LATERAL BUCKLING of LAMINATED COMPOSITES with DELAMINATION

MASTER of SCIENCE THESIS

HÜSEYİN ERSEN BALCIOĞLU

SUPERVISOR
ASSIST. PROF. DR. MEHMET AKTAŞ

Graduate School of Natural and Applied Sciences of Uşak University

JULY 2012

T.C.
UŞAK UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF MECHANICAL ENGINEERING

LATERAL BUCKLING of LAMINATED COMPOSITES with DELAMINATION

MASTER of SCIENCE THESIS

HÜSEYİN ERSEN BALCIOĞLU

UŞAK 2012

M. Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"LATERAL BUCKLING of LAMINATED COMPOSITES with DELAMINATION"** completed by **HÜSEYİN ERSEN BALCIOĞLU** under supervision of **ASSIST. PROF. DR. MEHMET AKTAŞ** and we certify that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

ASSIST. PROF. DR. MEHMET AKTAŞ **………………………………………..**

Supervisor, Department of Mechanical Engineering

This study was certified with unanimity by committee member as Master of Science Thesis at Department of Mechanical Engineering.

ASSOC. PROF. DR. YELİZ PEKBEY **………………………………………..**

Department of Mechanical Engineering, Ege University

ASSOC. PROF. DR. Halit GÜN **………………………………………..**

Department of Mechanical Engineering, Uşak University

Date: 13/07/2012

This thesis was certified as Master Science Thesis by board of director Uşak University Graduate School of Science Engineering and Technology

ASSIST. PROF. DR. MEHMET AKTAŞ **………………………………………..**

Director, Graduate School of Natural and Applied Sciences

THESIS DECLARATION

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions. This master thesis was completed under the guidance of Assist. Prof. Dr. Mehmet AKTAŞ, at the Graduate School of Natural and Applied Sciences of Uşak University.

Hüseyin Ersen BALCIOĞLU

LATERAL BUCKLING of LAMINATED COMPOSITES with DELAMINATION

(M.Sc. Thesis)

Hüseyin Ersen BALCIOĞLU

UŞAK UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

July 2012

ABSTRACT

Fiber reinforced laminated composite materials have superior mechanical properties, like corrosion resistance, flexibility, high impact strength, low weight/volume ratio compared, with the metallic materials. Therefore, laminated composite materials have been alternatively used in air, sea and land transportation vehicles instead of metallic materials.

The main objective of this study is to investigate effect of delamination damage, which occurs in laminated composite, on lateral buckling load of composite materials. For this purpose, woven E-glass/epoxy laminated composite plates with eight layers were produced. In order to create the delamination damage teflon film having 12 μm thickness, was used. Delamination was located mid-plane of laminated composite plate.

In the study, two different delamination shapes were used as rectangular and circular. To investigate the effect of delamination, which have different shape and size, on lateral buckling load of laminated composites; test specimens were classified in two different categories which consist of different twenty two series. In the first of these categories (eight different series), the rectangular and circular delamination areas were selected as fixed and 600 mm^2. In this category, the aspect ratio of square delamination and also minor and major axis ratio of circular delamination were taken as a/b=1, 2, 3 and 4. As for that in the second category (fourteen different series), the ratios of square and circular delamination were selected as a/b=0.5, 0.6, 0.75, 1, 1.3, 1.6, and 2. To better understanding effect of delamination on the lateral buckling behavior, the experimental and numerical results of specimens with and without delamination were compared with each other's. Ansys 12.1 software was used to investigate the lateral buckling behavior of laminated composites with delamination. Obtained numerical results have good agreement with experimental results.

In addition, Weibull distributions, which have 95% reliability, were obtained with using critical buckling load values. ReliaSoft Weibull 8++ program was used for statistical study.

Keywords: Lateral buckling, delamination, laminated composites, finite element analysis, Weibull distribution.

Science Code: 625.01.00.

Number of Page: 119

Supervisor: Assist. Prof. Dr. Mehmet AKTAŞ

DELAMİNASYONLU TABAKALI KOMPOZİTLERİN YANAL BURKULMASI

(Yüksek Lisans Tezi)

Hüseyin Ersen BALCIOĞLU

UŞAK ÜNİVERSİTESİ

FEN BİLİMLERİ ENSTİTÜSÜ

Temmuz 2012

ÖZET

Metalik malzemelere kıyasla fiber takviyeli tabakalı kompozit malzemeler; korozyon dayanımı, esneklik, yüksek darbe dayanımı ve düşük ağırlık/hacim oranı gibi daha üstün mekanik özelliklere sahiptirler. Bundan dolayı tabakalı kompozit malzemeler; hava, deniz ve kara taşıtlarında metalik malzemelere alternatif olarak kullanılmaya başlanmıştır.

Bu çalışmanın temel amacı tabakalı kompozitlerde meydana gelen delaminasyon hasarının kompozit malzemelerin yanal burkulma yüküne olan etkisini incelemektir. Bu amaçla sekiz tabakalı dokuma cam elyaf/epoksi kompozit plakalar üretilmiştir. Delaminasyon hasarını oluşturmak için 12 μm kalınlığa sahip teflon film kullanılmıştır. Delaminasyon tabakalı kompozit plakaların orta düzlemine yerleştirilmiştir. Çalışmada kare ve dairesel olmak üzere iki farklı delaminasyon şekli kullanılmıştır. Farklı şekil ve boyutlardaki delaminasyonun tabakalı kompozitlerin yanal burkulma yüküne etkisini incelemek için, delaminasyona sahip deney numuneleri yirmi iki farklı seri içeren iki farklı kategoride sınıflandırılmıştır. Bu kategorilerin ilkinde (sekiz farklı seri), kare ve dairesel delaminasyonun alanı sabit ve 600 mm^2 olarak seçilmiştir. Bu kategoride, kare delaminasyonun kenarları oranı ve dairesel delaminasyonun küçük ve büyük eksenleri oranı a/b=1, 2, 3 ve 4 olarak alınmıştır. İkinci kategoride ise (on dört farklı seri); kare delaminasyonun kenarları oranı ve dairesel delaminasyonun küçük ve büyük eksenleri oranı a/b=0.5, 0.6, 0.75, 1, 1.3, 1.6 ve 2 olarak seçilmiştir. Delaminasyonun yanal

burkulma davranışına olan etkisini daha iyi anlamak için delaminasyonlu ve delaminasyonsuz numunelerin deneysel ve nümerik sonuçları birbiriyle karşılaştırılmıştır.

Delaminasyonlu tabakalı kompozitlerin yanal burkulma davranışını nümerik olarak incelemek için Ansys 12.1 sonlu elemanlar programı kullanılmıştır. Elde edilen nümerik sonuçlar deneysel sonuçlarla uyumlu çıkmıştır.

Ayrıca yanal burkulma yük değerleri kullanılarak %95 güvenilirliğe sahip Weibull dağılımları elde edilmiştir. İstatistiki çalışma için ReliaSoft Weibull 8++ programı kullanılmıştır.

Anahtar Kelimeler: Yanal burkulma, delaminasyon, tabakalı kompozit, sonlu elemanlar analizi, Weibull dağılımı.

Bilim Kodu: 625.01.00.

Sayfa Adedi: 119

Tez Yöneticisi: Yrd. Doç. Dr. Mehmet AKTAŞ

ACKNOWLEDGEMENTS

First of all, I am deeply indebted to Assist. Prof. Dr. Mehmet AKTAŞ, who has never been false in his advices through this master thesis. He has patiently supervised my studies and has shared his experiences in a friendly atmosphere.

Special thanks to also extend to my dissertation committee members, Assoc. Prof. Dr. Yeliz PEKBEY and Assoc. Prof. Dr. Halit GÜN, for their academic support and encouragement through my theses.

I would like to thank Assist. Prof. Dr. Yusuf ARMAN from Dokuz Eylül University for his prevent and patience.

I would also like to express my appreciation for the financial support of Uşak University Scientific Research Coordination Agency (BAP, Project Number: 2012 TP/005).

I am very grateful to my parents for their understanding, support and love. They endeavored very hard to support me all over past years.

Finally, I would like to thank my wife. Without her help and love, the completion of this dissertation is impossible. For this reason, this master thesis is dedicated to her.

Hüseyin Ersen BALCIOĞLU

INDEX

LIST OF FIGURES

LIST OF TABLES

CHAPTER ONE: INTRODUCTION

1.1. Introduction

Composite materials are constructed of two or more materials, commonly referred to as constituents, and have characteristic derived from the individual constituents. The mechanical and physical properties of the composite can be clearly controlled by changing properties of their constituent material. These constituent materials are comprised of two parts in the composite materials. A stiff part which is named fiber implanted in a less stiff continuous part which is named matrix. The most commonly used in production of fibers are glass, carbon, aramid, boron, alumina, polyolefin, nylon and asbestos. Common used matrixes for composites are mud, cement, polymers, metals and ceramics. For laminated composite, generally polymer resins are chosen as a matrix material. Polymer resin is a clear liquid plastic product that hardens to create a thick, durable, glossy coating. Polymer resins for composites can be broken down into two major categories, thermoset and thermoplastic. Thermoset resins which consist of two components generally come in liquid form, and when mixed with a catalyst, a chemical reaction occurs forming a solid. While connective component binds fibers, catalyst component provides the hardening of connective component. Thermoset molecules crosslink with each other during curing, thus once cured, they cannot change. Common types of thermoset resins are epoxy, polyester, vinylester, polyurethane, and phenolic. Thermoplastic resins have molecules that are generally not cross-linked, meaning, the resin can be repeatedly melted and reused. Usually, no chemical change occurs when thermoplastic is cured. Thermoplastic resin usually starts out in solid pellet form, and changes shape with the addition of heat and pressure. Common types of thermoplastic resins are polyamide (PA or Nylon), polybutylene terephthalate (PBT), polyethylene terephthalate (PET), polycarbonate (PC), polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC).

With stacked of fiber lamina, which take together with matrix, compose laminated composite. In the world of composites, laminated composites are the most widely used composites by the means of the familiar manufacturing and performance characteristics.

Laminated composites are usually classified into three categories based on their matrix material as polymer matrix composites (PMCs), metal matrix composites (MMCs) and ceramic matrix composites (CMCs). Also we can classify by the structures of reinforcement as particulate and type of fiber (short fiber, long fiber, continuous fiber, discontinuous fiber and weave).

In the recent years, application of composite materials has been increasingly common in the field of engineering. Composite materials have countless advantages more over conventional materials by the agency of their superior properties like high strength and stiffness to weight ratio, strength of corrosion, design flexibility, improved fatigue life, fabrication and life cycle cost. Because of these specific properties; composites have used in industry of buildings, ship, aircraft, and military as a structures material.

In spite of the fact that composite materials have superior properties, none of materials are perfect. When composites are exposed to extreme of force, impact, and pressure, they can be damaged. Failures can be occurred the internal structure of the material during the manufacturing of laminated composites. In laminated materials, repeated cyclic stresses, impact, and so on can cause layers to separate which is named delamination, so that significant loss of mechanical toughness has been observed. Delamination is a mode of failure for composite materials.

With innovation of design, usages of slender materials are gradually increased in the structures. This usage seems economically, in fact brings a lot of buckling problem for solving. When a structure which subjected to compression, undergoes visibly large displacements transverse, then we can say it buckled. Buckling may be demonstrated by pressing the opposite edges of a flat sheet of cardboard towards one another. Buckling plays a very important role in the design and produce composite material. Optimum design of structures against buckling may be accomplished by finding the minimum weight design of a structure, which satisfies the prescribed buckling load constraint. On the other hand, it can be maximized the fundamental buckling load for a structure while keeping its weight or volume constant. Alternatively, it may be to maximize the buckling load for a structure with a given volume, mass, or weight. According to form of load, types of buckling can be occurred as flexural-torsional buckling, lateral-torsional buckling, lateral buckling, plastic buckling, and dynamic buckling in the material.

A type of buckling is laterally buckling that often seen in thin-walled structures which are not supported as laterally. When a simple beam is loaded in flexure, the top side is in compression, and the bottom side is in tension. When a slender member is subjected to an axial force, failure takes place due to bending. If the beam is not supported in the lateral direction (i.e., perpendicular to the plane of bending), and the flexural load increases to a critical limit, the beam will fail due to lateral buckling of the compression flange. Therefore the lateral buckling of fiber reinforced laminated composite has been an important area of research for a longtime. Researchers have reported a large of studies as experimental, numerical, both of experimental and numerical or analytical in literature in this area. Some of the important studies are introduced below.

