reinforced hybrid composites. This is because the challenge due to anisotropy and different damage modes that can be occurred under fatigue loading in composite materials such as matrix cracking, fiber breakage and delamination (Wharmby, Ellyin, and Wolodko 2003).

Fatigue of composites is generally monitored by following reduction in stiffness in the literature (Belingardi and Cavatorta 2006; Cavatorta 2007). According to some researchers this is because fewer experiments are required in order to obtain a comprehensive analysis (A. Bezazi et al. 2003). As reported in the study of Van Paepegem and Degrieck (Van Paepegem and Degrieck 2002), reduction in stiffness curves consist of three apparent regions: in the first region, stiffness degradation rate is high, degradation in this region is visible, in the second region, the rate slows down and stiffness degrades almost linearly as a function of number of cycles, in the third region, degradation rate increases dramatically leading to failure of specimen.

The motivation of the current study is to investigate fatigue performance and mechanical properties of epoxy-based carbon and glass fiber reinforced composites in different configurations. The plates are manufactured by using vacuum assisted resin transfer molding technique and they are cut in order to obtain cross-ply $[0°/90°]_8$ and angle-ply $[\pm45°]_8$ configurations. In the scope of the study, in order to determine the constituents' content, matrix digestion and burn-out tests were performed on the samples. A series of mechanical tests, tensile, compression and three-point bending are performed on the samples in order to get information about their mechanical characteristics. Subsequently, load-controlled three-point bending fatigue tests were also performed on the samples to compare the fatigue performance of cross-ply and angle-ply configurations.

This thesis involves five chapters. In Chapter 1, the information based on hybrid composites and the studies in literature related with their mechanical properties and fatigue performance is given. At the end of the chapter, the motivation of this thesis is also summarized. In Chapter 2, a brief information about composite materials, hybrid composites and their fatigue behavior are given in order to provide a little inside about basic terminology. A detailed literature review on studies related with hybrid composites is also provided in this chapter. Experimental studies which were performed within the scope of this thesis are explained in detail in Chapter 3. The results of the tests carried on the hybrid laminates are given in Chapter 4. Finally, concluding remarks on the results of this thesis are presented in the last chapter.

CHAPTER 2

FUNDAMENTAL CONCEPTS AND RELEVANT LITERATURE

2.1. Definition of Composites

A composite material can be described as combination of two or more different materials which shows better characteristics than its constituent materials. The constituents of a composite material are named as reinforcement and matrix. The matrix material is generally in a form of resin and it is used to hold the reinforcement in the requested orientation. It surrounds the other constituent and is used as a shelter for reinforcement to protect it from environmental and chemical attacks. The matrix material helps to transfer applied load effectively (Sai 2016; Kumar and Bhanuprakash 2017; Callister 2007). The role of dispersed phase, reinforcement, in a composite material is enhancing the mechanical characteristics of the matrix material. In Fig. 2.1. schematic representation of constituents of a composite material is illustrated.

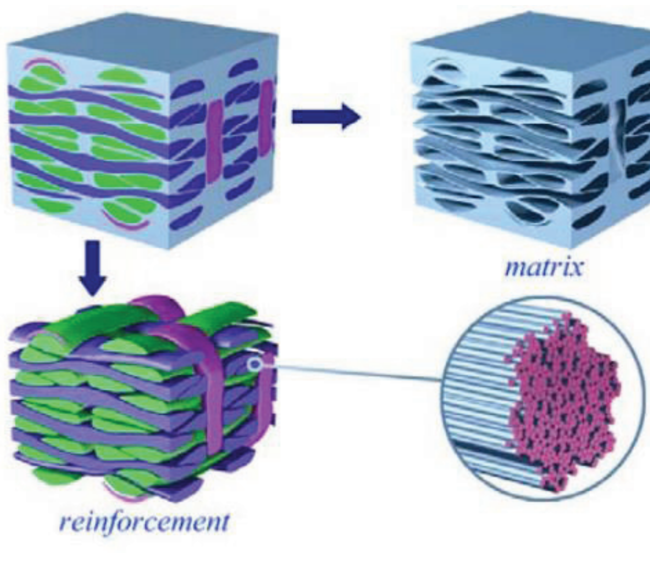


Figure 2.1. The constituents of a 3D woven composite (Source: Drach et al. 2013)

2.2. Classification of Composites

The basic classification of composite materials is illustrated in the Fig. 2.2. As illustrated in the figure, there are three main types of composites according to this classification; particle –reinforced, fiber-reinforced and structural composites with their sub-categories (Callister 2007).

Particle-reinforced composites are generally categorized under two sections: large-particle (particle size of 1 μm to 2 mm) and dispersion-strengthened (particle size of 0.01 to 1 μm). This composite type is used where the properties such as wear resistance, heat resistance and electrical properties need to be modified or improved (Ostrava 2015).

Fiber-reinforced composites are the composites which can be obtained with placing high strength fibers in a matrix. In this composite type, both of the constituents maintain their characteristics. Additionally, with combination of fibers and matrix material, a superior characteristic can be produced which cannot be obtained with either of the constituents acting alone. Commercially used, generally preferred fibers are glass, carbon and Kevlar fibers. Other types of fibers are also used, such as aluminum oxide, boron and silicon carbide, but are not widely used, such as glass and carbon fibers. These listed fiber types can be embedded in a matrix material in continuous or discontinuous forms (Mallick 2007). In Fig.2.3. examples of continuous and discontinuous forms of fibers are illustrated.

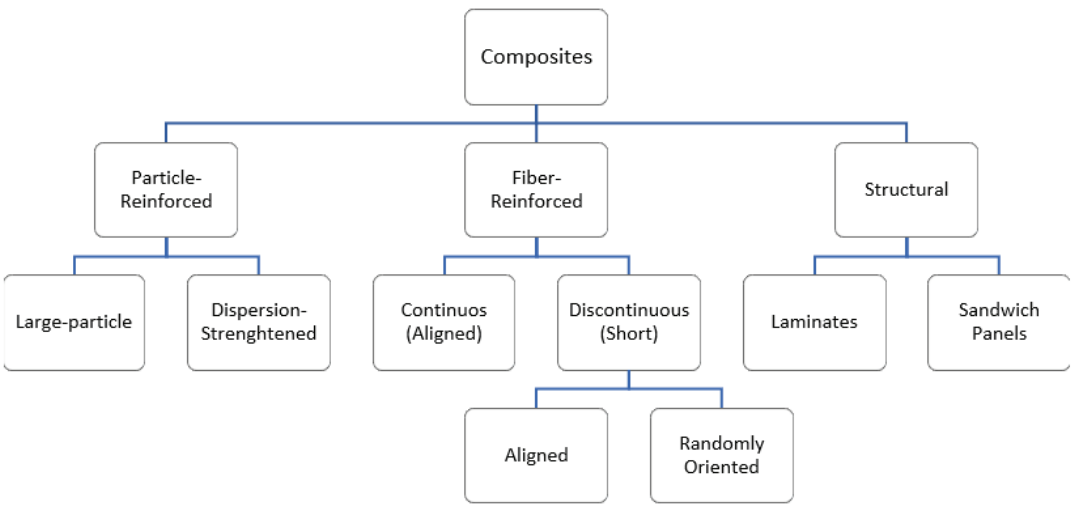


Figure 2.2. Basic classification of composite materials

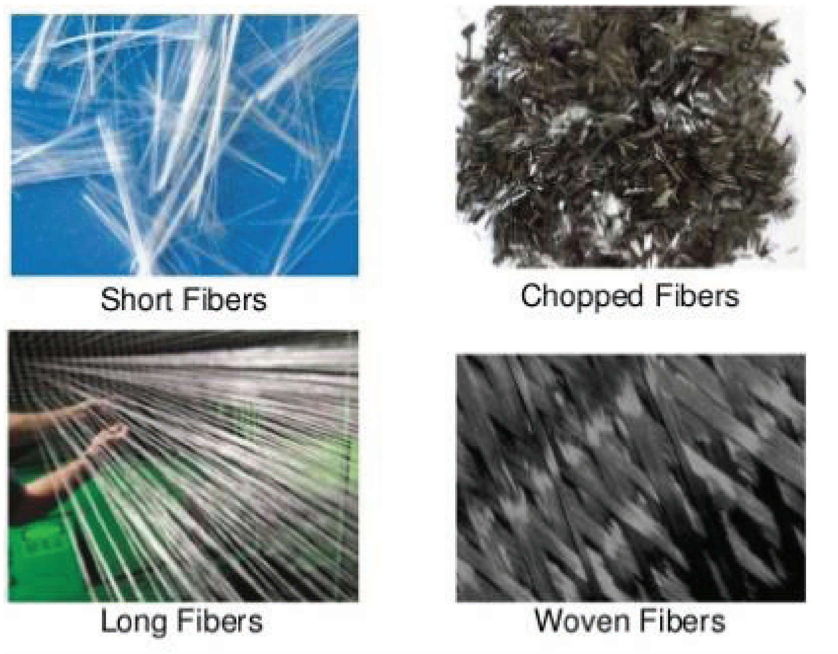


Figure 2.3. Continuous and discontinuous forms of fibers
(Source: McDaniel and Knight 2014)

Structural composites have two subcategories: i) laminated composites and ii) sandwich panels. Laminated composites are the advanced composite materials formed sequential fabric layers. Each fabric layer is called as a “ply”, by using two or more plies of resin-impregnated fabric form a “laminate” (Oxyblack 2017). Fig.2.4. shows the fundamental constituents of a laminate.

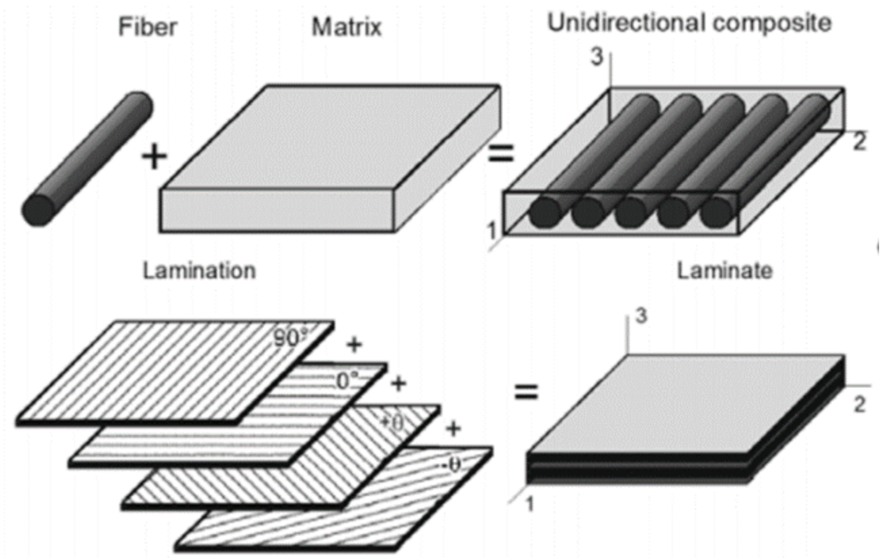


Figure 2.4. The constituents of a laminate (Source: Kulakov and Aniskevich 2012)

Other type of structural composites is sandwich panels which comprise generally two faces and a core. The faces are generally identical in terms of used material and the sizes. They resist to in-plane and bending loads. The core bonded between two faces can be any kind of material and there are many available geometries for core such as honeycomb, web-core, thrust-core etc. (Vinson 1999).

2.3. Hybrid Composites

A hybrid composite is a composite that is obtained by using multiple type of reinforcing materials, for instance glass and Kevlar, in a single matrix (Hull 1981). Hybridization is generally done in order to make suitable the properties of materials to the particular requirements of the considered structure and to get a new composite material sustaining the complementary benefits of its constituents, while alleviating their drawbacks (Kretsis 1987; Gururaja and Rao 2012; Wu, Wang, and Li 2018). For this reason, hybrid composites can offer more effective solutions than traditional fiber-reinforced composites consisting of a single reinforcing material in some engineering applications and they are widely used in industry (Pandya, Veerraju, and Naik 2011). Major applications of these composites are lightweight structural components in aerospace, automotive and constructional applications, sporting goods, wind turbine blades and orthopedic instruments.

Figure 2.5. The parts manufactured by using carbon-glass fiber reinforced epoxy hybrid composites (Source: Ravishankar, Nayak, and Kader 2019)

In order to obtain a hybrid polymeric composite, various fibers and matrix materials can be selected. However, carbon and glass fibers that are embedded in a resin system is, by far, most commonly used system. Carbon fibers have the strength and stiffness necessary for some specific engineering applications. In addition to this, they have lower density compared to glass fibers. Though, their fracture strain and impact resistance are low which can be insufficient for the applications where the composite structure subjected to flexural or compressive loading. On the other hand, glass fibers have high elongation, but they lack the strength and stiffness necessary for high performance engineering applications. By incorporating these two fiber types in a single resin, carbon-glass hybrid composites can be manufactured that have the coupling of high strength, stiffness and elongation. Another important consideration is the cost. Carbon fibers are relatively expensive, whereas glass fibers are inexpensive compared to carbon fibers. Because of that, use of carbon and glass fibers together in a single resin system, is one of the preferred techniques in automobile industry, in order to reduce the weight and at the same time without a significant increase in cost (Wang, Wu, and Li 2018).

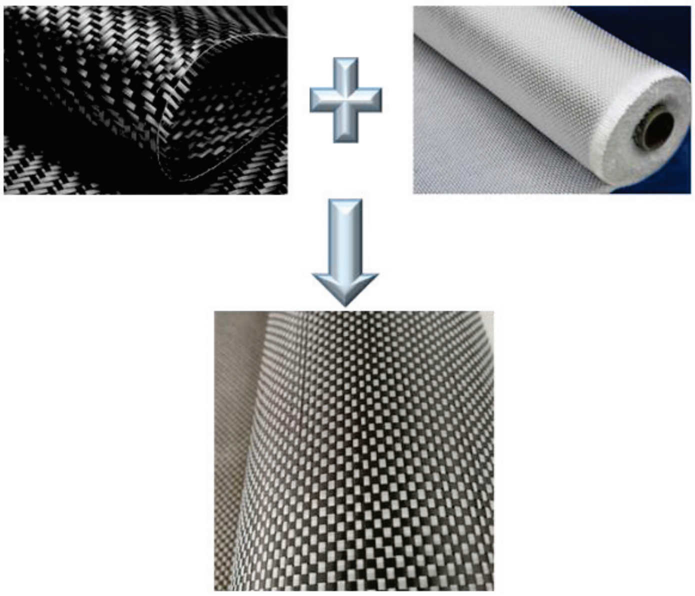


Figure 2.6. Carbon-glass fiber reinforced hybrid fabrics

There are five types of hybrid composites based on the mixing of reinforcing material (Kretsis 1987; Ravishankar, Nayak, and Kader 2019):

- interply hybrids: layers of different types of fibers are stacked
- intraply hybrids: multiple types of fibers are present in the same layer
- intermingled hybrids: different fiber types are mixed randomly, so the hybrid composite have no concentration of a specific fiber type
- selective placement: reinforcement materials are positioned where extra strength is required, on the base laminate layer
- superhybrid composites: comprised of metal composite plies which are placed according to a specified configuration and stacking sequence.

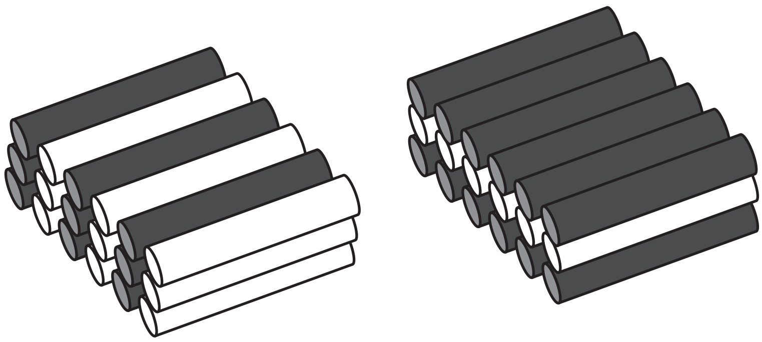


Figure 2.7. Schematic representation of intraply (left) and interply (right) hybrid composites

Different variants of these arrangements illustrated in figure can be engaged such as angle-ply and cross-ply configurations.

2.4. Manufacturing Techniques for Fiber-Reinforced Composites

There are numerous manufacturing techniques available for fiber-reinforced composites which are mainly categorized under two sections according to mold type; open mold processes and close mold processes (Hull 1981). The categorization is given in Fig.2.8. Since in this thesis vacuum assisted resin transfer molding (VARTM) technique is used in order to manufacture the hybrid composite laminates, only this technique is explained in detail under the heading.

VARTM technique proposes several cost benefits over conventional resin transfer moulding techniques owing to lower tooling costs, potential for room temperature processing and scalability for large structures. Over the past few decades, in some engineering areas such as marine and wind energy market, this technique has been used in order to manufacture high-performance composite structures. However, low repeatability and dimensional tolerances in comparison with autoclave technique, in addition to lower material performance of the resin against prepreg restricted its aerospace applications. In recent times, enhanced understanding of the technique physics together with developments in infusible toughened resins and automation equipment allowed consideration of the technique for structural aerospace parts. Due to the fact that, this technique merges the advantages of resin transfer molding technique such as repeatability, better quality and clean handling with the advantages of hand lay-up technique such as flexibility and scalability, usage of VARTM technique is increasing day by day (Heider and Gillespie 2007).

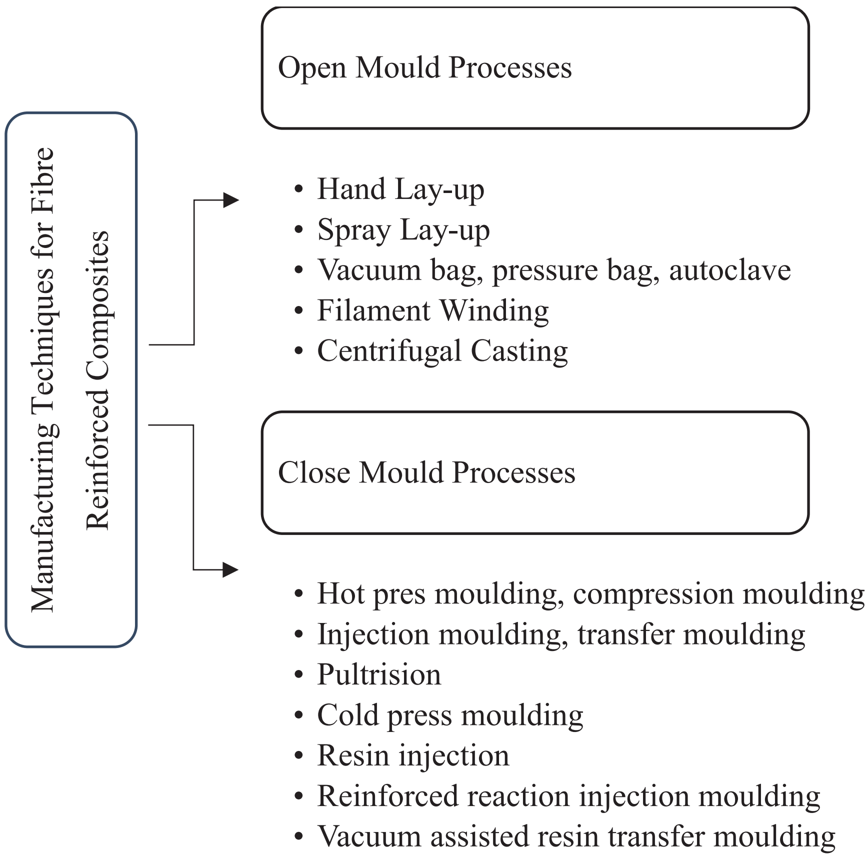


Figure 2.8. Manufacturing techniques for fiber reinforced composite materials

The schematic representation of the technique is illustrated in Fig.2.9. in order to visualize the components used during the process.

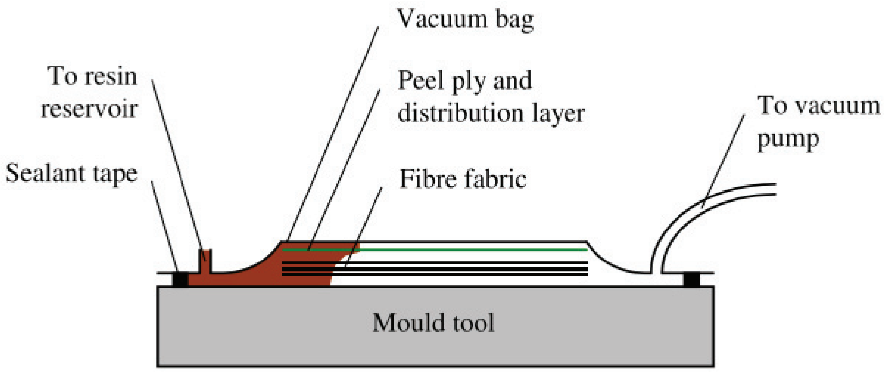


Figure 2.9. Schematic representation of VARTM technique (Source: Dong 2008)

The VARTM technique generally consists of the following steps (Hsiao and Heider 2012):

- First, clean the mold tool and coat the surface of it with the release agent.
- Place the fabrics on the mold.
- After placing the fabrics, place the peel ply on the fabrics. Then, place the flow distribution medium layer on top of the fabrics and the peel ply in order to increase the speed of the resin. This step is up to preferences and it is generally applied when large composite parts are manufactured. This layer should not touch the vent port so, its height should be less than the height of the peel ply and the fabrics.
- Put one of the ports which will be used as resin injection port on the flow distribution medium layer and put the other one which will be used as resin vent port on the peel ply. Connect the ports with tubes that have helical shaped openings.
- Place the sealing tape around the fabrics.
- Connect the vent port to the vacuum source and the resin injection port to the reservoir.
- Apply the vacuum inside the system.

- Check if there is a leakage from the vacuum bag.
- After checking the system, open the resin injection port. When resin reaches the vent port, wait for a while and then, close the injection port.
- Until resin cures, do not close the vent port. When it cures, close the vent port and demold the part from the mold.

2.5. Fatigue

Fatigue is a failure form that occurs in structures subjected to cyclic loadings. This failure type can be also described as degradation in properties of a material under repeated loadings. The most distinctive feature of this failure type is that it generally occurs after a long period of time. Due to fatigue, failure can occur at stress levels remarkably lower than the ultimate strength of materials. In some cases, it may occur at stresses lower than the yield strength of materials. Fatigue is a critical failure form because it is a brittle failure type and it comprises almost 90% of failures of metallic materials; other material types, such as composites, are also prone to fatigue failure (Budynas and Nisbett 2015; Callister 2007).

2.5.1. Fatigue Variables

Generally, there are three possible dynamic stress-time modes: reversed, repeated and random stress cycles as illustrated in Fig.2.10.

As illustrated in the repeated stress cycle, stress varies between maximum and minimum stress levels. This stress variation is generally described by mean stress, stress range, stress amplitude and stress ratio which are shown in the Fig.2.10. These variables can be calculated by using following equations:

$$\sigma_m = \frac{\sigma_{max}+\sigma_{min}}{2} \tag{2.1}$$

$$\sigma_r = \sigma_{max} - \sigma_{min} \tag{2.2}$$

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (2.3)$$

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (2.4)$$

Where, σ_{max} is the maximum stress level, σ_{min} is the minimum stress level, σ_m is the mean stress, σ_r is the stress range, σ_a is the stress amplitude and R is the stress ratio.

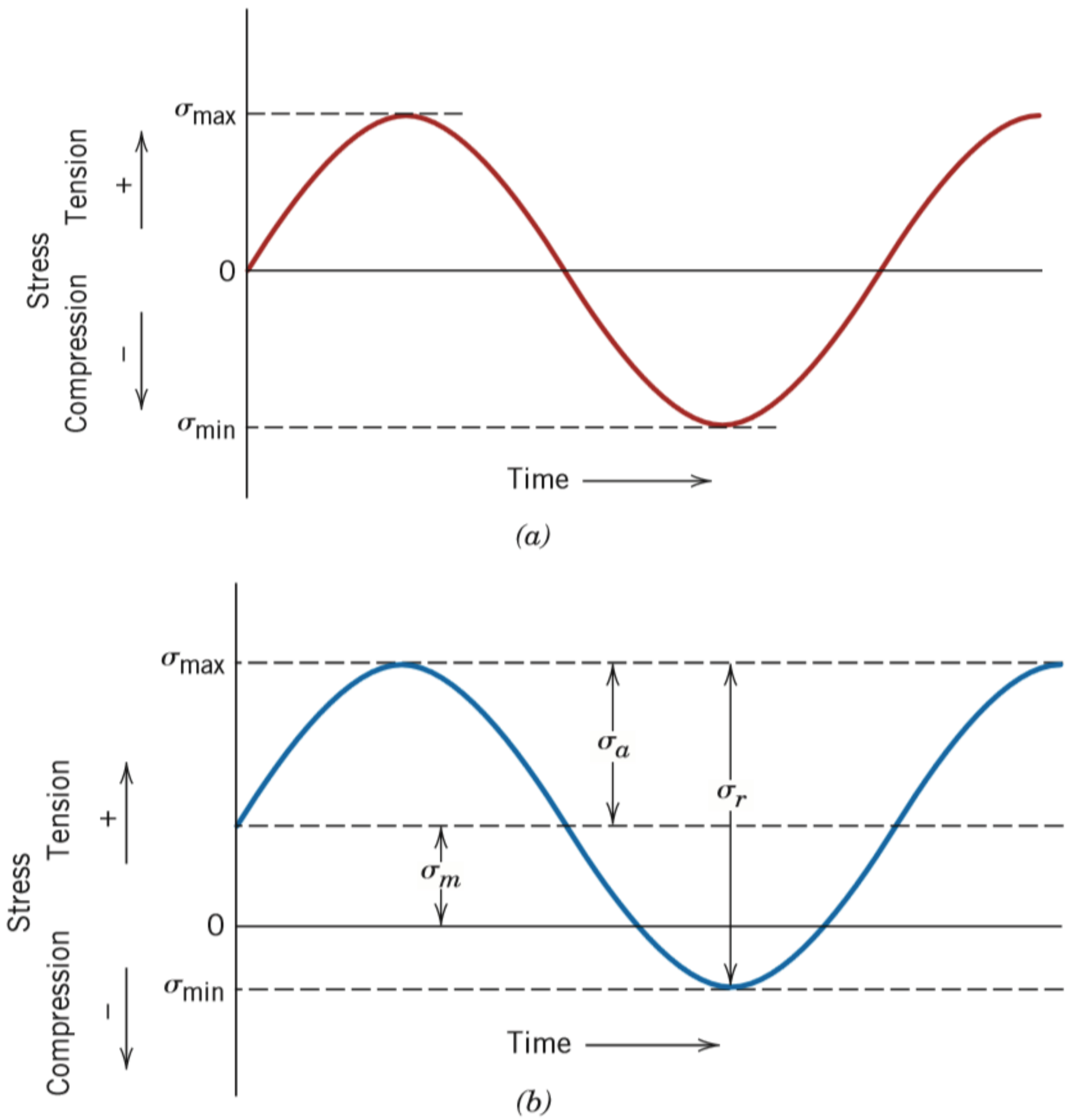


Figure 2.10. (Cont. on next page)