1.2. Literature Review

When the applied load on structure goes beyond maximum buckling load of material can withstand structure damage with buckle. Composite beams, which are not supported perpendicularly, the axis of bending have been exposed to lateral buckling. As a result of buckling; types of failure can be occurred as matrix cracks, delaminations or fiber cracks. Considerable amounts of researcher have investigated to understand lateral buckling of materials. Sapkas and Kollar, presented the stability analysis of composite beams which have different cross-section, analytically. In this study; they have derived an explicit expression for the lateral-torsional buckling load of composite beams [1]. Lee studied lateral buckling of thin-walled composite beams with monosymmetric sections. In order to make this study; the analytical model which extended to a geometrically nonlinear model for thin-walled laminated composites with arbitrary open cross-section and general laminate stacking sequences is developed by the author [2]. Kim and coworkers proposed an improved numerical method to evaluate the exactly element stiffness matrix for lateral buckling analysis of thin walled composite I and channel section beams with symmetric and arbitrary laminations subjected to end moments. For this purpose, they developed the bifurcation type buckling theory of thin-walled composite beams subjected to pure bending [3]. Lopatin and Morozov formulated an equation by using the generalized Galerkin method for a buckling problem of the cantilever circular cylindrical composite shell subjected to uniform external lateral pressure. Also they verified the analytical results with finite element method [4]. Lee and coworkers studied lateral buckling of a laminated composite I-section beam subjected to various types of loadings analytically. In addition, they discussed the effects of the location of applied loading on the buckling capacity [5]. Machado and Cortinez investigated the effects of the in-plane prebuckling deformations as well as the effect of shear flexibility on the lateral buckling of bisymmetric thin-walled composite beams, analytically. They used the Ritz variation method in order to discretize the governing equation [6].

Lee and Kim studied the lateral buckling of a laminated composite beam with channel section. They derived general analytical model based on the classical lamination theory, and accounts for the material coupling for arbitrary laminate stacking sequence configuration and various boundary conditions [7]. Attard and Kim studied lateral buckling of beams with shear deformations using hyper elastic formulation. In their study, they derived equilibrium for the lateral buckling of a prismatic straight beam [8]. Japón and Bardudo performed a non-linear plastic analysis of steel arches under lateral buckling [9]. Pi and coworkers have performed nonlinear inelastic finite element model for analyzing the lateral buckling behavior of cold-formed Z-section beams. The method includes the effects of web distortion, the rotation of the yielded cross-section, the prebuckling in-plane deflections, the initial crookedness and twist, the residual stresses, material inelasticity, and the lipped flanges [10]. Wang and Li examined the lateral buckling of thin walled members with shear lag using spline finite element method. They developed a spline finite element method, based on the displacement variation principle in their study [11]. Pi and Trahair have investigated inelastic lateral buckling strength and design of steel arches under general loading. For this intention, they used an advanced nonlinear inelastic finite element method [12]. Ascione and coworkers investigated a numerical model, which is capable of taking into account the contribution of shear deformation, on the lateral buckling of fiber reinforced plastic (FRP) pultruted beams with open cross-sections. However; they adopted a more general approach in order to analyze different types of loads and constraint [13]. Trahair investigated the lateral buckling strength of steel I-section monorail beams. He used finite element computer program in order to analyze the elastic buckling of monorails and simple closed form approximations [14]. Wang and Li, studied a closed form solution for a simply supported I beam subjected to uniform moment. They used Galarkin's method of weighted residuals to propose an approximate solution [15]. Vaz and Patel studied lateral buckling of bundled pipe systems for high-temperature products which use in the oil and gas industry [16].

Ohga and coworkers examined effects of the lateral pressure and reduced stiffness buckling strength of sandwich cylindrical shell by using finite element method [17]. Mohebkhah studied the nonlinear flexural-torsional analysis of I-beams using a three dimensional model in ANSYS. In this context, he investigated the effects of unbraced length and central off-shear center loading on the moment gradient factor in nonlinear behavioral zone [18]. Mohri and coworkers studied lateral buckling of thin-walled beam-column elements under combined axial and bending loads. They derived analytical solutions based on a non-linear stability model for simply supported beam-column elements with bi-symmetric I sections under combined load [19].

Limited amount of research has been conducted to assess the lateral buckling of laminated composite materials. Eryiğit and coworkers, investigated the effects of hole diameter and hole location on the lateral buckling behavior of woven fabric laminated composite cantilever beams both of experimentally and numerically. They used two different types of samples; which have a single circular hole and without hole. To supported experimental results, they simulated the tests with using finite element method [20].

As you know, delamination resulting from axial compressive loading on composite materials has an important place for researchers. In laminated composite materials; repeated cyclic stresses, impact and so on can cause layers to separate due to significant loss of mechanical toughness. So that, many researchers have investigated effect of delamination on composite materials. Gui and Li investigated the local buckling behavior of stitched composite laminates with an embedded elliptical delaminations near the surface. The results showed that stitching has a significant effect on buckling strains and buckling mode [21]. Hu and coworkers have investigated the buckling analysis of laminates with an embedded delamination numerically. They created delaminations by using Mindlin plate theory in finite element method. They demonstrated that the contact analysis is very important for buckling analysis [22]. Cappello and Tumino have investigated the buckling and post-buckling behavior of unidirectional and cross-ply laminated composite plates with multiple delaminations. For this purpose, they have performed linear and nonlinear finite element model. Numerical test results showed that the delamination length, position and stacking sequence of the plies influence the critical load of the plate [23]. Kim and Hong have presented a finite element model for studying the buckling and post buckling behavior of composite laminates with embedded delaminations. Results showed that the buckling load and post buckling behavior of composites depend on the buckling mode which is determined by the delamination size and boundary conditions [24]. Tafreshi have carried out a series of finite element analyses on the delaminated composite. He diversified the delamination thickness and length, material properties and stacking sequences. He compared the results with the results of previous experimental study [25]. Toudeshky and coworkers have studied a numerical investigation on the buckling of composite laminates containing delaminations under compressive load. They developed a nonlinear computer code to handle the numerical produce of delamination buckling growth using layer wise-interface elements [26].

Aslan and Şahin have studied the effects of the delaminations size on the critical buckling load and compressive failure load of E-glass/epoxy composite laminates with multiple large delaminations. Also, in order to support their study, they used Ansys finite element program. Their test results exhibited that the longest and near-surface delamination size influences the buckling load and compressive failure load of composite laminates [27]. Hwang and Liu have investigated the behavior of laminated composite with multiple delaminations under uniaxial compressions. They supported their nonlinear study with finite element model including contact elements to prevent the overlapping situation. Their results indicate that, the beneath delaminations have no significant effects on the buckling stress [28]. Arman and coworkers have invstigated the effect of a single circular delamination around the circular hole on the critical buckling load of laminated composites experimentally and numerically. They obtained good agreement between the numerical and experimental results [29].

1.3. Thesis Outline

The main purpose of this study is to investigate the effect of delamination on lateral buckling behavior of laminated composited plates, experimentally and numerically. In this context; the shapes of delaminations have been varied as square, rectangular, circular and elliptical. The square aspect ratio and circular minor and major axis ratio were varied for obtaining rectangular and elliptical delamination shapes. This diversify was made totally eleven different a/b aspect ratio in two different categories which consist of twenty two series. In the first of these categories, there were eight different series of specimens with square and circular delamination which included four different a/b ratio (1, 2, 3, 4) and fixed 600 mm^2 area. As for that in the second category, fourteen different series of specimens with square and circular delamination which have seven fixed a/b ratio (0.5, 0.6, 0.75, 1, 1.3, 1.6, 2). To better understanding effect of delamination on lateral buckling, experimental and numerical results of test specimens with delamination were compared experimental and numerical results of test specimens without delamination.

To supported result of experimental tests, finite element analysis has been performed using finite element software Ansys 12.1. Also, Weibull distributions, which have 95% reliability, were achieved with using critical buckling load values which obtained from lateral buckling test. To carry out statistical study, ReliaSoft Weibull 8++ program was used.

This thesis is organized into seven chapters. Chapter two has included issue of composite materials, information about buckling and effect of delamination on buckling behavior. Chapter three has talked about manufacturing method of laminated composite with delamination. Also determination of mechanical properties for laminated composites and achieving of lateral buckling test were given in this chapter. Weibull distribution analysis is presented in chapter four. Finite element study and results of lateral buckling have been explained in chapter five. Chapter six contains conclusions of numerical and experimental results and recommendations for further research. Finally chapter seven includes references which have been presented in thesis.

1.4. Sponsorship

This thesis sponsored by Uşak University Scientific Research Coordination Agency (BAP), (Project Number: 2012 TP/005). Woven glass fabrics have been bought from Emsal Boya Limited Liability Company. Matrix materials which consist of two components have been provided by Duratek Limited Liability Company. Teflon film which used to create delamination damage has been provided by Nalbantoğlu Ironmongery Company. Lateral buckling test fixture was produced by Gümüşoğlu Machine.

CHAPTER TWO: COMPOSITE MATERIALS and BUCKLING

2.1. Introduction to Composite Materials

Mankind has been aware of composite materials since several hundred years and applied innovation to improve the quality of life. For an example; people used mud bricks to make buildings ages ago. Used mud bricks consist of straw and mud. Mud hold together piece of straw; if piece of straws bring extra strength to mud. So that a new material, which have superior properties when compared properties of constituent materials, compose with combining of two different materials. If we adapt this example in nowadays; we put iron bar in cement when make building. The other composite material is wood which we used unconsciously for ages. Wood is composite material because it is compose of two distinct constituents. Stiff and strong fibers surrounded by a supporting structure of softer cells. As shown in examples, composite materials always find a place in life of human. Ashby [30], presents a chronological variation of the relative importance of each group from 10000 B.C. and extrapolates their importance through the year 2020 (Figure 2.1).

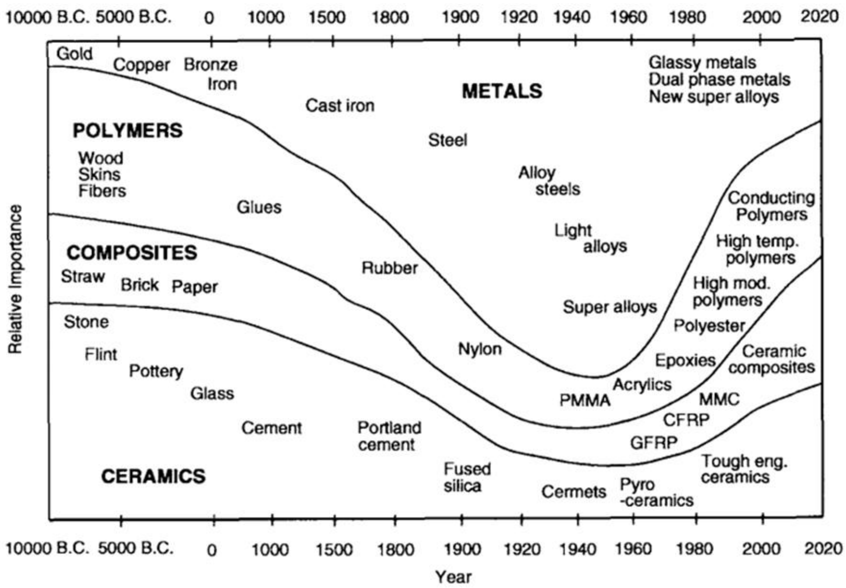


Figure 2.1 Relative importance of material development through history [30]

A composite material can be defined as a combination of two or more materials that results in better properties than those of the individual components used alone. The constituents of a composite are generally arranged so that one or more discontinuous phases are embedded in a continuous phase. The discontinuous phase is termed the reinforcement (fiber) and the continuous phase is the matrix. Table 2.1 shows mission of reinforcement and matrix phase in composite materials.

Table 2.1 Mission of reinforcement and matrix phase in composite materials

Reinforcement Phase	Matrix Phase
• Provides strength, stiffness, and other mechanical properties to the composite • Dominate other properties such as the coefficient of thermal expansion, conductivity, and thermal transport	• Gives a form to the composite material • Protects the reinforcements from the harmful effect of environmental • Distributes loads to the reinforcements • Contributes to properties that depend upon both the matrix and the reinforcements, such as toughness

The physical and mechanical properties of composites are depending on the properties, geometry and concentration of the constituents. Increasing the volume amount of reinforcements can improve the properties of a composite as strength and stiffness to a point. If the volume amount of reinforcements is too high there will not be enough matrix to keep them together, so they can be damaged with separate. On the other hand, the geometry of individual reinforcements and their arrangement within the matrix can affect the performance of a composite. So that the type of reinforcement and matrix, the geometric arrangement and volume fraction of each constituent must be taken into account when composite materials produce [31].

2.2. Comparison of Composite Materials with Metals

Selection of material is important in design. From selected material is anticipate to provide the desired strength. Of the late years composite materials are used widely in structures as alternative to metallic materials.

Some of the differences are given between composites and metals as below.

- Composites can provide structures that are 25-45% lighter than the conventional aluminum structures designed to meet the same functional requirements. This is due to the lower density of the composites.
- Depending on material form, composite densities range from 76876 to 111043 g/cm^3 as compared to 170835 g/cm^3 for aluminum. Some applications may require thicker composite sections to meet strength/stiffness requirements, however, weight savings will still result.
- Unidirectional fiber composites have specific tensile strength (ratio of material strength to density) about 4 to 6 times greater than that of steel and aluminum.
- Unidirectional composites have specific modulus about 3 to 5 times greater than that of steel and aluminum.
- Fatigue limit of composites may approach 60% of their ultimate tensile strength. For steel and aluminum, this value is considerably lower.
- Fiber composites are more versatile than metals and can be tailored to meet performance needs and complex design requirements such as aeroelastic loading on the wings and the vertical & the horizontal stabilizers of aircraft.
- Fiber reinforced composites can be designed with excellent structural damping features. For instance, they are less noisy and provide lower vibration transmission than metals.
- High corrosion resistance of fiber composites contributes to reduce life cycle cost.
- Composites offer lower manufacturing cost by reducing number of detailed parts and expensive technical joints required to form large metal structural

components. In other words; composite parts can eliminate joints/fasteners thereby providing parts simplification and integrated design.

- Long term service experience and durability of composite material are limited in comparison with metals [32].

In figure 2.2 the comparison of composites with steel and aluminum were given such as weight, thermal expansion, specific strength and stiffness and fatigue resistance.

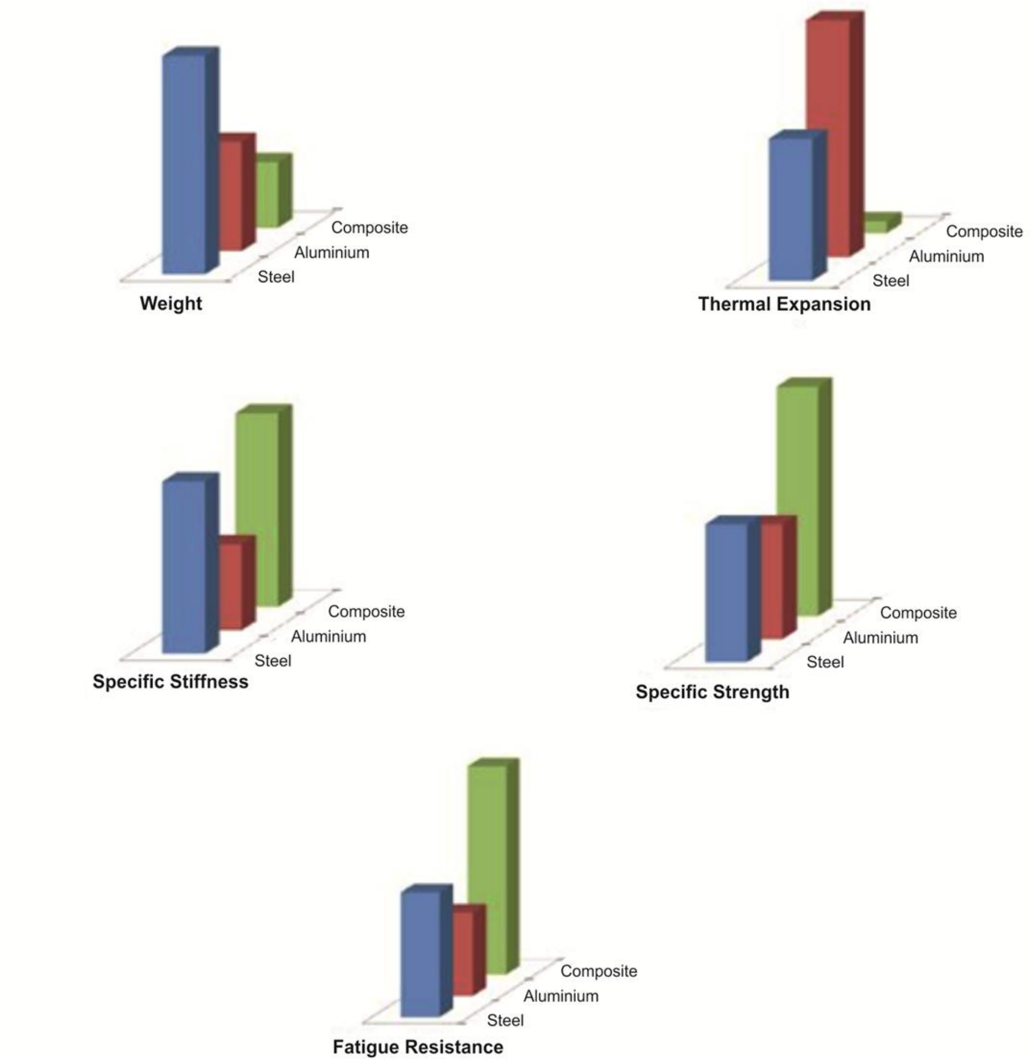


Figure 2.2 Comparison of composites with steel and aluminum

2.3. Reinforcement Properties

Reinforcement phase provides the strength and stiffness. Generally, reinforcement phase is harder, stronger and stiffer than the matrix phase. In the composite materials, the fibers or a particles usually are used as reinforcement. Figure 2.3 shows types of reinforcements in composite structures.

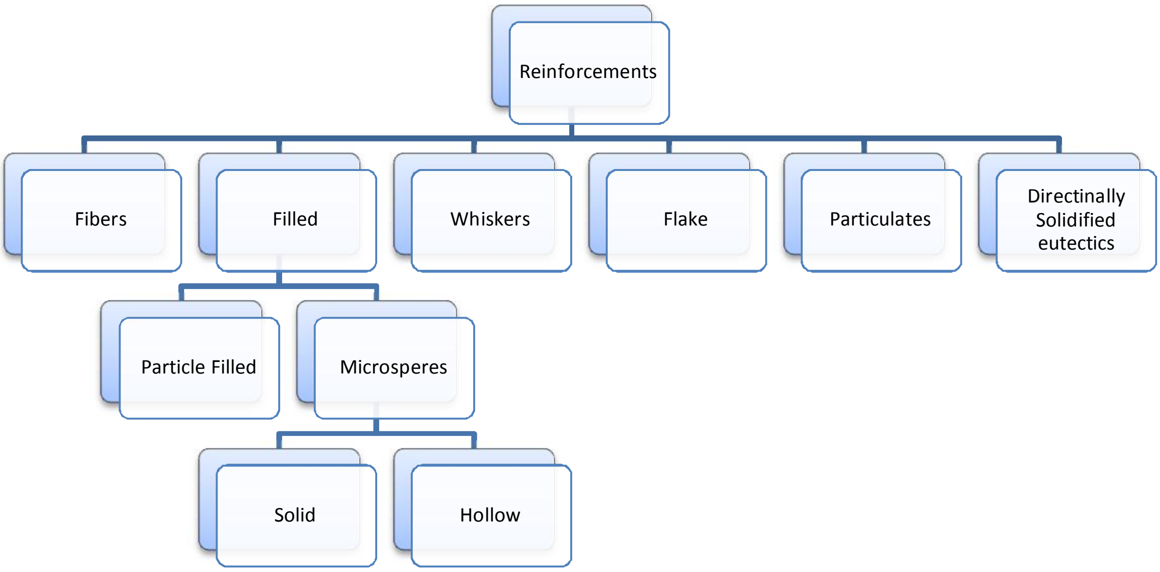


Figure 2.3 Types of reinforcements in composite structures

Fibers are the important class of reinforcements, due to satisfy the desired conditions and transfer strength to the matrix by influencing and enhancing their desired properties. Glass fibers are the earliest known fibers used to reinforce materials. Ceramic and metal fibers were subsequently found out and put to extensive use to render composites stiffer more resistant to heat. Fibers fall short of ideal performance due to several factors. The performance of a fiber composite is evaluated by its length, shape, and orientation, composition of the fibers and the mechanical properties of the matrix.

Organic and inorganic fibers are used to reinforce composite materials. Almost all organic fibers have low density, flexibility, and elasticity. Inorganic fibers are of high modulus, high thermal stability and possess greater rigidity than organic fibers.

Mainly, the following different types of fibers namely, glass fibers, silicon carbide fibers, high silica and quartz fibers, alumina fibers, metal fibers and wires, graphite fibers, boron fibers, aramid fibers and multiphase fibers are used to reinforce composite materials [33].

Single crystals grown with nearly zero defects are named whiskers. They are usually discontinuous and short fibers of different cross sections made from several materials like graphite, silicon carbide, copper, iron etc. Typical lengths are in 3 to 55 µm ranges. Whiskers can have extraordinary strengths up to 7000 MPa. Whiskers of ceramic material have high moduli, useful strengths and low densities. Specific strength and specific modulus are very high and this makes ceramic whiskers suitable for low weight structure composites. They also resist temperature, mechanical damage and oxidation more responsively than metallic whiskers, which are denser than ceramic whiskers. However, they are not commercially viable because they are damaged while handling [33].

Flakes are often used in place of fibers as can be densely packed. Flakes are not expensive to produce and usually cost less than fibers. Flakes have various advantages over fibers in structural applications. Flake composites have a higher theoretical modulus of elasticity than fiber reinforced composites. They are relatively cheaper to produce and be handled in small quantities [33].

Filled composites result from addition of filer materials to plastic matrices to replace a portion of the matrix, enhance or change the properties of the composites. The fillers also enhance strength and reduce weight. Fillers produced from powders are also considered as particulate composite. The filler particles may be irregular structures, or have precise geometrical shapes like polyhedrons, short fibers or spheres. The benefits offered by fillers include increase stiffness, thermal resistance, stability, strength and abrasion resistance, porosity and a favorable coefficient of thermal expansion.

2.4. Matrix Properties

Although it is undoubtedly true that the high strength of composites is largely due to the fiber reinforcement, the importance of matrix material cannot be underestimated as it provides support for the fibers and assists the fibers in carrying the loads. It also provides stability to the composite material. Resin matrix system acts as a binding agent in a structural component in which the fibers are embedded. When too much resin is used, the part is classified as resin rich. A resin rich part is more susceptible to cracking due to lack of fiber support, whereas a resin starved part is weaker because of void area sand the fact that fibers are not held together and they are not well supported. In a composite material, the matrix material serves the following functions:

- Holds the fibers together.
- Protects the fibers from environment.
- Distributes the loads evenly between fibers so that all fibers are subjected to the same amount of strain.
- Improves transverse properties of a laminate and also impact and fracture resistance of a component.
- Provide alternate failure path along the interface between the fibers and the matrix.
- Carry interlaminar shear.

The matrix plays a minor role in the tensile load-carrying capacity of a composite structure. However, selection of a matrix has a major influence on the interlaminar shear as well as in-plane shear properties of the composite material. The interlaminar shear strength is an important design consideration for structures under bending loads, whereas the in-plane shear strength is important under torsion loads. The matrix provides lateral support against the possibility of fiber buckling under compression loading. The interaction between fibers and matrix is also important in designing damage tolerant structures. Finally, the process ability and defects in a composite material depend strongly on the physical and thermal characteristics, such as viscosity, melting point, and curing temperature of the matrix.

The desired properties from the matrix are as follows:

- Reduced moisture absorption.
- Low shrinkage.
- Low coefficient of thermal expansion.
- Good flow characteristics to penetrate the fibers completely and eliminates voids in composite.
- Reasonable strength, modulus and elongation.
- Must be elastic for transferring the load to fibers.
- Should be easily processable in to the final composite shape.
- Dimensional stability.

As the load is primarily carried by the fibers, the overall elongation of a composite material is governed by the elongation to failure of the fibers that is usually 1-1.5%. A significant property of the matrix is that it should not crack. The function of the matrix in a composite material will vary depending on how the composite is stressed. For example, in case of compressive loading, the matrix prevents the fibers from buckling On the contrary, a bundle of fibers could sustain high tensile loads in the direction of the filaments without a matrix.