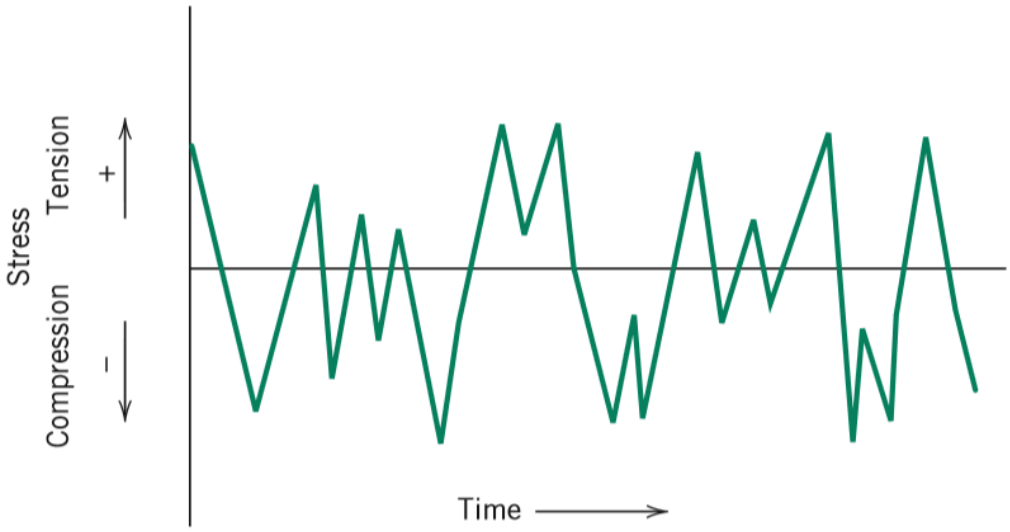


Figure 2.11. (a) Reversed stress cycle, (b) Repeated stress cycle, (c) Random stress cycle (Source: Callister 2007) (Cont.)

2.5.2. S-N Curves

The total number of cycles for which a sample resists before failure is called as "fatigue life" that is represented by N. The graph that can be obtained by plotting values of stress and number of cycles is called as "S-N curve" or "Wöhler curve". The graph can be plotted in semi logarithmic (S vs. log N), logarithmic (log S vs. log N) or linear scale (S vs. N) (Callister 2007; Ugural 2015; Budynas and Nisbett 2015). In the Fig.2.11., typical S-N curves for ferrous materials and non-ferrous materials are illustrated.

As illustrated in the Fig.2.11., for ferrous materials, also for titanium and its alloys, the S-N curve turns to horizontal after a point. At stress levels below that horizontal line, failure will not happen in the specimen for an infinite number of cycles. Therefore, this limiting stress is called as endurance/fatigue limit. This limit cannot be observed for nonferrous materials, also for nonmetallic materials as illustrated in figure. For this kind of materials, the fatigue strength is obtained for a designated number of cycles. For the cases where failure does not happen even if the designated number of cycles is reached, the fatigue test can be stopped and the stress value at that number of cycles is stated on the graph as 'run-out'(Yılmaz 2019).

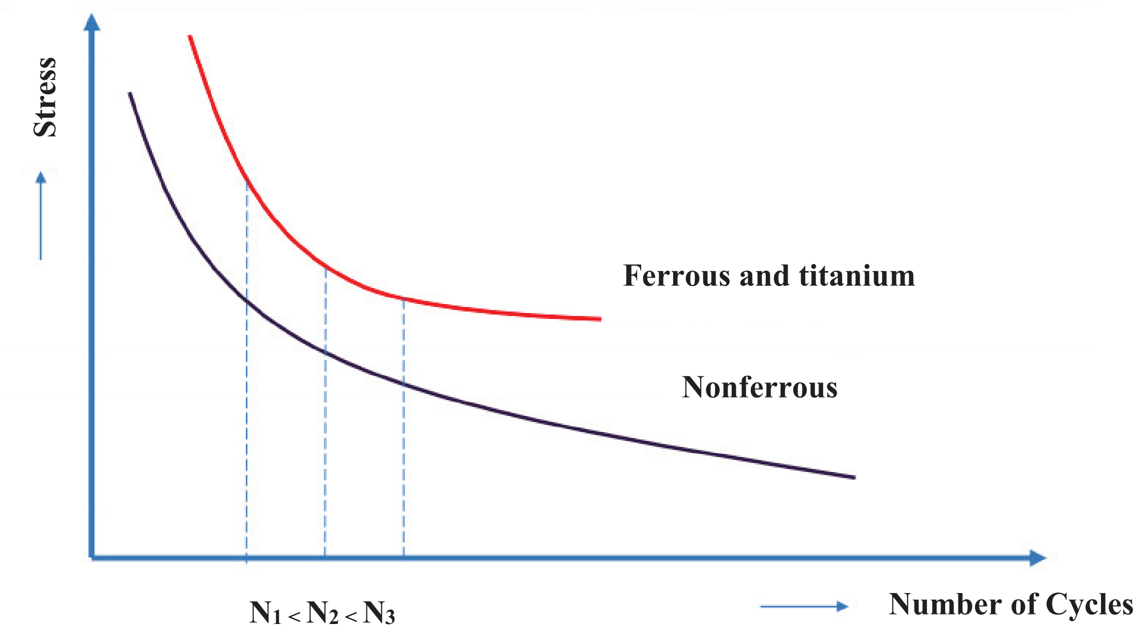


Figure 2.12. S-N curves for ferrous and non-ferrous materials

2.5.3. Fatigue of Fiber Composites

Metallic fatigue, which comprises almost 90% of failure type of all metallic materials, has been extensively studied and reported in the literature for a long time. For engineering metals and their alloys, there are available design data even covering fatigue behavior. Fatigue in metals generally proceeds by a single crack initiation and progression of this crack until catastrophic failure of the material with little or no warning. Unlike metallic fatigue, fatigue of composites presents an enormous challenge due to anisotropic nature of those materials. Damage accumulates in a general rather instead of a localized fashion in composites. The mechanism of this damage accumulation includes delamination, debonding, matrix cracking and fiber breakage in microscale (Harris 2003; Talreja 2013). This damage accumulation can lead to reduction in stiffness. This reduction in fiber composites has been extensively studied in literature, however a few of those studies are related with hybrid composites.

In composites, damage generally starts with local separation between the constituents at weak points, for instance they can detach by fracture of very fine fibers. This damage initiation can happen already after a small number of cycles. Thereafter, microcrack formation starts at the damaged areas by fatigue of matrix. In this way, the composite material is progressively damaged, and this can be monitored by degradation in stiffness. The failure of the composite material finally occurs when the number of microcracks has increased so much and they merge (Roesler, Harders, and Baeker 2006).

2.5.4. Literature Review on Fatigue of Fiber Reinforced Hybrid Composites

Materials in engineering applications don't subject to static loadings at all times. Generally, they undergo fatigue loading conditions and because of this; resistance of the materials used in those applications to fatigue is an essential consideration during design.

Damage accumulation in a composite material during fatigue was generally monitored by investigating the stiffness degradation in literature (Van Paepegem and Degrieck 2002; Belingardi, Cavatorta, and Frasca 2006; Belingardi and Cavatorta 2006; Cavatorta 2007; A. Bezazi et al. 2003; A. R. Bezazi et al. 2003). As reported in the study of Van Paepegem and Degrieck (Van Paepegem and Degrieck 2002), stiffness degradation curves consist of three apparent regions: in the first region, stiffness degradation rate is high, degradation in this region is visible, in the second region, the rate slows down and stiffness degrades almost linearly in terms of number of cycles, in the third region, degradation rate increases dramatically leading to failure of the sample.

Schulte et al. (Wharmby, Ellyin, and Wolodko 2003) investigated the tension-tension fatigue behavior of carbon/epoxy samples with stacking sequence of $[0/90/0/90]_{2S}$ by associating the fatigue performance of samples with stiffness degradation. The authors observed three distinct regions in stiffness degradation. In the first region, stiffness decreased 2-5% due to transverse matrix cracking, in second region, dominant damage mechanism was delamination and longitudinal cracks along 0º fibres causing 1-5% stiffness degradation, in the final region, sudden decrease in stiffness was observed. Wharmby et al.(Wharmby, Ellyin, and Wolodko 2003) investigated the tension-tension fatigue performance of E-glass fibre/epoxy laminates in cross-ply and multidirectional orientations. The results of their study revealed that the samples those having cross-ply orientation were able to carry higher loads before damage initiation. However, sudden stiffness degradation and failure were observed within those samples.

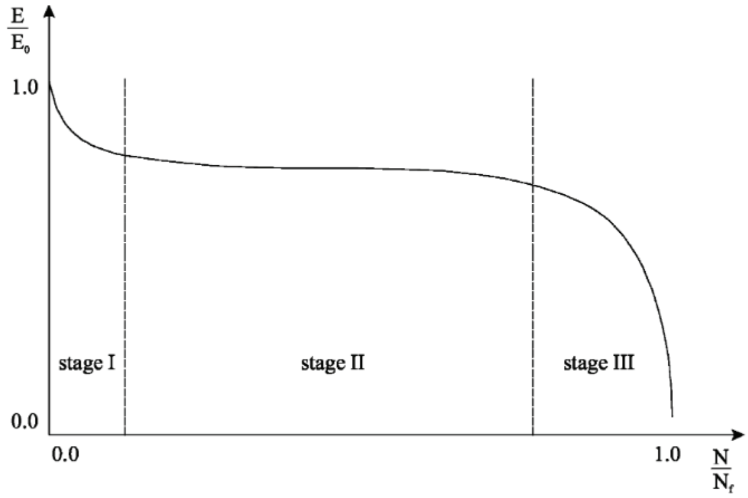


Figure 2.13. Common degradation in stiffness curve for fiber-reinforced composite materials (Source: Van Paepegem and Degrieck 2002)

In literature, there are many available studies related with flexural fatigue behavior of fibre-reinforced composites. However, a few of those studies are based on the flexural fatigue behavior of hybrid fibre-reinforced composites due to their more complex nature than a composite material with a single reinforcing fiber type.

In 2006, Belingardi and his coworkers (Belingardi, Cavatorta, and Frasca 2006), evaluated the flexural fatigue performance of glass-carbon/epoxy hybrid composites under displacement-controlled four-point bending fatigue tests with stress ratio of 0.10. The plate in this study was fabricated by using vacuum bagging technique. It was not only consisting of hybrid carbon-glass hybrid fabric, it was also consisting of glass and carbon fabrics. Samples were cut in order to obtain an [±45º] configuration. Stiffness loss during fatigue testing and the influence of test frequency on the fatigue behavior of the material under study was examined in this study. Fatigue tests were carried out up to 10^6 cycles. The authors showed that the stiffness loss during testing was negligible at the beginning, after one thousand cycles, stiffness started to decrease almost linearly with the number of cycles. They also showed that the testing frequency, between 4-10 Hz, had no notable effect on fatigue performance of samples.

Belingardi and Cavatorta (Belingardi and Cavatorta 2006), studied the flexural fatigue performance of hybrid carbon-glass/epoxy composites in [0º/90º] and [±45º] configurations. The plates were fabricated by using same fabrics and same fabrication technique with the study which is briefly explained in above paragraph. Samples were cut to obtain cross-ply and angle-ply configurations. The results of this study showed that, for both of configurations, below 30% of UFS for both specimen types, there was no significant stiffness degradation. For applied load level higher than 45%, in samples those having [0º/90º] configuration suffer higher stiffness losses than the angle-ply samples. The authors also examined the influence of testing frequency on fatigue performance of samples and they observed no notable effect in 4-10 Hz range for both samples.

Cavatorta (Cavatorta 2007), compared the flexural fatigue performance of hybrid composites which consist of glass and carbon fibers, fabricated by using vacuum bagging and resin transfer molding techniques. Plates were fabricated with same fabrics (glass-carbon hybrid, glass and carbon fabrics) and stacking sequence (C/H/G/H/G//symmetric). The displacement-controlled fatigue tests were performed with a stress ratio of 0.1 and 10 Hz testing frequency. The results of this study showed that, below 30% of UFS for both specimen types, there was no notable stiffness degradation. For higher stresses, the results showed that performance of the samples fabricated by using vacuum bagging was better than the samples fabricated using RTM.

To evaluate the fatigue performance of materials, different damage criteria (N_S, N_3, N_5, N_{10} and N_R) are available in literature (Belingardi and Cavatorta 2006; Belingardi, Cavatorta, and Frasca 2006; A. Bezazi, Boukharouba, and Scarpa 2009; A. Bezazi et al. 2003; A. R. Bezazi et al. 2003). N_x corresponds to x% reduction in displacement (or load) according to initial displacement (or load). N_R failure criterion is the least strict one because it is equal to number of cycles up to failure of the sample and N_s failure criterion is the strictest one. The selection of the damage criterion depends on the application (A. Bezazi, Boukharouba, and Scarpa 2009). Generally, N_5 and N_{10} criteria are selected to construct S-N curves of hybrid composites. After N_{10} failure criterion, various damage mechanisms can be observed and the description of these mechanisms may not be interpreted correctly. For instance, when higher failure criterion is selected, a significant effect of local heating in the sample can be observed and this effect cannot be neglected while interpreting the results.