2.5. Classification of Composite Materials

Composite materials are commonly classified at two distinct basic headers according to their constituent materials. The first basic header of classification is usually made with respect to the reinforcement constituent. Composite materials are named fiber reinforced or particular reinforced by structure of reinforcement (Figure 2.4).

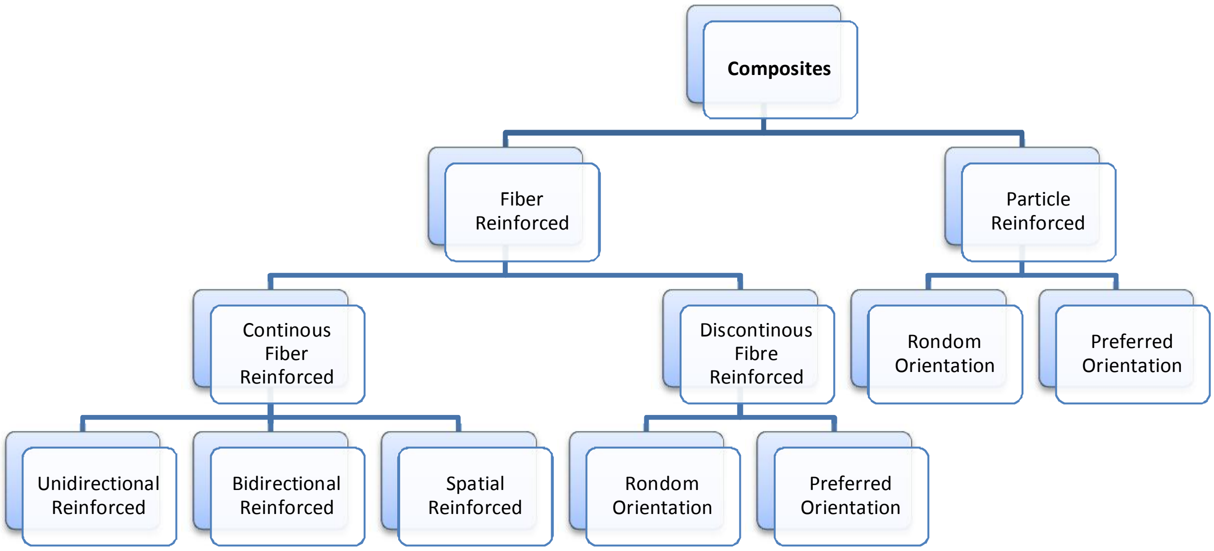


Figure 2.4 Classification of composite materials by reinforced materials

Another classification of composites has been done according to the matrix used, into three broad categories. They are Organic Matrix Composites (OMCs), Metal Matrix Composites (MMCs) and Ceramic Matrix Composites (CMCs). The term organic matrix composites generally assumed to include two classes of composites, namely Polymer Matrix Composites (PMCs) and carbon matrix composites commonly referred to as carbon-carbon composites (Figure 2.5).

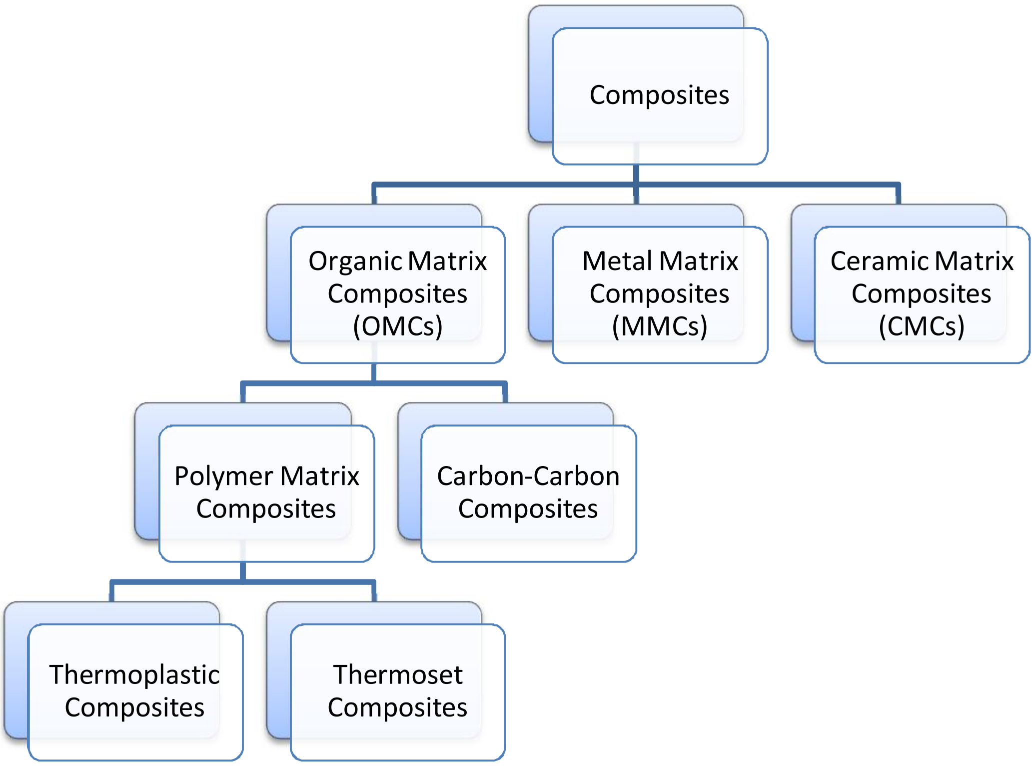


Figure 2.5 Classification of composite materials by matrix materials

2.5.1. Fiber Reinforced Composites

A composite material is a fiber composite if the reinforcement is in the form of fibers. The fibers used are either continuous or discontinuous (short fibers) in form. The short fibers (discontinuous) may be distributed at random orientations, or they may be aligned in some manner forming oriented short-fiber composites. By the means of convenience of application and exchangeable of mechanical properties, fiber reinforced composite materials is used widely in structural applications. In fiber reinforced composite materials; fiber of glass, carbon, aramid, boron generally are used as reinforcement material. Table 2.2 shows the mechanical properties of some commonly used materials made in the form of fibers.

Table 2.2 Properties of some commercially important high-strength fibers

Type of fiber	Tensile strength (ksi)	Tensile modulus (ksi)	Elongation at failure (%)	Density (g/cm^3)	Coefficient of thermal expansion (10^{-6} ^oC)	Fiber diameter (µm)
Glass						
E-glass	500	10	4.7	2.58	4.9-6	5-20
S-2 Glass	650	12.6	5.6	2.48	2.9	5-10
Quartz	490	10	5	2.15	0.5	9
Organic						
Kevlar 29	525	12	4	1.44	-2	12
Kevlar 49	550	19	2.8	1.44	-2	12
Kevlar 149	500	27	2	1.47	-2	12
Kevlar 1000	450	25	0.7	0.97	…..	27
PAN based carbon						
Standard modulus	500-700	32-35	1.5-2.2	1.8	-0.4	6-8
Intermediate modulus	600-900	40-43	1.3-2	1.8	-4.6	5-6
High modulus	600-800	50-65	0.7-1	1.9	-0.75	5-8
Pitch based carbon						
Low modulus	200-450	25-35	0.9	1.9	…..	11
High modulus	275-400	55-90	0.5	2	-0.9	11
Ultra high modulus	350	100-140	0.3	2.2	-1.6	10

Fibers fall short of ideal performance due to several factors. The performance of a fiber composite is evaluated by its length, shape, and orientation, composition of the fibers and the mechanical properties of the matrix. Fiber materials can be used as continuous or discontinuous in a matrix material. Continuous fiber can be oriented different angles as single layer or multi-layer. But discontinuous fiber don't have like that subject. They have either random or biased orientation. Figure 2.6 show use of fiber in fiber reinforced composites as modal.

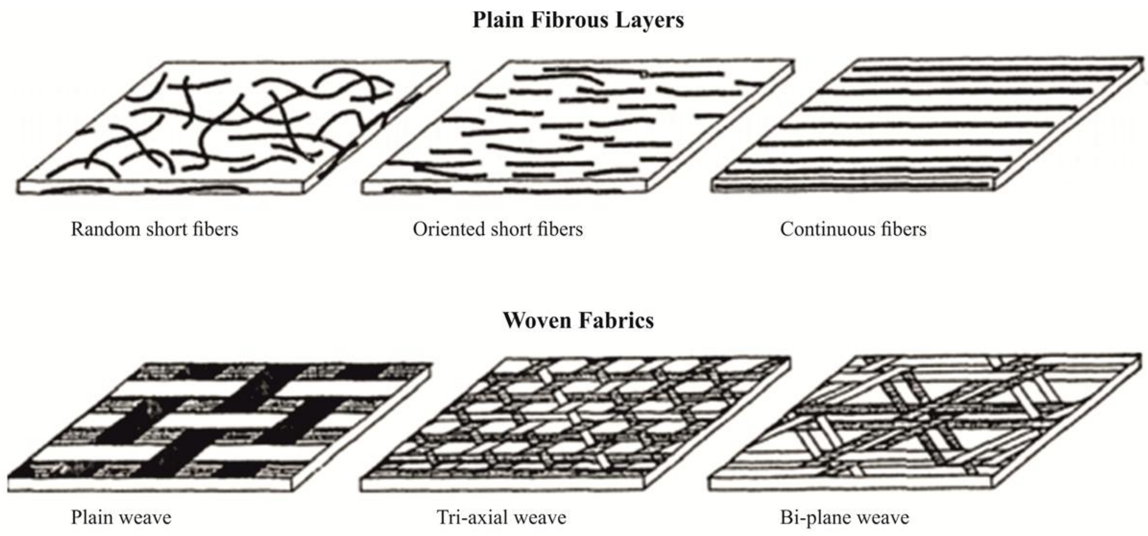


Figure 2.6 Typical reinforcement types of continuous and discontinuous fibers

The orientation of the fiber in the matrix is an indication of the strength of the composite and the strength is greatest along the longitudinal directional of fiber. Optimum performance from longitudinal fibers can be obtained if the load is applied along its direction. The slightest shift in the angle of loading may drastically reduce the strength of the composite. Properties of angle-plied composites may vary with the number of plies and their orientations. Composite variables in such composites are assumed to have a constant ratio and the matrices are considered relatively weaker than the fibers.

2.5.2. Particular Reinforced Composites

Microstructures of metal and ceramic composites, which show particles of one phase strewn in the other, are known as particle reinforced composites. Square, triangular and round shapes of reinforcement are known, but the dimensions of all their sides are observed to be more or less equal. Figure 2.7 present micro view of particular reinforced composite.

The dispersed size is of a few microns in particular composite and volume concentration of particulate composite, which strengthen with dispersed size particulate, is greater than 28% In particulate composites, the particles strengthen the system by the hydrostatic coercion of fillers in matrices and by their hardness relative to the matrix.

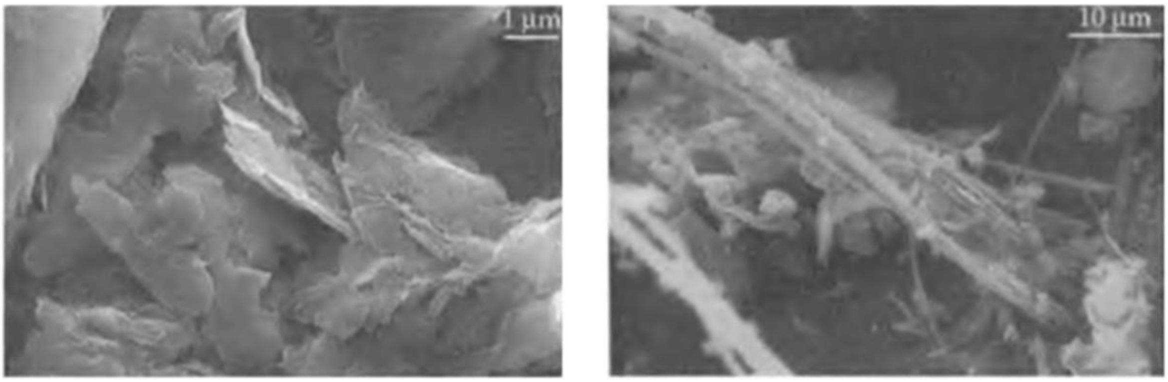


Figure 2.7 Micro view of talc particles in composite

There are many good reasons for using particulate fillers in plastic, metal or ceramic matrices, in addition to the obvious usual reduction in cost of the final product. In the case of plastics, the addition of fillers provides a reduction of shrinkage during the cure of a thermoset polymer system or the injection molding of a thermoplastic resin. This reduced shrinkage results in important benefits such as avoidance of the warp or cracking that may occur, especially in the case of large molded parts. The filled polymer has a much greater thermal conductivity than the unfilled resin. This provides an important advantage in processes such as injection molding, where the cycle time is often determined by the time to cool the part in the mold. The faster cooling rate of the filled plastic will provide cost savings due to the faster cycle time. Another advantage of the higher thermal conductivity is the faster dissipation of localized hot spots, which could cause thermal decomposition of a polymer or failure of a sensitive electronic component adjacent to the plastic.