Bezazi et al.(A. Bezazi et al. 2003), compared the three-point bending performance of cross-ply Kevlar, glass and Kevlar-glass/epoxy hybrid laminates according to N_{10} criterion. For laminates containing only glass or Kevlar fibers, the fatigue tests were performed in load-controlled mode, for hybrid laminates tests were performed in displacement-controlled mode. The authors observed the degradation in stiffness until the failure of the samples in two phases: The first phase was very long and in that phase stiffness degradation was very slow due to matrix cracking and slow propagation of these cracks. The second phase was very short compared with the first phase and in that phase degradation in stiffness suddenly accelerated until the failure of samples due to failure of fibers. The results of the study also showed that the laminates consisting of glass fibers only, had better fatigue performance than other laminates.

Bezazi et al.(A. R. Bezazi et al. 2003) investigated the influence of stacking sequence and reinforcement type on the static and cyclic behavior of different laminates with Kevlar and glass fibers. The fatigue curves were drawn according to N_5 and N_{10} criteria. The authors revealed that due to poor adhesion between fiber and matrix, the laminates constituted of Kevlar fibers is more sensitive to fatigue.

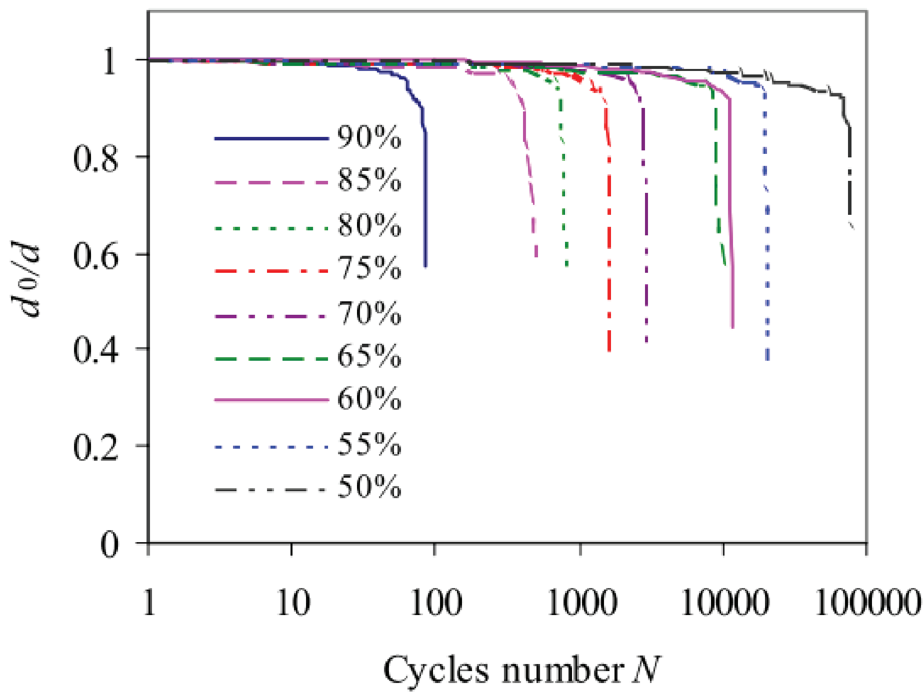


Figure 2.14. Alteration in stiffness of the GFRP composites according to the number of cycles for the applied load levels (Source: A. Bezazi et al. 2003)

2.5. Mechanical Characterization of Fiber Reinforced Hybrid Composites

The increasing usage of hybrid composites materials in aerospace, automotive and wind turbine blades applications requires information about their mechanical properties. Therefore, mechanical properties of fiber reinforced hybrid composites are investigated by different mechanical testing techniques in literature. Most commonly, tensile, compressive and/or bending testing techniques are applied on these composites.

(a)

(b)

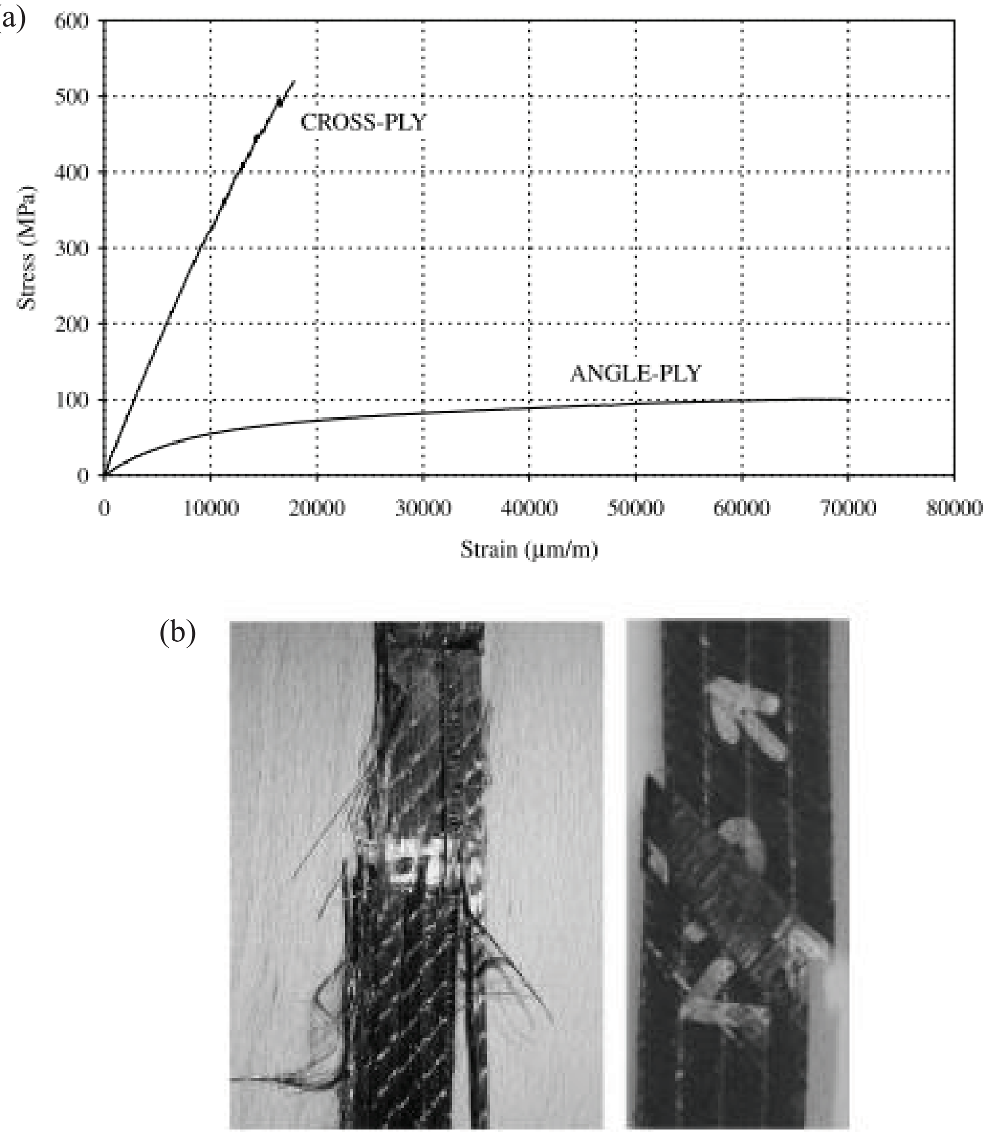


Figure 2.15. (a) Stress-strain curves for hybrid samples, (b) Breaking patterns (Source: Belingardi and Cavatorta 2006)

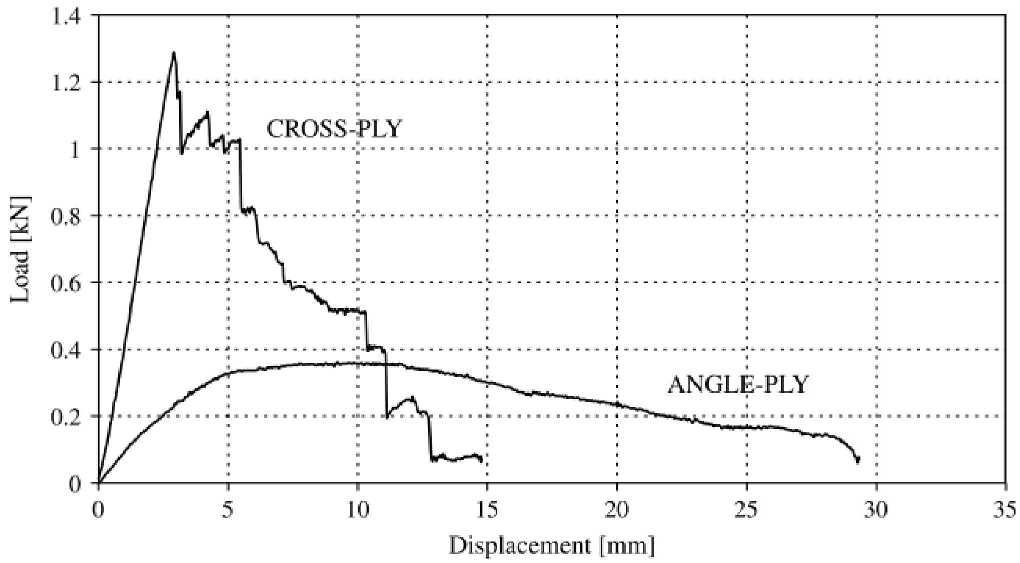


Figure 2.16. Load-displacement curves for samples under flexural test (Source: Belingardi and Cavatorta 2006)

In some studies which were explained in the previous section, static tensile and bending tests were also performed on the samples in order to find the strength and elastic modulus of them. In the study of Belingardi and his coworkers (Belingardi, Cavatorta, and Frasca 2006), tensile tests were carried out on glass/carbon-epoxy hybrid samples which were manufactured by vacuum bagging technique. Test were performed with the cross-head speed of 1 mm/min and tests were performed until failure of the samples. The results of the tests indicated that failure occurred because of failure of the epoxy due to shear at a 45° with respect to the specimen axis.

In the study of Belingardi and Cavatorta (Belingardi and Cavatorta 2006), authors compared the mechanical properties of hybrid composites made of glass and carbon fibers in two different configurations. The results of tensile tests performed within the scope of study in the below figure. As visible from the figure, for cross-ply samples a linear behavior was observed, however for angle-ply samples a non-linear behavior was observed because of considerable contribution of epoxy. The breaking pattern of the samples under tensile tests are also shown in the figure. In this study, four-point bending tests were also performed on the samples in order to compare their strength and flexural elastic modulus. It was revealed that cross-ply samples were able to carry higher loading levels than angle-ply samples and also, their flexural elastic modulus was five times greater than those for angle-ply samples.

CHAPTER 3

EXPERIMENTAL

3.1. Materials

In this thesis, intraply biaxial [±45°] carbon-glass hybrid fabrics were used as the reinforcement material and two components epoxy system, constituted of Momentive^{TM} L160 epoxy resin and Momentive^{TM} H160 hardener were used as the matrix material with the resin to hardener weight ratio of 100:25.

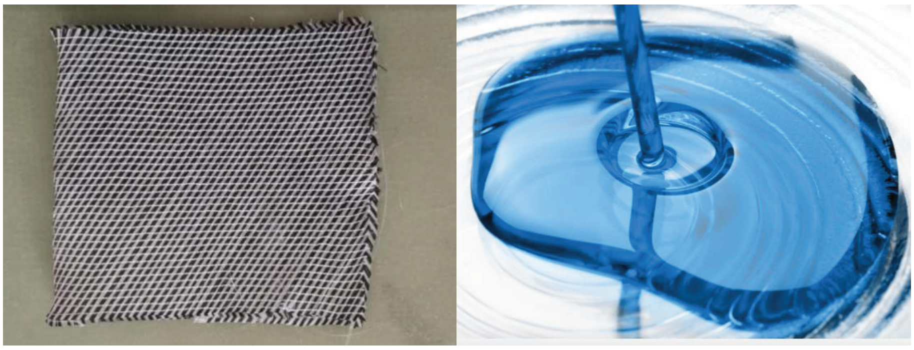
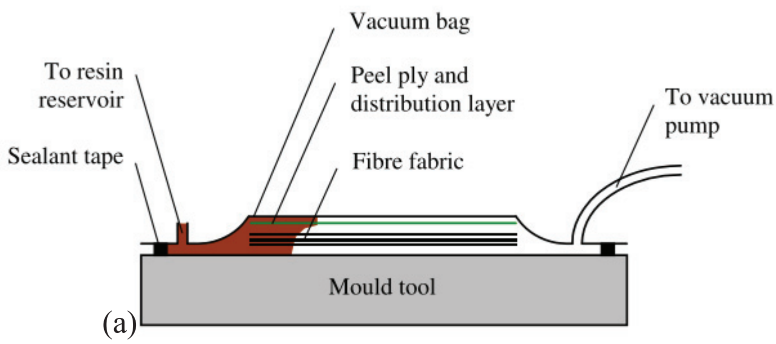


Figure 3.1. The carbon-glass hybrid fabric and epoxy resin

3.2. Manufacturing of Composites Laminates

The plates were manufactured by using VaRTM technique with $[\pm 45^{o}]_8$ orientation at ambient temperature. First of all, the release agent is applied on the mould tool in order to facilitate the demolding process. Then fiber fabrics are placed on the mould tool in requested orientation. After placement of fabrics, peel ply and distribution layer are placed on the fabrics. Next, the system is closed and sealed with a vacuum bag and sealant tapes. The epoxy resin is prepared by mixing epoxy and its hardener with weight ratio of 100:25. After the epoxy and the hardener are mixed completely, the epoxy resin is injected to the system. In Fig.3.2. a schematic representation of vacuum assisted resin transfer molding technique and the set-up used during the manufacturing of hybrid plates in this study is illustrated.



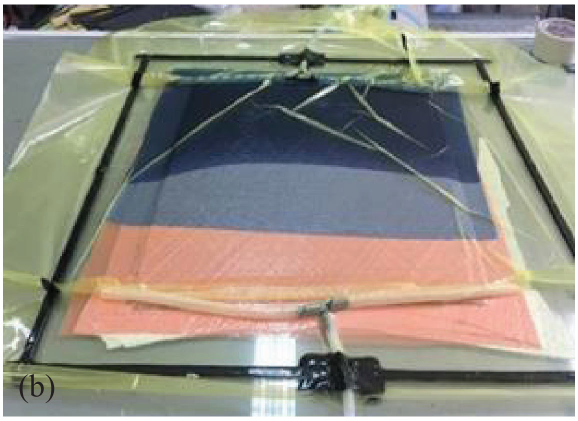


Figure 3.2.(a) A schematic representation of vacuum-assisted resin transfer molding technique (Source: Dong 2008) and (b) The set-up used in the manufacturing of hybrid laminates

After the resin cured completely, demolding of the manufactured plates from vacuum and post-curing them in an oven at 60 ºC for 16 h were performed, respectively.

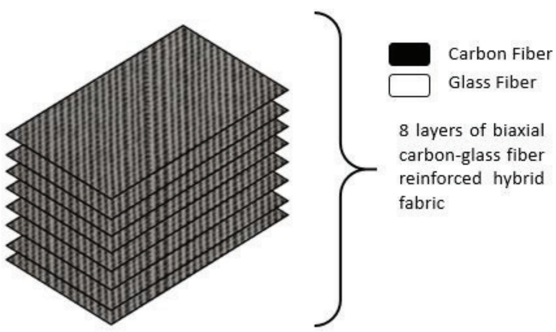


Figure 3.3. Schematic representation of manufactured plate

Post-cured plates were cut into requested sizes by using water-cooled diamond saw. The thicknesses of prepared samples were in the range of 6.71 to 7.08 m, with an average of 6.83 mm. One of the plates was cut in order to have cross-ply [0º /90º] configuration and another one was cut to have angle-ply [±45º] configuration.

3.3. Determination of Constituents' Contents

Fiber contents of the hybrid composite plates were evaluated by using matrix digestion test in accordance with ASTM D3171-99 standard (ASTM D 3171 1999). Digestion was performed on three samples for each configuration as recommended in the standard. Samples were cut by using water-cooled diamond saw. They were separately placed in beakers. Then, approximately 20 mL sulfuric acid added to beakers and the system was placed on a hot plate. When the solution became dark, approximately 35 mL hydrogen peroxide added in order to oxidize the resin. With the addition of hydrogen peroxide, the color of solution became white and the carbon and glass fibers were floated. At the end of the test, the matrix digested, and the fibers are left in the beaker. Hence, the content of matrix was calculated according to the results of this test. In order to determine carbon and glass contents separately, burn out at 800 ºC was performed on the samples that were subjected matrix digestion test before. Since carbon fibers are flammable, after burn-out, only glass fibers were left in the crucibles. Fig.3.4. shows the carbon-glass fibers after matrix digestion test and glass fibers after burn-out.

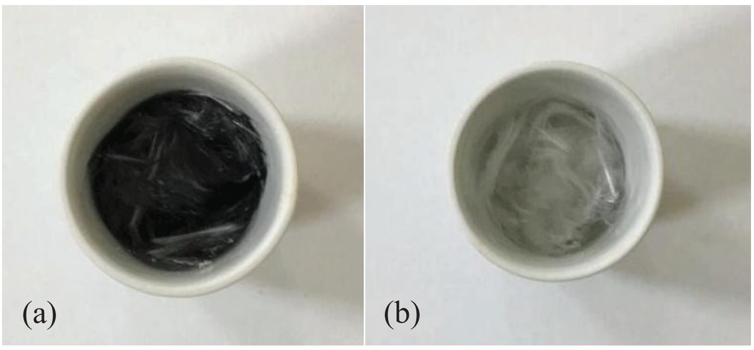


Figure 3.4. (a) Carbon and glass fibers after matrix digestion test, (b) Glass fibers after burn-out

3.4. Mechanical Testing

In order to compare the mechanical properties of composite samples in cross-ply and angle-ply configurations, a series of mechanical tests were performed on the samples. All tests were performed at ambient temperature in accordance with ASTM standards.

3.4.1. Tensile Test

The tensile strength and elastic modulus of hybrid composite plates were obtained by applying tensile tests in accordance with ASTM D3039 standard (ASTM D3039 2002). According to this standard five samples for each configuration were prepared with dimensions of 250 mm in length and 25 mm in width. Tests were carried out at ambient temperature and with a 2 mm/min cross-head speed. They were performed until the failure of samples. In Fig.3.5., a specimen under tensile test is illustrated.

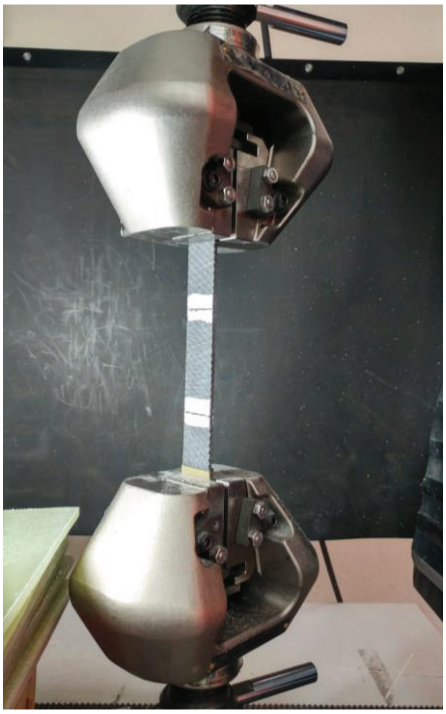


Figure 3.5. A sample under tensile test

3.4.2. Compression Test

The compressive strength and modulus of hybrid composite plates were obtained by applying compression tests with an antibuckling fixture. These tests were performed according to ASTM D6641 (ASTM D6641 2001). The dimensions of samples for this testing were 140 mm in length and 12.7 mm in width. The gauge length was 12.7 mm. Tests were run up to failure of the samples. In Fig.3.6., a specimen under compression test is illustrated.

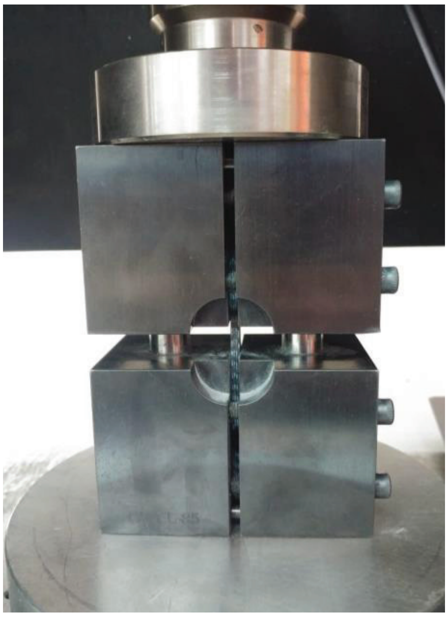


Figure 3.6. A sample under compression test with anti-buckling fixture

3.4.3. Three-Point Bending Test

The flexural strength and modulus of the carbon-glass/epoxy hybrid composite plates were determined by applying three-point bending tests. In these tests, load is applied to the middle of the samples. The upper surface of the sample was in compression and bottom surface was in tension. After the tests, force and displacement values were determined from the results.

Two ASTM standards are available in the literature in order to determine the flexural characteristics of reinforced and unreinforced plastics materials. One of the standards is ASTM D 790 and the another one is ASTM D 6272 . Since the latter test standard is related with four-point bending tests, in this study bending tests were performed in accordance with ASTM D790 (ASTM D 790 2003).

Tests were carried out at ambient temperature on a MTS servo hydraulic testing machine which was instrumented with a PC that allows control of the machine and monitoring of the data during testing. Tests were performed at a constant cross-head speed of 2.91 mm/min and tests were run up to failure of the samples. Five samples were tested as recommended in the standard. Fig.3.7. shows a specimen under three-point bending test.

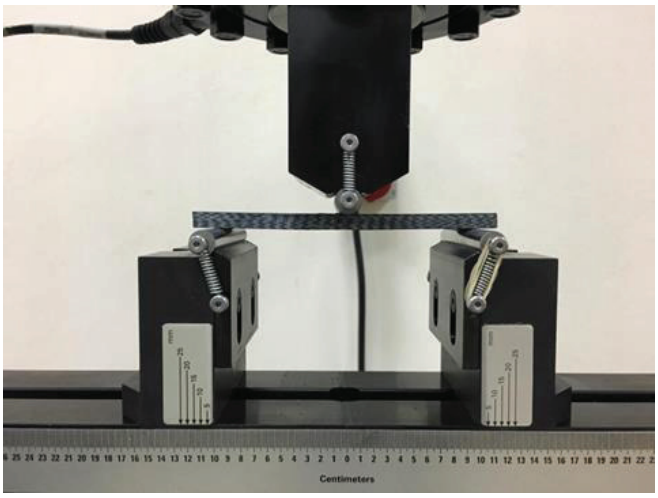


Figure 3.7. A sample under three-point bending test

Ultimate flexural strength and modulus of the tested samples were calculated by means of following equations:

$$\sigma_f = {}^{3PL}/_{2bd^2} \tag{3.1}$$

Where σ_f is flexural stress at ouer fiber, P is applied load at a given point, L is support span, b and d are width and depth of the tested beam, respectively.

$$E_B = {}^{L^3 m}/_{4bd^3} \tag{3.2}$$

Where E_B is modulus elasticity in bending, L is support span, m is slope of the tangent to the initial straight-line portion of the load-deflection curve, b and d are width and depth of the tested beam, respectively.

3.5. Fatigue

In order to compare fatigue performance of cross-ply and angle-ply samples three-point bending fatigue tests were carried out. The tests were carried out using the same specimen geometry with static three-point bending tests. Fig.3.8. shows schematic representation of specimen geometry. They were performed in load-controlled mode, stress ratio R was fixed at 0.1 and testing frequency was chosen as 3 Hz. The fatigue tests were performed at different stress levels for both configurations.

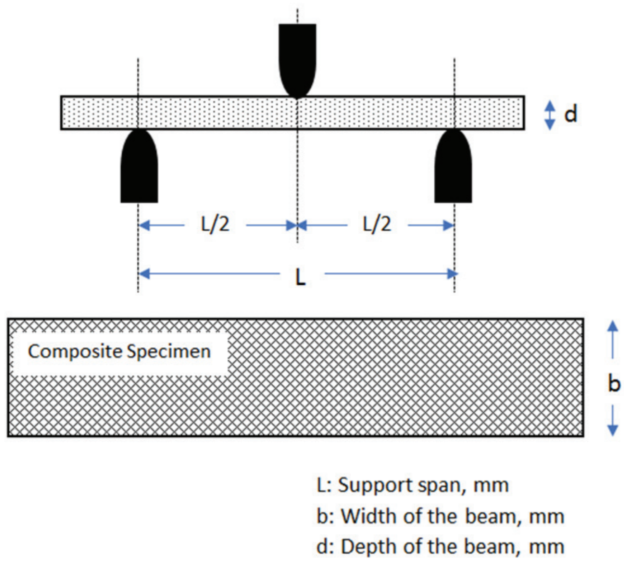


Figure 3.8. Geometry of samples

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, first results of the tensile, three-point bending and compression tests of angle-ply and cross-ply hybrid composites are discussed, respectively. At the end of the chapter, three-point bending fatigue tests results of both composites are compared. Their stiffness degradation curves under bending fatigue tests and S-N curves are constructed.

4.1. Tensile Tests

In order to determine the tensile strength and elastic modulus of the composites fabricated by biaxial intraply carbon-glass hybrid composites with vacuum-assisted resin transfer molding technique.

Tensile test results for samples those having angle-ply and cross-ply configurations are given in force-displacement curves. According to these results, their ultimate tensile strength and elastic modulus are calculated, and they are listed in the below table.

With regard to force-displacement curves, it can be said that cross-ply samples were able to withstand higher load levels. However, after the maximum loading level, a sudden fracture was observed for these samples. This described behavior can be seen clearly in the force-displacement curve of cross-ply samples. Angle-ply samples were able to carry smaller loads, almost fifteen times smaller than cross-ply samples because of shear failure of epoxy. The described behavior of the composites shows a good agreement with the work of Wharmby, Ellyin and Wolodko (Wharmby, Ellyin, and Wolodko 2003) in which the tension fatigue of glass fiber reinforced epoxy composites examined in two different configurations and with the work of Belingardi and Cavatorta (Belingardi and Cavatorta 2006). The results of latter literature work can be seen clearly from the figure given in Chapter 2.