There are many types of particulate to reinforce composites. They may be classified as mineral, natural or synthetic, inorganic or organic. The mineral particulates include calcium carbonate, clay, feldspar, nepheline syenite, talc, alumina trihydrate, natural silicas and mica. There are many organic particulate such as wood flour, carbon black, various starches, ground rice hulls, peanut shell and reclaimed rubber. Specific particulate fillers can generate composite material characteristics such as electrical conductivity, biodegradability, thermochromic, photochromic, low surface friction or magnetic properties, resistance to abrasion, decrease of shrinkage.

2.5.3. Polymer Matrix Composites

Polymeric matrices are the most common and least expensive in composite applications. They are found in nature as amber, pitch, and resin. Some of the earliest composites were layers of fiber, cloth, and pitch. Polymers are easy to process; offer good mechanical properties, generally wet reinforcements well, and provide good adhesion. They are a low-density material. Because of low processing temperatures, many organic reinforcements can be used. A typical polymeric matrix is either viscoelastic or viscoplastic, meaning it is affected by time, temperature, and moisture. The terms thermoset and themoplastic are often used to identify a special property of many polymeric matrices.

A thermosetting material is the one which when cured by heat or chemical reaction is changed into an infusible and insoluble material. Thermosetting resins undergo irreversible chemical cross-linking reaction upon application of heat. On the other hand, thermoplastics do not undergo a chemical reaction on application of heat. They simply melt on application of heat and pressure to form a component. Some of the significant differences between thermosets and thermoplastics are given in Table 2.3;

Table 2.3 Some of the significant differences between thermosets and thermoplastics

Thermosets	Thermoplastics
• Resin cost is low.	• Resin cost is slightly higher.
• Thermosets exhibit moderate shrinkage.	• Shrinkage of thermoplastics is low.
• Interlaminar fracture toughness is low.	• Interlaminar fracture toughness is high.
• Thermosets exhibit good resistance to fluids and solvents.	• Thermoplastics exhibit poor resistance to fluids and solvents.
• Composite mechanical properties are good.	• Composite mechanical properties are good.
• Prepregability characteristics are excellent.	• Prepregability characteristics are poor.
• Prepreg shelf life and out time are poor.	• Prepreg shelf life and out time are excellent.
• It cannot be used again with recycling.	• It can be recycling and use again.

Different types of thermosets and thermoplastic resins commonly in use are given in Table 2.4;

Table 2.4 Common used thermosets and thermoplastic resins

Thermosets	Thermoplastics
• Phenolics & Cyanate ester	• Polypropylene
• Polyesters & Vinyl esters	• Nylon (Polyamide)
• Polyimides	• Poly-ether-imide (PEI)
• Epoxies	• Poly-ether-sulphone (PES)
• Bismaleimide (BMI)	• Poly-ether -ether-ketone (PEEK)

Polyesters, epoxy and other resins in liquid form contain monomers, which convert into polymers when the resin is cured. The resulting solid is called thermosets, which is tough, hard, insoluble and infusible. The infusibility property of thermosets distinguishes from the thermoplastics. Cure and polymerization refer to the chemical reactions that solidify the resin. Curing is accomplished by heat, pressure and by addition of curing agents at room temperature.

The most widely used matrices for advanced composites have been the epoxy resins. These resins cost more than polyesters and do not have the high temperature capability of the Bismaleimides or polyimides. However, they are widely used due to the following advantages.

- Adhesion to fibers and to resin;
- No by-products formed during cure;
- Low shrinkage during cure;
- High or low strength and flexibility;
- Resistance to solvents and chemicals;
- Resistance to creep and fatigue;
- Wide range of curative options;
- Adjustable curing rate;
- Good electrical properties.

Thermoplastics, as stated earlier, can be repeatedly softened by heating, and hardened by cooling. Thermoplastics possess several advantages over the thermosets, one of the most important being that they do not need storing under refrigeration. They also possess improved damage tolerance, environmental resistance, fire resistance, recyclability and potential for fast processing. There are three different reasons for increased use of thermoplastic. First of these reasons is that processing can be faster than that of thermoset composites since no curing reaction is required. Thermoplastic composites require only heating, shaping and cooling. The second reason is that the properties are attractive, in particular, high delamination resistance and damage tolerance, low moisture absorption and the excellent chemical resistance of semi-crystalline polymers. As a third reason in the light of environmental concerns, thermoplastic composites offer other advantages also. They have low toxity since they do not contain reactive chemicals (therefore storage life is infinite).

Because it is possible to remelt and dissolve thermoplastics, their composites are also easily recycled or combined with other recycled materials in the market for molding compounds. Thermoplastics usually require high temperature and pressure during processing and generally lack good solvent resistance. Process conditions for high performance thermoplastics are temperature in the range of 300 to 400°C and pressure between atmospheric pressure for thermo folding process to 20 times the atmospheric pressure for high performance press forming. Due to their high strains to failure, thermoplastics are the only matrices currently available that are suited to thermo-forming and other forms of rapid manufacture. Thermo loading is the most straight forward thermoplastic forming technique where a straight line is heated and folded. The process is used in volume applications like aircraft floor boards. Thermo folding operations can be carried out on solid laminate materials as well as on sandwich panels.

2.5.4. Carbon-Carbon Matrix Composites

Carbon fiber reinforced carbon is a high strength composite material, which is also resistant to high temperature in a nonoxidising atmosphere. It is composed of a carbon matrix into which reinforcing carbon fibers are embedded. Such a material was first used under extreme thermal and mechanical loads in space technology. The criteria for selection of carbon-carbon composites as a thermal protection system are based on maintenance of reproducible strength levels at 1650°C, sufficient stiffness to resist flight loads and large thermal gradients, low coefficient of thermal expansion to minimize induced thermal stresses and tolerance to impact damage.

Carbon-carbon composites are used in many applications due to their low specific weight, high heat absorption capacity, resistance to thermal shock, high resistance to damage, exceptional frictional properties at high energy levels, resistance to high temperatures and chemical inertness.

Although, there are a lot of advantages as mentioned above the disadvantages of carbon-carbon composites are the lack of resistance to oxidation at temperatures in excess of 500°C and economic problems namely long manufacturing time and high production cost.

To allow the use of carbon-carbon composites in an oxidising atmosphere, they must be compounded with materials that produce oxidation protective coatings through thermo-chemical reaction with oxygen above 2000°C. Important areas of use of carbon-carbon composites are aircraft brakes, brake system for high-speed trains and racing cars. Its application as braking material is due to high-energy absorption capacity, low specific weight and the fact that it does not contain any environmentally harmful elements like asbestos. Some other examples of its use include heavy duty clutches, tools for high temperature production of alloys like titanium, etc. There are two production methods to obtain a carbon matrix reinforced with carbon fibers.

- Chemical vapour impregnation - where a preform is compressed by deposition of carbon from a gaseous phase.
- The liquid phase impregnation - where a carbon preform is compressed by means of multiple impregnations with resin and intermediate carbonization steps.

2.5.5. Metal Matrix Composites (MMCs)

Metallic matrices are essential constituents for fabrication of Metal Matrix Composites (MMCs), which have potential for structural materials at high temperatures. Most metals and alloys make good matrices. However, practically, the choices for low temperature applications are not many. Only light metals are responsive, with their low density proving an advantage. Titanium, aluminum and magnesium are the popular metallic matrices, which are particularly useful for aircraft applications. If metallic matrices have to offer high strength, they require high modulus to reinforcements. The strength-to-weight ratios of resulting composites can be higher than most alloys. Metal matrix has the advantage over polymeric matrix in applications requiring a long-term resistance to severe environments, such as high temperature. The yield strength and modulus of most metals are higher than those for polymers, which is an important consideration for applications requiring high transverse strength and modulus as well as compressive strength for the composite. Another advantage of using metals is that they can be plastically deformed and strengthened by a variety of thermal and mechanical treatments. However, metals have a number of disadvantages, namely, they have high specific gravities, high melting points (therefore, high process temperatures), and a tendency toward corrosion at the fiber/matrix interface.

Metal matrix composite production technology is complicated and requires satisfaction of the following conditions, of which the most significant are as follows:

- Maintaining the reinforcing fibers strength.
- Ensuring a strong bond of fibers with matrices and between the matrix layers.
- Providing the correct fiber length, greater than the critical length.
- Even distribution of fibers in the matrix.
- Orientation of fibers in the direction of the applied load.
- Achieving the required shape and dimensions of the MMC.
- Obtaining MMC strength reasonably near to theoretical.

2.5.6. Ceramic Matrix Composites (CMCs)

The motivation to develop ceramic matrix composites (CMCs) was to overcome the problems associated with the conventional technical ceramics like alumina, silicon carbide, aluminum nitride, silicon nitride or zirconia. They fracture easily under mechanical or thermo-mechanical loads because of cracks initiated by small defects or scratches. The crack resistance is like in glass very low. To increase the crack resistance or fracture toughness, particles were embedded into the matrix. However, the improvement was limited, and the products have found application only in some ceramic cutting tools. So far only the integration of long multi-strand fibers has drastically increased the crack resistance, elongation and thermal shock resistance, and resulted in several new applications.

Carbon (C), special silicon carbide (SiC), alumina (Al_2O_3) and mullite (Al_2O_3–SiO_2) fibers are most commonly used for CMCs. The matrix materials are usually the same that is carbon, silicon carbide, alumina and mullite. Generally, CMCs names include a combination of type of fiber and matrix types. For example, C/C stands for carbon-fiber-reinforced carbon (carbon/carbon), or C/SiC for carbon fiber reinforced silicon carbide (Table 2.5).

Table 2.5 Mechanical properties of some ceramic matrix composite materials

Type of material	Al_2O_3/Al_2O_3	Al_2O_3	CVI-C/SiC	LPI-C/SiC	LSI-C/SiC	Si-SiC
Porosity (%)	35	<1	12	12	3	<1
Density (g/cm^3)	2.1	3.9	2.1	1.9	1.9	3.1
Tensile strength (MP(a)	65	250	310	250	190	200
Elongation (%)	0.12	0.1	0.75	0.5	0.35	0.05
Young's modulus (GP(a)	50	400	95	65	60	395
Flexural strength (MP(a)	80	450	475	500	300	400

While ceramic matrix composites are still in the early stages of component design, fabrication and testing, these materials are considered as prime candidates for application of futuristic aircraft gas turbine engines. The selection of matrix materials for ceramic composites is strongly influenced by thermal stability and processing considerations. These include oxides, carbides, nitrides, borides and silicides. All these materials have melting temperatures above 1600°C.

2.6. Advantages and Disadvantages of Composite Materials

Any material in the nature is always excellent. According to the conditions of use, every material has value of performance. When conditions of use change its performance can increase or decrease. References to this definition, use of composite materials sometimes provide advantage or disadvantage. Summary of the advantages of composite materials exhibited as below estipulate;

- High resistance to fatigue and corrosion degradation.
- High strength or stiffness to weight ratio. As enumerated above, weight savings are significant ranging from 25-45% of the weight of conventional metallic designs.
- Due to greater reliability, there are fewer inspections and structural repairs.
- Directional tailoring capabilities to meet the design requirements. The fiber pattern can be laid in a manner that will tailor the structure to efficiently sustain the applied loads.
- Fiber to fiber redundant load path.
- Improved dent resistance is normally achieved. Composite panels do not sustain damage as easily as thin gage sheet metals.
- It is easier to achieve smooth aerodynamic profiles for drag reduction. Complex double curvature parts with a smooth surface finish can be made in one manufacturing operation.
- Composites offer improved torsional stiffness. This implies high whirling speeds, reduced number of intermediate bearings and supporting structural elements. The overall part count and manufacturing and assembly costs are thus reduced.
- High resistance to impact damage.
- Thermoplastics have rapid process cycles, making them attractive for high volume commercial applications that traditionally have been the domain of sheet metals. Moreover, thermoplastics can also be reformed.
- Like metals, thermoplastics have indefinite shelf life.

- Composites are dimensionally stable i.e. they have low thermal conductivity and low coefficient of thermal expansion. Composite materials can be tailored to comply with a broad range of thermal expansion design requirements and to minimize thermal stresses.
- Manufacture and assembly are simplified because of part integration (joint/fastener reduction) thereby reducing cost.
- The improved weather ability of composites in a marine environment as well as their corrosion resistance and durability reduce the down time for maintenance.
- Close tolerances can be achieved without machining.
- Material is reduced because composite parts and structures are frequently built to shape rather than machined to the required configuration, as is common with metals.
- Excellent heat sink properties of composites, especially carbon-carbon, combined with their lightweight have extended their use for aircraft brakes.
- Improved friction and wear properties.
- The basic material properties of a composite laminate have allowed new approaches to the design of aeroelastic flight structures.

Thanks to the above advantages; composite materials are commonly used in a lot of engineering field as alternative to metals. Although these advantages, composite materials are not perfect. Some of the disadvantages of composite materials are given below;

- High manufacturing cost and difficult repair.
- Composites are more brittle than metals. Thus, they are more easily damaged.
- Transverse properties may be weak.
- Matrix is weak, therefore, low toughness.
- Reuse and disposal may be difficult.

However, proper design and material selection can circumvent many of the above disadvantages.

New technology has provided a variety of reinforcing fibres and matrices those can be combined to form composites having a wide range of exceptional properties. Since the advanced composites are capable of providing structural efficiency at lower weights as compared to equivalent metallic structures, they have emerged as the primary materials for future use.

2.7. Application Areas of Composite Materials

Composites are one of the most widely used materials because of their adaptability to different situations and the relative ease of combination with other materials to serve specific purposes and exhibit desirable properties.

Some of the application area of composite materials is given below as main headings.

2.7.1. Aeronautics Industry

The designs in aeronautics industry materialized with optimization of safety, velocity and, economic. Composite materials created a suitable material group for this aim. When based on specific strength and stiffness, these criterions overtop to composite materials according to conventional materials. Especially, advanced composite materials have widely application area in aeronautics industry. By the means of superior mechanical properties compared to lightweight, polymeric matrix composites have used in aircraft and helicopter as structural component.

The most important thing for an aircraft is weight reduction to attain greater speed and increased payload that is why composite materials are found to be ideal in aircrafts and space vehicles. Carbon fibers either alone or in the hybridized condition is used for a large number of aircraft components. Carbon and Kevlar have become the major material used in many wing, fuselage and empennage components. FRP with epoxy as the resin is used for the manufacture of helicopter blades. One of the main reasons why FRP is used for rotor blades is the ability of the material to tailor the dynamic frequency of the blade to its operating parameters. Figure 2.8 presents components which consist of composite materials in Boeing 787 airplane.

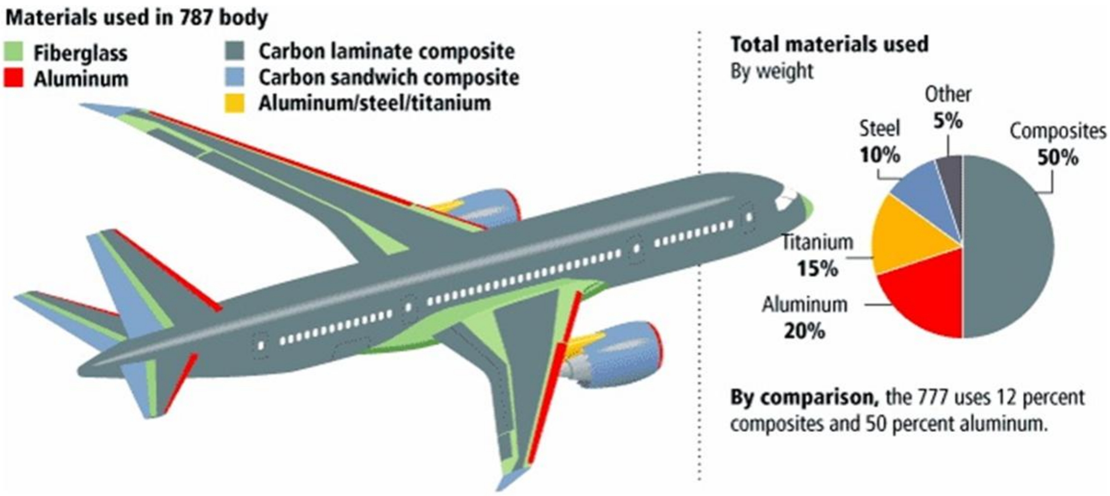


Figure 2.8 Composite components in Boeing 787

2.7.2. Marine Industry

Properties of materials such as lightweight and high corrosion resistance have a great importance in ship design. Like in all other areas, uses of composites in the marine field are growing rapidly for years. Fiberglass boat manufacturers use a variety of materials including glass roving, woven fabrics, mats, vinlyester and polyester resins, epoxy, balsa, foam and honeycomb cores, E-glass, S-glass, carbon and Kevlar fibers, with E-glass being the fiber of choice. The manufacturing techniques used for boats include hand lay-up, spray-up, Resin Transfer Molding (RTM) and Sheet Molding Compound (SMC) processes. Currently the majority of fiberglass boats are produced using an open mold process. Boat builders use composite materials for the boat hulls, as well as decks, showers, bulkheads, cockpit covers, hatches, etc. The demand for high performance fibers is increasing in order to reduce weight, gain speed and save fuel. There is growing interest in carbon and Kevlar fibers for high performance applications such as power and racing boats. Figure 2.9 shows covering of inside of a ship with E-glass/epoxy composite material using hand-lay up method.

Figure 2.9 An application of composite materials in marine industry

2.7.3. Automotive Industry

The uses of carbon fiber reinforced plastics (CFRP) are becoming increasingly widespread in the automotive industry that foresees a growth of 65% over the next 5 years. Many manufacturers are working on developing and applying these technologies so they can build lighter vehicles that make an important contribution to reducing fuel consumption and air pollution, through improvements that include increasing the strength of the vehicle's structures. An example of CFRP for car structure is given in Figure 2.10.

Figure 2.10 A car chassis consists of carbon fiber

The reason that automotive field prefer composite materials is that, the exterior part of the car such as hood or door panels requires sufficient stiffness. The other requirement is that it should offer maximum resistance to damage tolerances. Resins like polyurethanes enable the damage tolerance to be limited to acceptable values. Further, a good surface finish is highly desirable. Crashworthiness and crash management strategies have been applied in the design of automobiles, particularly racing cars. Maximum energy absorption on impact at high speeds is the goal of the design of the front end of the vehicle for maximum energy absorption to protect or safeguard occupants from forces that cause serious injury or death.

2.7.4. Sports Equipment

The other application area of composite materials is manufacturing of sports equipment. Because capability of movement increase with reduce weight. GFRP and CFRP composites most used thanks to lightweight.

Composite materials are constitute materials for sports equipment such as canoe, mountain bicycle, golf club, tennis racket, surfboard, snowboard, sports shoes etc. a bicycle body made of CFRP is given Figure 2.11.

Figure 2.11 A bicycle body consists of carbon fiber

2.7.5. Biomedical Applications

Biomedical applications encompass those that pertain to the diagnosis and treatment of conditions, diseases and disabilities, as well as the prevention of diseases and conditions. They include implants, surgical and diagnostic devices, pacemakers, electrodes for collecting or sending electrical or optical signals for diagnosis or treatment, wheelchairs, devices for helping the disabled, exercise equipment, pharmaceutical packaging and instrumentation for diagnosis and chemical analysis. Implants are particularly challenging, as they need to be made of materials that are biocompatible, corrosion resistant, wear resistant, fatigue resistant, and that are able to maintain these properties over tens of years. Due to these advantages metal matrix composite materials use as an inlay for teeth (Figure 2.12). Carbon–carbon composites are used for implants. Composites with biocompatible polymer matrices are also used for implants. Electrically conducting polymer-matrix composites are used for electrodes for diagnostics. Composites with biodegradable polymer matrices are used for pharmaceutics.

Figure 2.12 The metal matrix composite inlays for teeth

2.8. Overview of Buckling

There are three basic characteristic in design of structural members as strength, stiffness, and stability. In materials science, the strength of a material is its ability to withstand an applied stress without failure. The applied stress may be tensile, compressive, and shear. In other words, we can say; strength refers to load carrying capacity. The stiffness of a structure is of principal importance in many engineering applications. Stiffness is the resistance of an elastic body to deformation by an applied force. Stiffness is closely related with elastic or Young modules of material. A high modulus of elasticity is sought when deflection is undesirable, while a low modulus of elasticity is required when flexibility is needed. Stability which is demanded for design of structure is simply a material's ability to maintain its original configuration under various loads and stresses. Lightweight structural members have been extensively used in many industrial fields. For that reason the stability problems of such structural members are of increasing importance [34].

In structural engineering, column is a vertical structural element that transmits, through compression. When the vertical load is increased on a slender column which has elastic material properties, column is exposed to three states as stable equilibrium, neutral equilibrium, and instability. The column under load is in stable equilibrium if a force, applied as vertically, produces a small flexural deflection which disappears and the column returns to its straight form when the vertical force is removed. If the column load is gradually increased, a condition is reached in which the straight form of equilibrium becomes named neutral equilibrium, and a small vertical force will produce a deflection that does not disappear and the column remains in this slightly bent form when the vertical force is removed. The load at which neutral equilibrium of a column is reached is called the critical or buckling load. The state of instability is reached when a slight increase of the column load causes uncontrollably growing lateral deflections leading to complete collapse. Columns are frequently used to support to beams which the upper parts of walls or ceilings rest [34].

Beams are horizontal structural elements that is capable of withstanding load primarily by resisting bending. Beams are conventional definitions of building or civil engineering structural elements, but some smaller structures such as truck or automobile frames, machine frames, and other mechanical or structural systems contain beam structures that are designed and analyzed in a similar fashion. Beams experience compressive, tensile and shear stresses as a result of the loads applied to them. In course of time, beams loss the original length under gravity load and starting from the edges bending deformation occur in the form of arc to the middle of beam. As a result on a count of bending while the top side of beam sustaining tension, the bottom side of beam is exposed to compression tension. Another state is buckling for beams under effect of force. When a slender structural beam is loaded as perpendicular to its axis, there exists a tendency which forced beam to failure by buckling. Buckling can be caused excessive displacement in structure. As a result of this, structure losing own stability, it fails [34].

In recent years, buckling has become more of a problem because the use of high strength material requires less material for load support structures and components have become more slender. Buckling failures can be occur sudden and catastrophic. Eventually, it must be given primary attention design of the beam so that they can safely support the loads. In science, buckling is a mathematical instability problem and an effect of load leading to a failure mode. Theoretically, buckling is caused by a bifurcation in the solution to the equations of static equilibrium. At a certain stage under an increasing load, further load is able to be sustained in one of two states of equilibrium: an undeformed state or a laterally deformed state. In practice, buckling is characterized by a sudden failure of a structural member subjected to high compressive stress, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding. Mathematical analysis of buckling makes use of an axial load eccentricity that introduces a moment, which does not form part of the primary forces to which the member is subjected. When load is constantly being applied on a member, such as column, it will ultimately become large enough to cause the member to become unstable. Further load will cause significant and somewhat unpredictable deformations, possibly leading to complete loss of load-carrying capacity. The member is said to have buckled, to have deformed [34].

There are different types of buckling as flexural buckling (Figure 2.13), flexural torsional buckling (Figure 2.14), lateral buckling (Figure 2.15), lateral-torsional buckling (Figure 2.16), plastic buckling and dynamic buckling. In structural elements like columns; flexural buckling (Figure 2.13) occurs about the axis and in this occurrence; slenderness ratio of columns have an important place. Braces constrained against flexural buckling use buckling stiffeners. When a beam is loaded in flexure the load bearing side (generally the top) carries the load in compression. If compression members have unsymmetrical cross-section with one axis of symmetry, or load on structural member is not on axis of symmetry, flexural-torsional buckling occurs (Figure 2.14). Flexural-torsional buckling is the simultaneous bending and twisting of a member. This mostly occurs in channels, structural tees, double-angle shapes, and equal leg single angles.