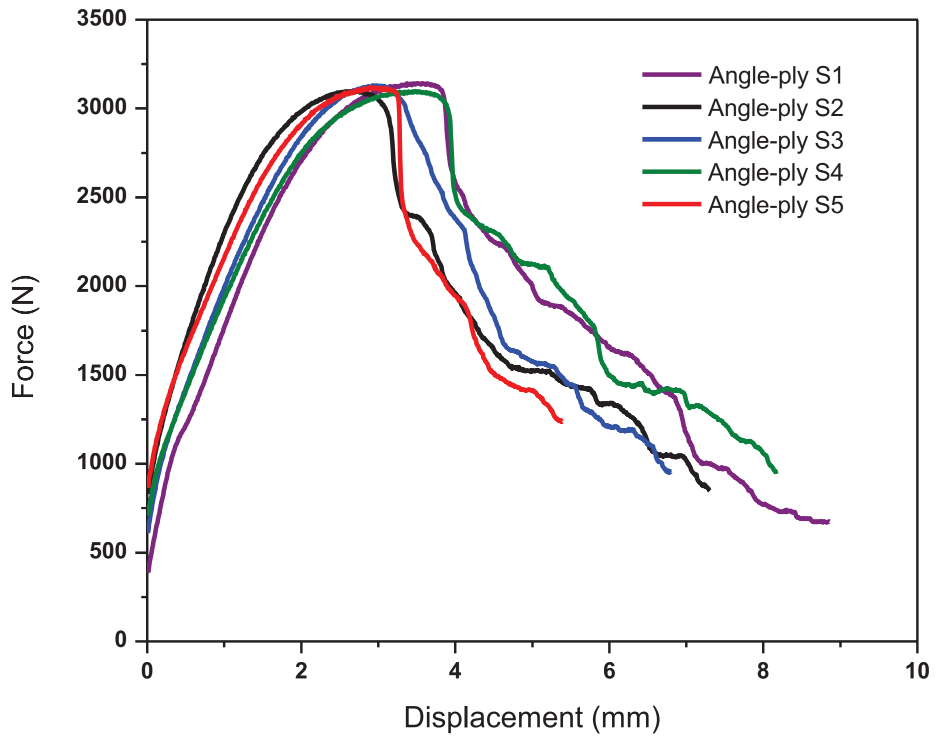


Figure 4.1. Force-displacement graph for angle-ply samples under tensile tests

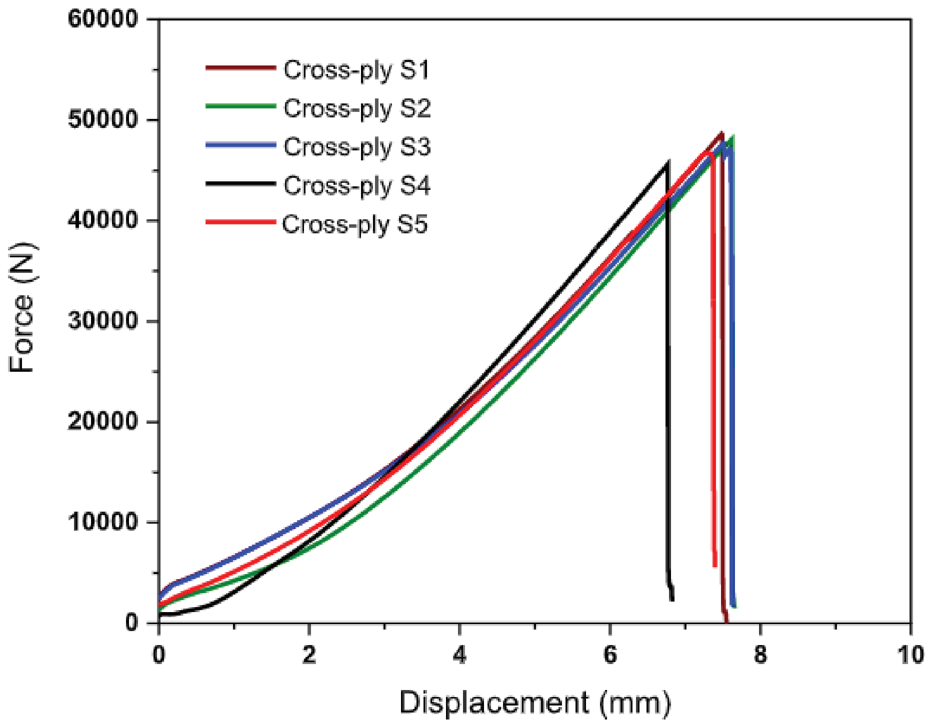


Figure 4.2.Force-displacement graph for cross-ply samples under tensile tests

According to the results listed in the Table 4.1., it can be observed that average ultimate tensile strength (UTS) of cross-ply samples which was calculated as 547.57 MPa is almost ten times greater than average UTS of angle-ply samples which was calculated as 52.47 MPa.

Table 4.1. Tensile properties of the hybrid composites

	Cross-ply		**Angle-ply**	
	UTS (MPa)	**E (GPa)**	**UTS (MPa)**	**E (GPa)**
Sample 1	557,65	38,52	51,87	5,63
Sample 2	559,70	30,33	52,76	6,64
Sample 3	542,35	33,31	51,72	6,03
Sample 4	541,34	37,32	52,50	6,37
Sample 5	536,79	30,71	53,49	7,19
Average	547,57	34,04	52,47	6,37
Standard Deviation	9,28	3,35	0,64	0,53

4.2. Compression Tests

In order to determine the properties of the composites fabricated by biaxial intraply carbon-glass hybrid composites with vacuum-assisted resin transfer molding technique under compression type of loading, compression tests were carried out on the samples.

Compression test results for samples those having angle-ply and cross-ply configurations are given in force-displacement curves. According to these results, their strength and elastic modulus are calculated, and they are listed in the Table 4.2. As visible from the table, five samples for each configurations were tested. Average ultimate compressive strength for cross-ply samples is calculated as 411.95 MPa and for angle-ply samples, it is calculated as 97.98 MPa.

With regard to force-displacement curves, it can be said that cross-ply samples were able to withstand higher load levels. However, after the maximum loading level, a sudden fracture was observed for these samples. This described behavior can be seen clearly in the force-displacement curve of cross-ply samples. Angle-ply samples were able to carry smaller loads, almost five times smaller than cross-ply samples.

Table 4.2. Compression properties of the hybrid composites

	Cross-ply		Angle-ply	
	UCS (MPa)	**E (GPa)**	**UCS (MPa)**	**E (GPa)**
Sample 1	389.76	3.81	94.66	1.62
Sample 2	387.21	3.99	104.69	2.31
Sample 3	417.09	4.96	100.47	2.02
Sample 4	432.39	4.48	97.11	1.97
Sample 5	433.34	3.61	92.97	2.25
Average	411.95	4.22	97.98	2.03
Standard Deviation	20.03	0.43	4.19	0.24

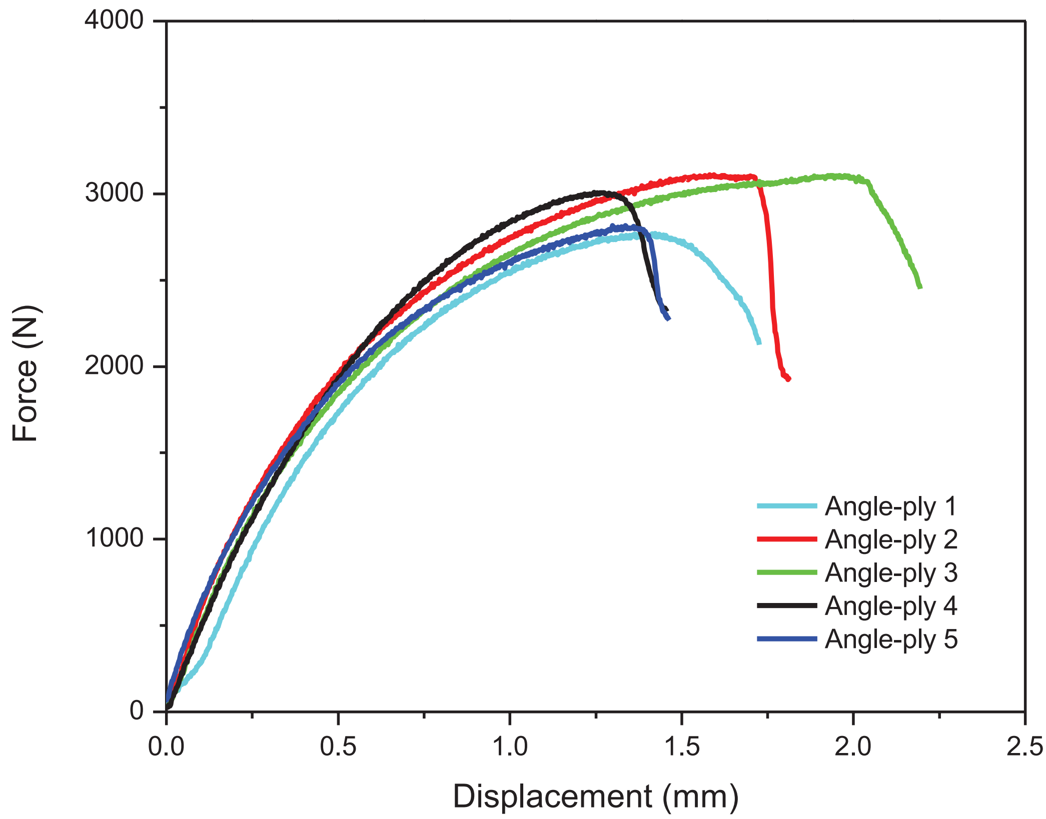


Figure 4.3. Force-displacement graph for angle-ply samples under compression test

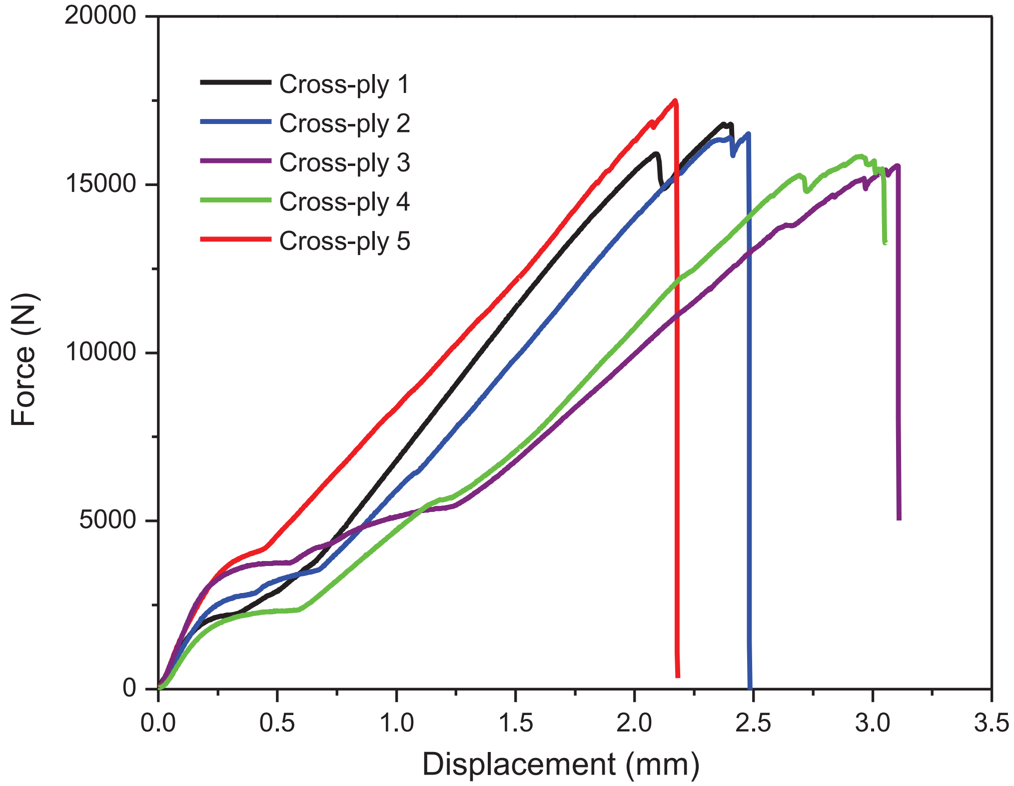


Figure 4.4. Force-displacement graph for cross-ply samples under compression test

4.3. Bending Tests

Static three-point bending tests were applied to hybrid carbon-glass fiber reinforced epoxy hybrid composite laminates by following the procedure recommended in ASTM D790 standard. Five samples for each configuration were tested in order to find average ultimate flexural strength of the composite laminates. According to the Fig.4.3. and Fig.4.4, until the first peak in stress-strain curves of samples, a linear behavior was observed for cross-ply samples, whereas a nonlinear behavior was observed for angle-ply samples due to rapid increase in displacement compared to very slow increase in applied load level. Table 4.3. summarizes the strength and elastic modulus of tested samples, their average and the standard deviations as revealed in static tests. Static tests result of samples were compatible with each other for both configuration types. Therefore, the obtained standard deviations were quite low. Average ultimate flexural strength of cross-ply samples was about four times greater than the UFS of angle-ply samples.

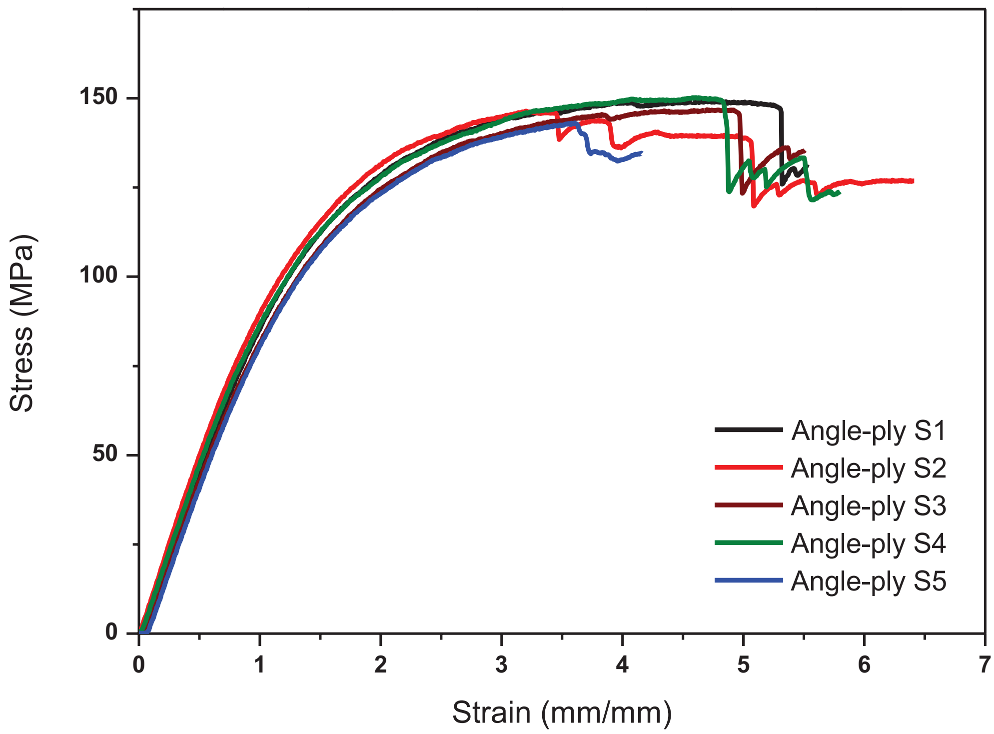


Figure 4.5. Flexural stress vs. strain graph for angle-ply samples

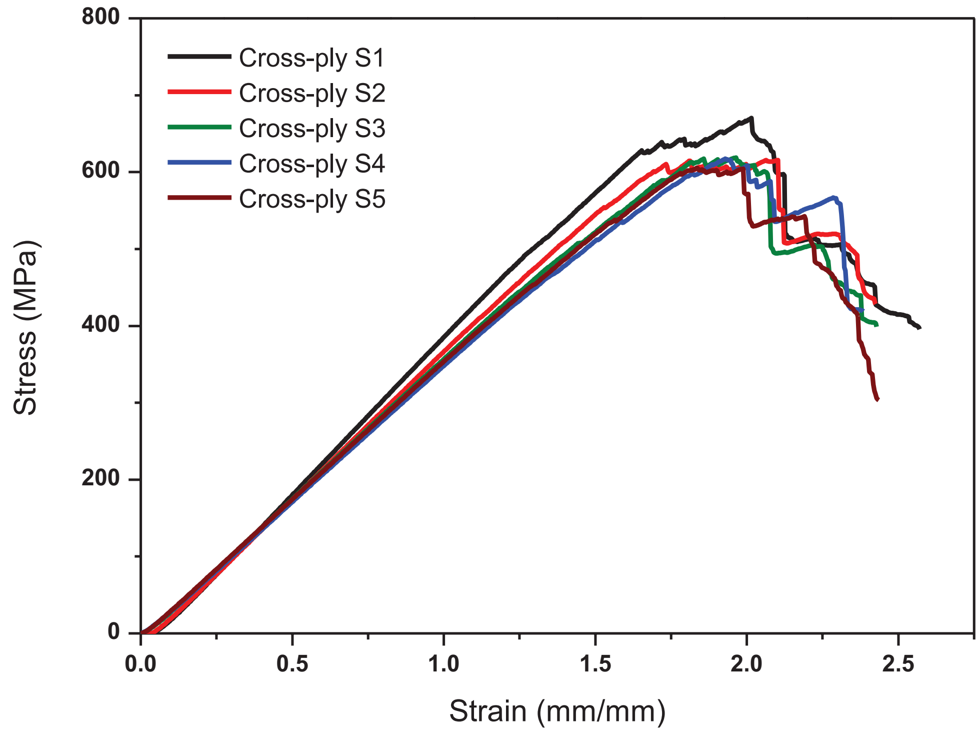


Figure 4.6. Flexural stress vs. strain graph for cross-ply samples

Table 4.3. summarizes the strength and elastic modulus of tested samples, their average and the standard deviations as revealed in static tests. Static tests result of samples were compatible with each other for both configuration types. Therefore, the obtained standard deviations were quite low. Average ultimate flexural strength of cross-ply samples was about four times greater than the UFS of angle-ply samples.

Table 4.3. Flexural properties of the hybrid composites

	Cross-ply		Angle-ply	
	UFS (MPa)	**E (GPa)**	**UFS (MPa)**	**E (GPa)**
Sample 1	636.35	40.85	149.25	7.84
Sample 2	610.45	38.57	146.44	7.01
Sample 3	616.49	36.29	146.83	7.45
Sample 4	617.25	34.84	150.19	7.91
Sample 5	605.01	35.31	143.09	7.53
Average	617.11	37.17	147.16	7.54
Standard Deviation	10.6	2.24	2.48	0.32

Angle-ply samples tend to deform more than cross-ply samples under flexural loading as illustrated in Fig.4.5. and Fig.4.6. It can be seen from the strain values which are given in their stress-strain curve under bending tests.

Figure 4.7. An angle-ply sample under bending test

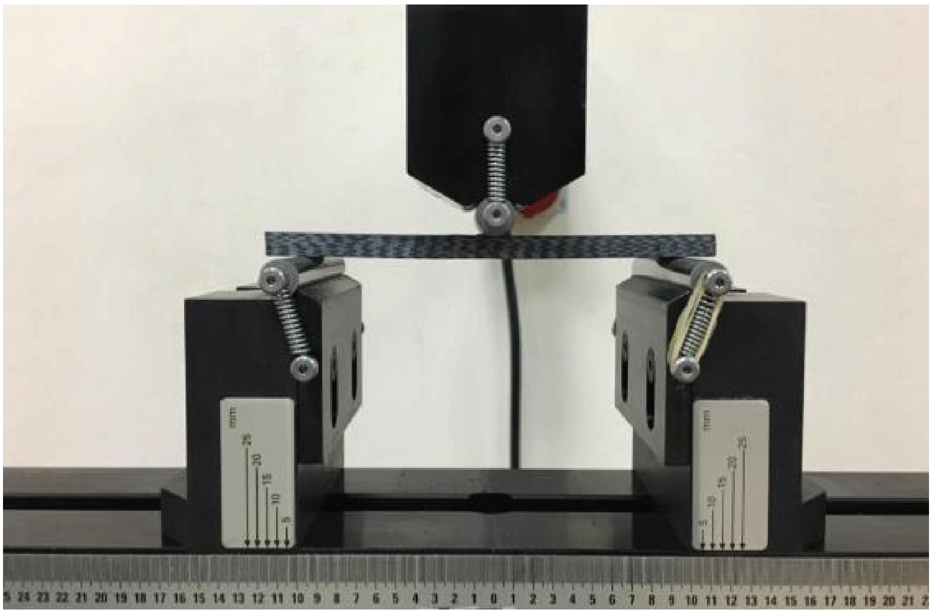


Figure 4.8. A cross-ply sample under bending test

The breaking patterns of hybrid samples in both configurations under bending are shown in Fig.4.7. As visible from the figure, deformation in samples were occurred parallel to fiber direction for both sample types.

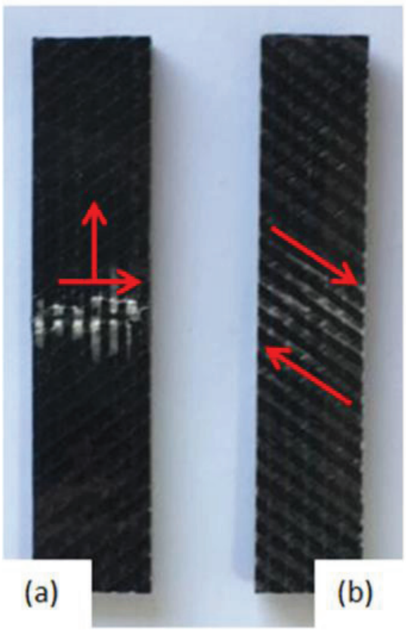


Figure 4.9. Breaking pattern of the hybrid samples: (a) cross-ply and (b) angle-ply

4.4. Fatigue Tests

As stated in literature (A. Bezazi et al. 2003; A. R. Bezazi et al. 2003; Cavatorta 2007; Belingardi, Cavatorta, and Frasca 2006; Belingardi and Cavatorta 2006), the follow-up of the degradation in stiffness is one of the most common techniques in order to evaluate the advancement of damage during fatigue loading conditions. To make a comparison between the fatigue performance of the hybrid laminates in cross-ply and angle-ply configurations, N_{10} failure criterion was chosen in this thesis.

To draw stiffness degradation curves, the displacement and cycle values from three-point bending fatigue test results were used. The degradations were calculated by dividing initial maximum displacement (d_0) with the maximum displacements for different fatigue cycles (d).

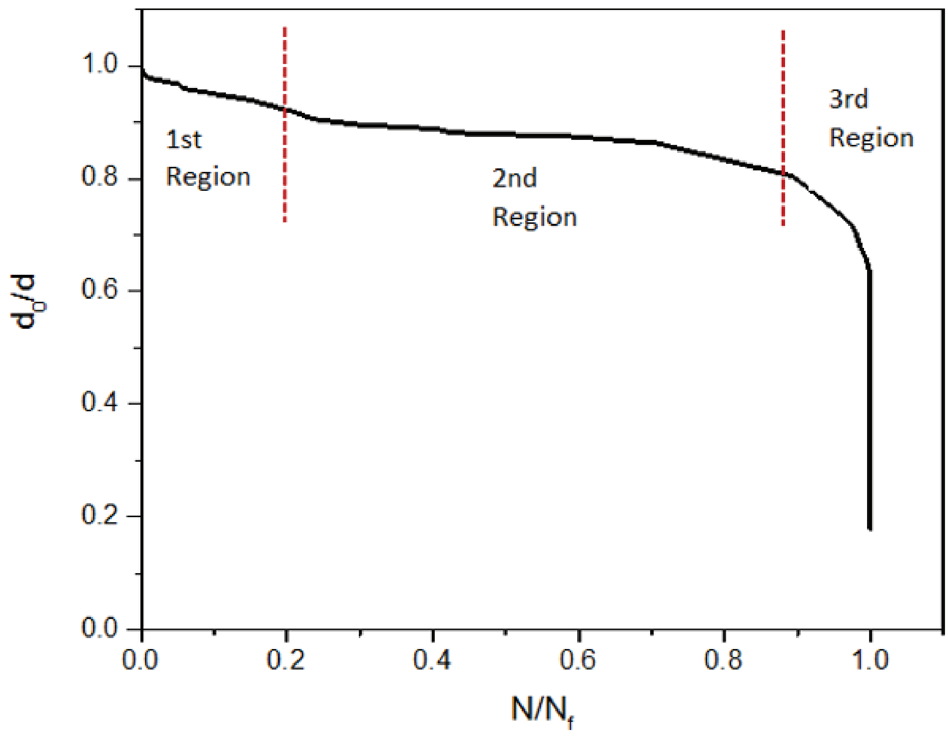


Figure 4.10. An exemplary stiffness degradation curve for cross-ply samples

Fig.4.10. represents an example of stiffness degradation curve in terms of number of cycles for cross-ply composite samples. As visible in the figure, the curve consists of three apparent regions which are similar to stiffness degradation curves

explained in the literature. In the 1st region, stiffness degrades rapidly due to matrix cracking. The rate of stiffness degradation gets smaller in the 2nd reigon and this slowdown is explained in the study of Bezazi and his coworkers (A. Bezazi et al. 2003) with stable propagation of cracks formed in the 1st region. Stiffness degrades suddenly up to failure of the samples and stiffness degradation rate gets far higher than previous regions due to fiber breakage.

Figure 4.11. represents an example of stiffness degradation curve according to number of cycles for both specimen types. As visible in the figure, the rate of stiffness degradation in first region much higher for angle-ply composites. This rate gets smaller in second region for both specimen types. In third region, by contrast with cross-ply samples, angle-ply samples suffer smaller losses in stiffness.

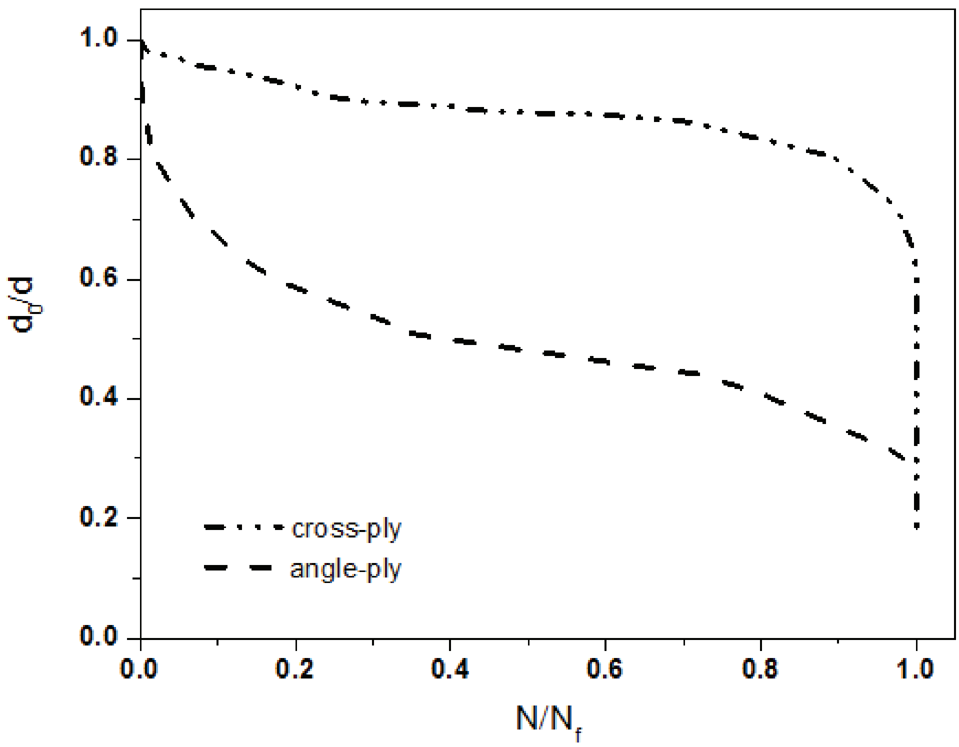


Figure 4.11. Exemplary stiffness degradation curves for angle-ply and cross-ply samples

Fig.4.12. shows the evolution of stiffness degradation of samples according to number of cycles in logarithmic scale, commonly used in studies related with fatigue of materials. As shown in the figure, fatigue tests were performed on cross-ply samples at

stress levels varied from 60 to 90% of UFS. Below 60% of UFS, tests were not performed because the samples didn't fail up to 10^6 cycles. At that specified stress level, 12% degradation in stiffness was observed. Considering the stiffness degradations observed in the samples and the applied stress levels, it can be interpreted that high stress levels are required to observe the damage initiation in cross-ply samples, but damage accumulates fast leading to the sudden failure of the samples. This observed behavior is in good agreement with the studies in literature related with fatigue behavior of composites.