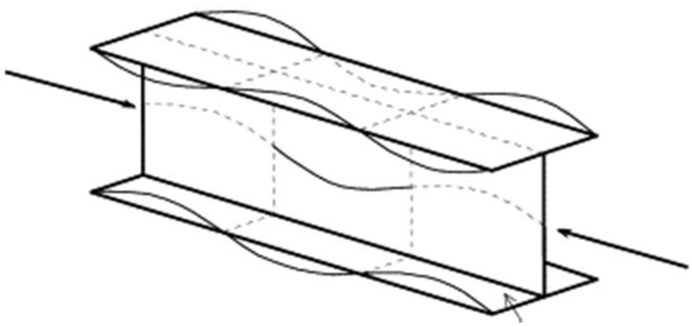


Figure 2.13 Flexural buckling of columns

Figure 2.14 Flexural-torsional buckling of columns

In the beam that is not supported perpendicular to the plane of bending, if the load so much as to cause of failure, the beam buckles by deflecting laterally. So that beam is exposed to lateral buckling Figure (2.15). During the bending, if vertical axis of beam twists, dual strain named lateral-torsional buckling occurs in the beam (Figure 2.16).

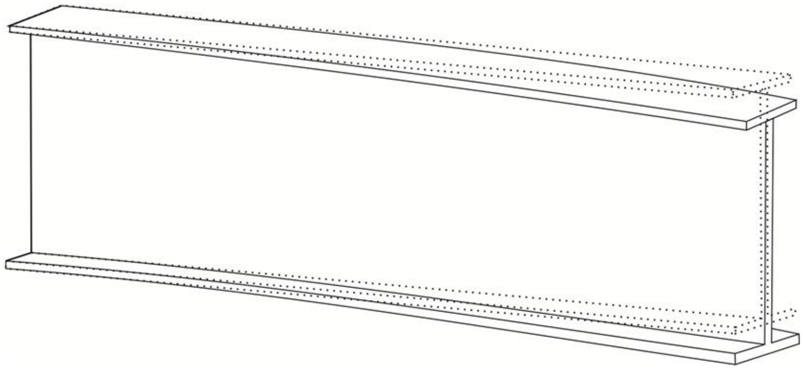


Figure 2.15 Lateral buckling of columns

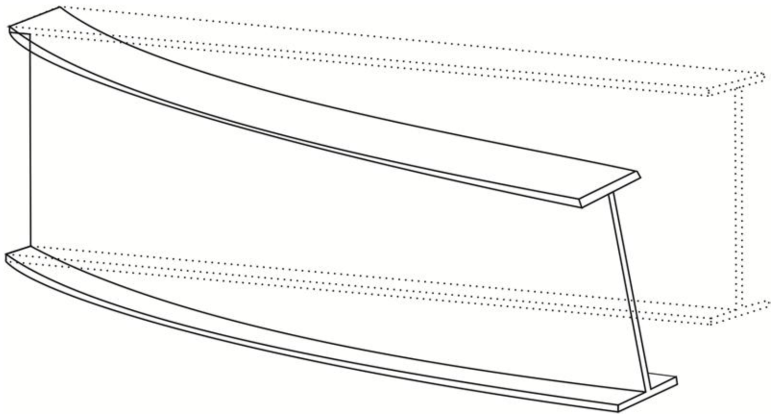


Figure 2.16 Lateral torsional buckling of columns

Buckling will generally occur slightly before the theoretical buckling strength of a structure, due to plasticity of the material. When the compressive load is near buckling, the structure will bow significantly and approach yield. When the compressive load is raised, the beam reintegrates. This behavior, which occurs premature buckling, is named plastic buckling. If the load on the column is applied suddenly and then released, the column can sustain a load much higher than its static buckling load. This cyclical shuttle generates a stress wave which travel from up side of beam to bottom side of beam. This stress wave enforces beam as dynamic so that a state that we say dynamic buckling have seen in beam [35].

2.9. Buckling in Delaminated Composite Materials

As a result of buckling, typical damages can be occur like matrix crack, fiber breaking, fiber-matrix debonding and delamination in composite materials. In laminated composites, layers can separate because of buckling load and discontinuity zone is composed. This discontinuity zone is named delamination damage. Delamination is often attributed to the high interlaminar stress occurring in two adjacent laminas. Strength of the laminate can be reduced due to this damage mode. Residual compressive strength of laminated composite also reduces by occurring delaminations. Delamination may originate due to manufacturing deflect, impact damage, high – low velocity impact load, three dimensional interlaminar stress, compressive loading and delamination buckling in laminated composite plates.

Buckling may occur in different types of model shapes in delaminated composites. As shown in Figure 2.17, at the critical load level, a compressed beam having a single delamination may respond in three possible modes of instability.

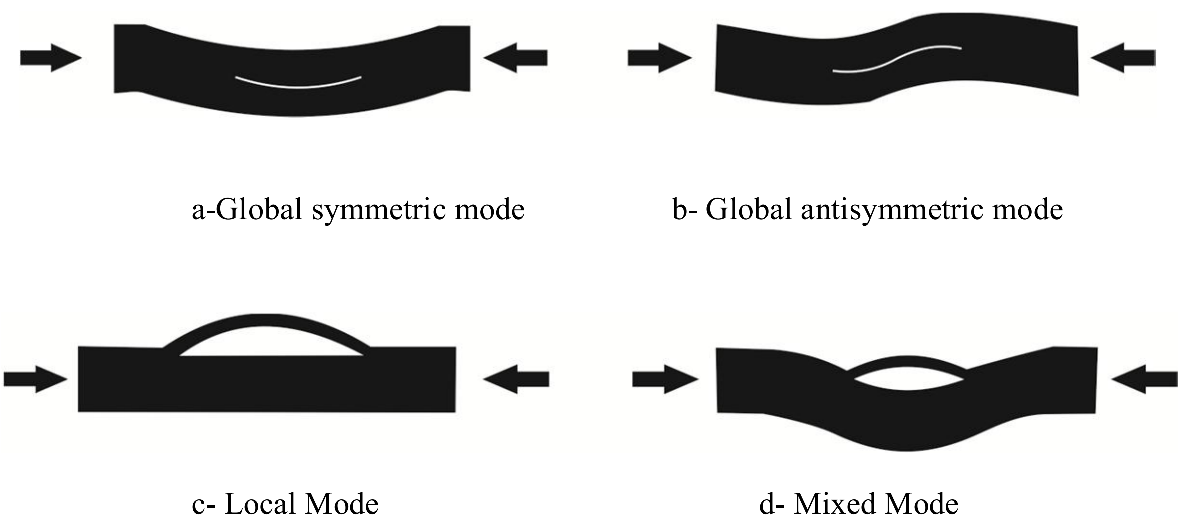


Figure 2.17 Buckling modes shape for delaminated composite

Delamination length and its position through the thickness are the two important parameters controlling the shape of these modes. If the entire beam buckles before any other mode of deflection could take place, the response is referred to as the "global" buckling mode. This usually occurs in relatively short and thick delaminated beams. In a global buckling mode, if the buckling shape is symmetric with respect to the midspan of the beam, it is identified as the "global symmetric" mode (Figure 2.17a). On the other hand, if the global buckling mode tends to deform into a kinked shape, the buckling shape is called the “global antisymmetric” mode (Figure 2.17b). When the delamination is thin, the first region that buckles is the delaminated region. Such a buckling is declared as the "local" buckling mode (Figure 2.17c). Finally, in an axially compressed delaminated beam, if both the global and local buckling take place at the same time, then the response is referred to as the "mixed" buckling mode (Figure 2.17d). The situations for multiply delaminated beams arc quite similar to the ones discussed for single delamination [36].

CHAPTER THREE: EXPERIMENTAL INVESTIGATION of LATERAL BUCKLING

3.1. Introduction to Laminated Composites

A composite is named a laminated composite when it consists of layers of at least two different materials that are bonded together. Lamination is used to combine the best aspects of the constituent layers in order to achieve a more useful material. The ability to structure and orient material layers in a prescribed sequence leads to several particularly significant advantages of composite materials compared with conventional monolithic materials. The most important among these is the ability to tailor or match the lamina properties and orientations to the prescribed structural loads. The properties that can be emphasized by lamination are strength, stiffness, low weight, corrosion resistance, wear resistance, beauty or attractiveness, thermal insulation, acoustical insulation, etc. [37]. Figure 3.1 showed fiber orientation in laminated composite.

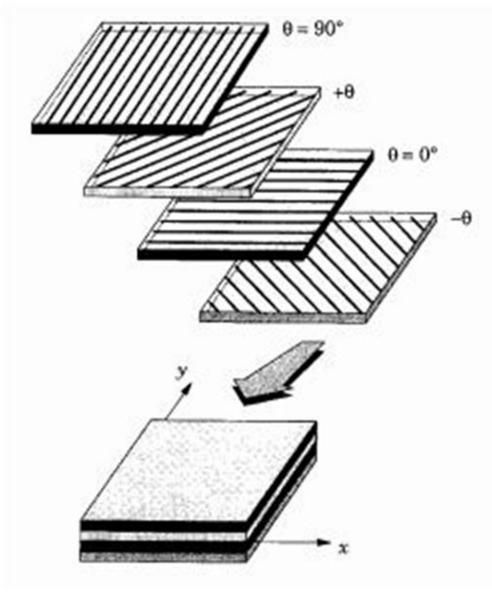


Figure 3.1 A laminated composite made up of lamina with different fiber orientations

Laminates made of fiber reinforced composite materials also have disadvantages. Because of the mismatch of material properties between layers, the shear stresses produced between the layers, especially at the edges of a laminate, may cause delamination. Similarly, because of the mismatch of material properties between matrix and fiber, fiber debonding may take place. Also, during manufacturing of laminates, material defects such as interlaminar voids, delamination, incorrect orientation, damaged fibers, and variation in thickness may be introduced. It is impossible to eliminate manufacturing defects altogether; therefore, analysis and design methodologies must account for various mechanisms of failure.

Laminated composite structures have the oldest and the most common usage field in structural engineering. High strength values obtain with composing of laminates which have different stacking sequences. These composite structures endure to heat and moisture. They use as alternative material instead of metal materials thanks to their light weight and good material properties. Continuous fiber reinforced laminated composite materials have various application area like industry of aircraft, ship and automotive.

3.2. Manufacturing of Laminated Composites

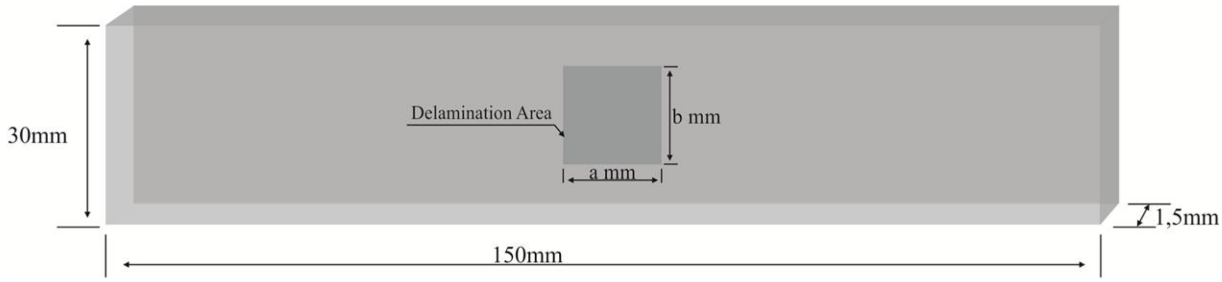
Laminated composite materials are produced with using hand lay-up method (Figure 3.2). In this method, resin mixed with a catalyst is deposited liberally on the gel coat or on a previous ply of impregnated reinforcement by a roller-dispenser, brush or spray gun.