Fig4.13. present the evolution of stiffness loss of angle-ply samples in terms of number of cycles in logarithmic scale. As visible in the figure, fatigue tests were performed on angle-ply samples at stress levels varied from 30% to 90% of UFS. Higher than 60% of UFS, stiffness degrades rapidly below 90% of initial stiffness. Therefore, fatigue tests at stress levels below than 60% of UFS were also performed on angle-ply samples.

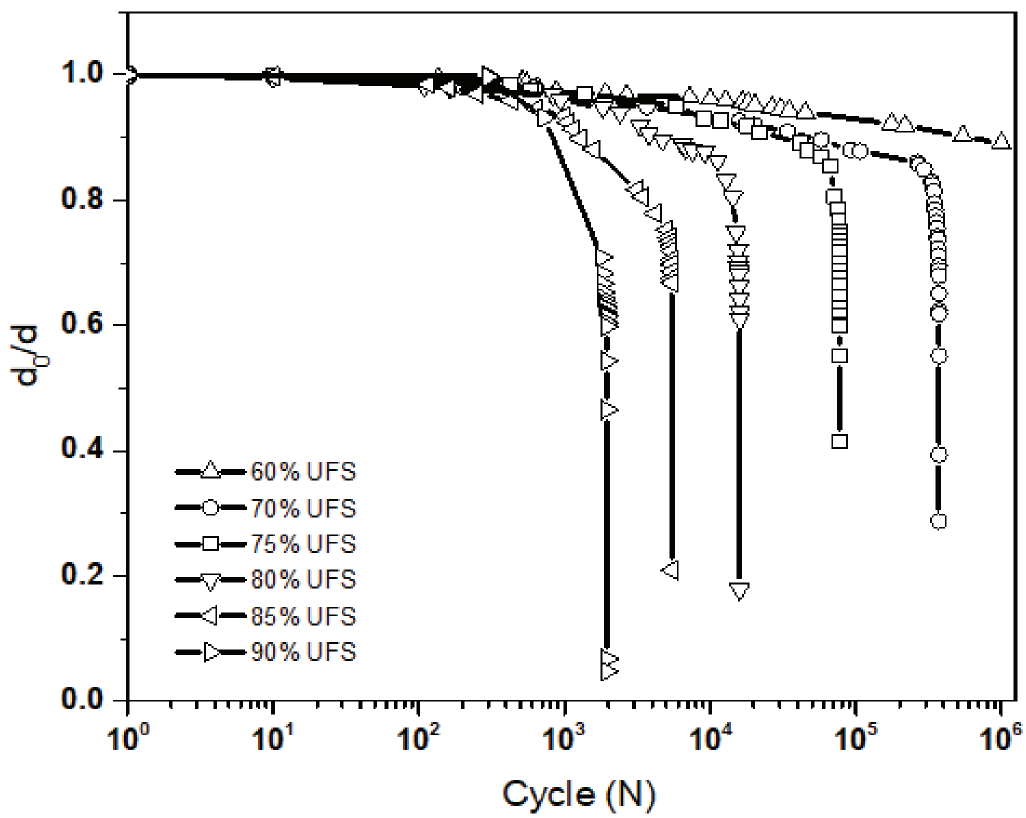


Figure 4.12. Stiffness degradation curves for cross-ply samples

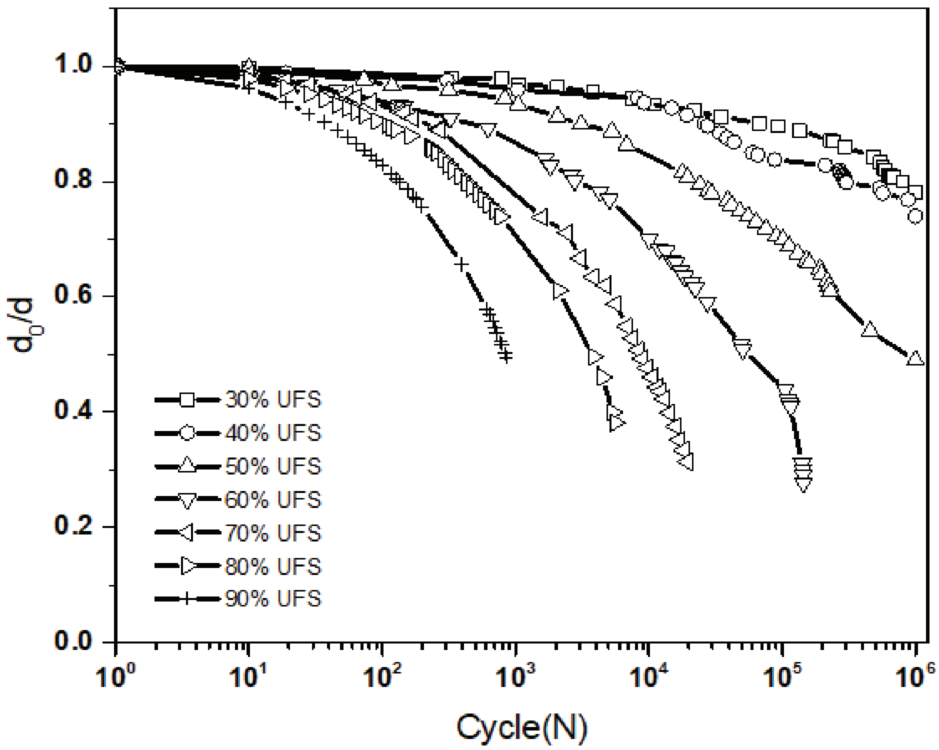


Figure 4.13. Stiffness degradation curves for angle-ply samples

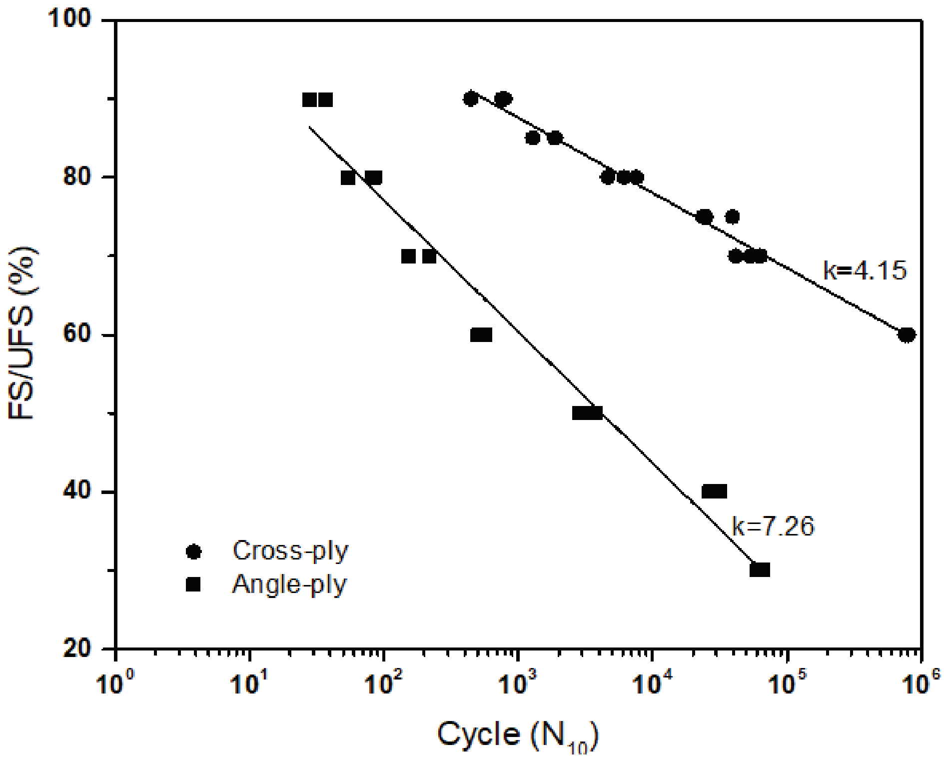


Figure 4.14. S-N curves for angle-ply and cross-ply samples

Fig.4.14 represents the Wöhler curve for the two configurations of hybrid laminate according to N_{10} failure criterion. The constructed curves illustrate the alteration of applied ultimate stress level according to number of cycles. As expected, fatigue life of the both laminates decrease as applied stress level increases. For same applied stress levels, cross-ply samples endured more. For instance, at 70% UFS cross-ply samples survived up to 10^4 cycles. However, angle-ply samples survived up to 10^2 cycles. Slopes of each curve, k, is also given in the figure. The value of slope is lower in the case of cross-ply samples (4.15) than the one of angle-ply samples (7.26). This difference between the slopes, affirms the rapid degradation in latter specimen type and it can be related with the different damage mechanisms within the two specimen types.

CHAPTER 5

CONCLUSIONS

Fiber-reinforced composite materials have been broadly used in most high-performance engineering applications such as aviation, military and automotive due to their outstanding characteristics compared to conventional structural materials for a long time. However, there has been a growing demand for higher performance composites than those composites which has been used over the past decades. Therefore, nowadays engineers and scientists are focusing intensively on developing stronger and lighter structural materials in order to follow current technologies for the structures having complex shapes such as wind turbine blades, airplane and automotive structures In accordance with this purpose, development of hybrid composites has become an important subject day after day.

The increasing usage of hybrid composites materials in given engineering applications requires information about their mechanical properties. Therefore, in literature there are studies related with their behavior under tension, compression and bending type of loadings.

The materials used in structural applications do not subject static loading at all times. Most commonly, they subject to cyclic loadings. Because of that reason, their performances under fatigue loading is a very important subject to consider. In literature, the performance of materials under flexural fatigue loading is generally obtained by monitoring the reduction in stiffness according to a chosen failure criterion. There are many available failure criteria in literature which can be selected according to the application. However, the most commonly used ones are N_5 and N_{10} which correspond to 5% and 10% reduction in stiffness.

The motivation of this thesis was to examine mechanical properties and three-point bending fatigue behavior of carbon-glass fiber reinforced epoxy hybrid composites in $[0°/90°]_8$ and $[\pm45°]_8$ configurations. Within the scope of the thesis, the hybrid composite plates were manufactured by using intraply carbon-glass hybrid fabric and epoxy resin with VARTM technique. The samples were prepared for mechanical tests in accordance with relevant ASTM standards. The constituents' content of manufactured plates was determined by applying matrix digestion in the solution of sulfuric acid and hydrogen peroxide. To examine and compare the mechanical properties of the hybrid composites, tensile, compression and bending tests were performed. Bending fatigue tests were also carried out on the samples to reveal their flexural fatigue behavior. The stiffness losses for angle-ply and cross-ply samples were investigated under fatigue loading according to N_{10} failure criterion. The experimental results revealed the following conclusions:

- According to results of tensile tests, it was observed that cross-ply samples were able to withstand higher load levels than angle-ply samples, but they failed with a sudden fracture. This observed behavior was not valid for angle-ply samples. In these samples, at lower load levels failure occurred because of shear failure of epoxy resin.
- In static three-point bending tests, for cross-ply samples a linear behavior was observed, whereas a nonlinear behavior was observed for angle-ply samples. Ultimate flexural strength of those samples was calculated around 615 MPa which was four times greater than the ultimate flexural strength of angle-ply samples.
- According to results of compression tests, it was observed that cross-ply samples can carry higher loads than angle-ply samples. The average compression strength of the cross-ply and angle-ply samples were calculated around 411 MPa and 97 MPa, respectively.
- Three-point bending fatigue performance of cross-ply samples is much better than the fatigue performance of angle-ply samples. They survived up to higher number of cycles than angle-ply samples. However, a sudden and sharp stiffness loss was observed for those samples after a point which is very close to failure of samples.
- Generally stiffness degradation curves consists of three distinct regions according to the studies in the literature. In the 1st region, stiffness degrades rapidly due to matrix cracking. The rate of stiffness degradation gets smaller in the 2nd region and this slowdown is explained with stable propagation of cracks formed in the 1st region. Stiffness degrades suddenly up to failure of the samples and stiffness degradation rate gets far higher than previous regions due to fiber breakage. According to results of three-point bending

fatigue tests which were carried out within the scope of thesis, it was found that rate of stiffness degradation in first and second regions was higher for angle-ply configurations. In final region, this rate was higher for cross-ply configuration so, no sudden failure was observed in $[\pm45°]_8$ samples.

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