Figure 3.2 A view from manufacturing process of laminated composite

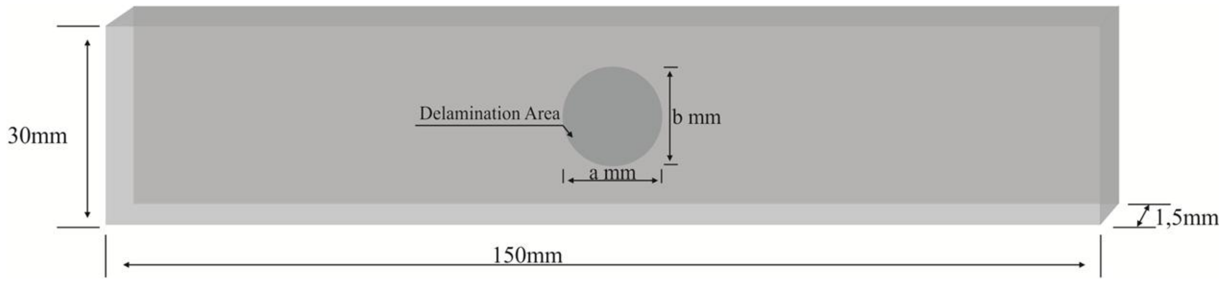
Lateral buckling test specimens were produced in composite laboratory of Department of Mechanical Engineering of Usak University. Firstly we selected reinforcement material which made of E–glass. The woven e-glass reinforcement material are of 200 gr/m^2 in weight. After that in order to create delamination area we embedded teflon film, which have 12 µm thickness, on mid layer.

In order to better find out delamination effect, the shapes of delaminations have been varied as square, rectangular, circular and elliptical. The square aspect ratio and circular minor and major axis ratio were varied for obtaining rectangular and elliptical delamination shapes. Test specimens with delamination were classified in two different categories which consist of different twenty two series. In the first of these categories, there were eight different series of specimens with square and circular delamination which have four different a/b ratio (1, 2, 3and 4) and fixed 600 mm^2 area. As for that in the second category, fourteen different series of specimens with square and circular delamination which have seven fixed a/b ratio (0.5, 0.6, 0.75, 1, 1.3, 1.6 and 2). To better understanding effect of delamination on lateral buckling, experimental and numerical results of test specimens with delamination were compared experimental and numerical results of test specimens without delamination.

The shape and size of delamination and test specimens were given in Figure 3.3 and Table 3.1 respectively. Teflon film, which placed mid plane of layers (Figure 3.4), obtains not to paste neighbor layers to it. So that, discontinuity area named delamination is created between two layers which is not stick to each other. Produced laminated composites made of woven E-glass/epoxy have eight layers. The fiber-volume fraction of laminated composite plates is approximately 65% in weight.



(a)



(b)

Figure 3.3 The shape and size of delamination and test specimen

Table 3.1 The size of square and circular delaminations

Delamination with Fixed Area (600mm^2)	
a/b a ratio for square delamination(mm)	**a/b ratio for circular delamination(mm)**
24.5/24.5=1	27.6/27.6=1
34.6/17.3=2	39.1/19.5=2
42.4/14.1=3	47.9/16=3
49/12.3=4	55.3/13.8=4
Delamination with Fixed a/b Ratio	
a/b ratio for square delamination(mm)	**a/b ratio for circular delamination(mm)**
15/30=0.5	15/30=0.5
15/25=0.6	15/25=0.6
15/20=0.75	15/20=0.75
15/15=1	15/15=1
20/15=1.3	20/15=1.3
25/15=1.6	25/15=1.6
30/15=2	30/15=2

Figure 3.4 A layer which prepared to create delamination area

As matrix material we use DTE 1100 as epoxy and DST 1105 as catalyst. They mixed 76% epoxy and 24% catalysts in weight. Epoxy resin is absorbed with using a roll brush. For the curing produce, prepared semi-finished product is pressed at 120^{o}C and under 8 MPa pressure for 2 hours. After curing process, final product was cooled to room temperature under same pressure to avoided warping effect.

Before cutting process, cooled laminated composite plates are drawn in 150x30 mm size (Figure 3.5). While drawing we paid attention to placed delamination area at the middle of test specimen. Finally, drawn plates are cut by helping diamond buzzer saw (Figure 3.6). Figure 3.7 showed a test specimen prepared for lateral buckling test.

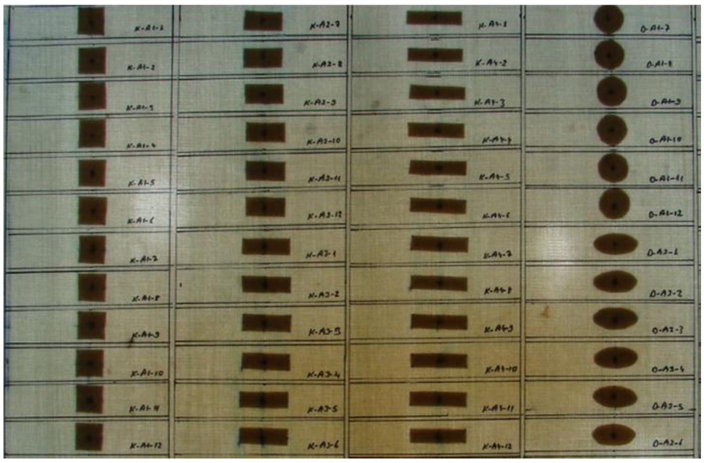


Figure 3.5 A view from drawn plate

Figure 3.6 Cutting process of laminated composite plates

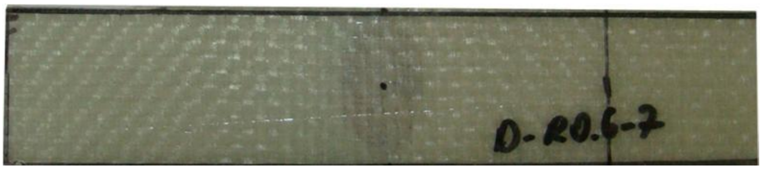


Figure 3.7 A specimen for lateral buckling test

For experimental studies, from each series seven test specimens were tested to lateral buckling test and we use eight specimens in order to determine mechanical properties.

3.3. Determination of Mechanical Properties

For determination of the mechanical properties of woven E-glass/epoxy laminated composites, which have eight layers, were produced. To measuring the stiffness and strength of unidirectional plates under tension, compression and in plane share loading conditions, composite plates were trimmed according to ASTM (American Society for Testing and Materials) standards. The mechanical properties which find out as result of tests are necessary to use in input data for Ansys 12.1 finite element software. The mechanical properties of laminated composites are measured in Department of Mechanical Engineering of Ege University in İzmir by using Shimadzu-AGIS Tensile Testing Machine with 100 kN load capacity at of 1 mm/min velocity. For each mechanical property, eight test specimens were tested.

3.3.1. Determination of the Tensile Properties

According to the ASTM D3039-76 standard test method, longitudinal Young modulus E_1, poison's ratio ν_{12} and longitudinal tensile strengths X_t are obtained by using longitudinal woven specimens [38]. The size of the longitudinal specimen has 12.7 mm wide and 229 mm long (Figure 3.8a). Young modulus E_2 and transverse tensile strength Y_t are obtained by using transverse woven specimens. The size of the transverse test specimen has 25.4 mm wide and 229 mm long (Figure 3.8b) [38]. During tensile tests, not to failure specimens from contact field, where surface is between specimen and connection crosshead of test machine, we bonded to test specimens woven E-glass/epoxy tabs as illustrated.

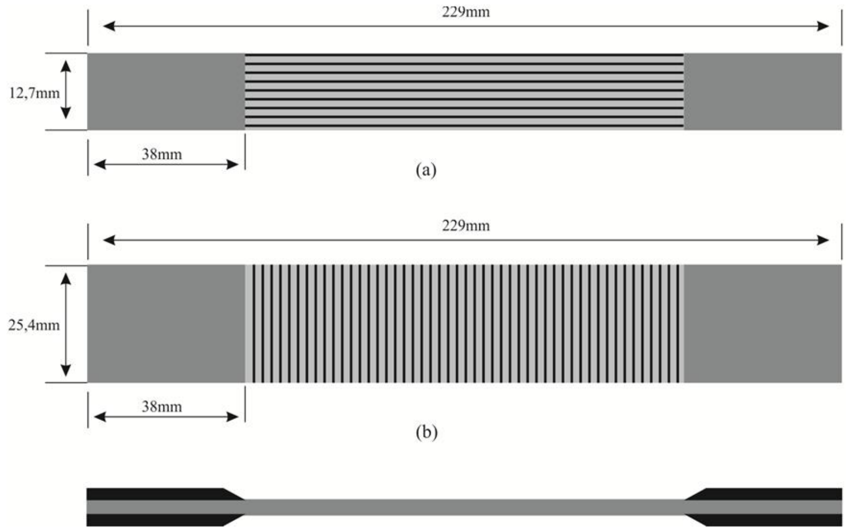


Figure 3.8 The dimensions of the tensile test specimens (a) for longitudinal (E_1, ν_{12} and X_t) and (b) for transverse (E_2 and Y_t) properties

To determine the tensile properties, specimens are placed in the tensile testing machine. The specimens are loaded step by step up to failure loads axial direction 1 mm/min. The load-deflection curve is drawn by software which is work compatible with the test machine which has axial video extensometer. The tensile strength of the woven composite plates (X_t and Y_t) are determined by dividing the failure load to cross-sectional area of the longitudinal and transverse specimens, respectively.

The results are given in Table 3.2 for all specimens. In the finite element model we used average of the results.

Table 3.2 The tensile properties of woven E-glass/epoxy specimens

Specimen Number	E_1 (MPa)	X_t (MPa)	E_2 (MPa)	Y_t (MPa)
1	26774	400	17611	291
2	26680	369	18732	322
3	25489	410	17370	321
4	24594	394	17189	316
5	27791	427	17552	283
6	26088	400	16553	301
7	26607	438	18167	315
Average	**26289**	**406**	**17596**	**307**

3.3.2. Determination of the Compressive Properties

When fiber reinforced composites are exposed to compressive load in fiber direction, fiber can buckle or failure because of locally large bending stresses. Due to this reason compression testing is the most difficult test type [39]. If the composite is compressively loaded in perpendicular to the fiber direction, matrix failure, fiber/matrix debonding will be occur [40]. Due to restrict mentioned above, compression test specimens must have specific long.

According to the ASTM D3410 standard test method, longitudinal specimens must have 140 mm long and 6.4 mm wide, as for transverse specimen must be 140 m long and 12.7 mm wide [41]. After bonded, the woven E-glass/epoxy tabs at the both side of standard specimens, gauge length of the specimen is scaled as Figure 3.9 [38].

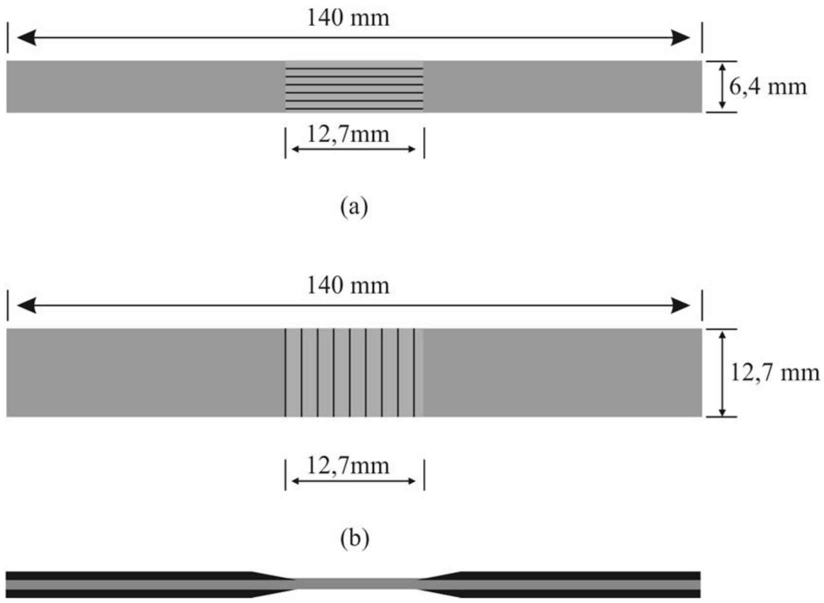


Figure 3.9 The dimensions of the compression test specimens (a) for longitudinal (X_c) and, (b) for transverse (Y_c) strengths

Then, compressive loads are applied up to failure load at 1 mm/min. crosshead velocity. Longitudinal and transverse compression strengths are calculated by dividing the failure load to the cross sectional area of the test specimen. The test results are given in Table 3.3.

Table 3.3 The compressive properties of woven E-glass/epoxy specimens

Specimen Number	**X_c (MPa)**	**Y_c (MPa)**
1	240	58
2	217	70
3	218	82
4	219	75
5	197	69
6	202	78
7	218	68
Average	**216**	**71**

3.3.3. Determination of the Shear Properties

To determine the shear modulus G_{12}, firstly we need to know Young modulus of specimen in 45° fiber direction. For this we cut the laminated composite as 45° from loading direction. The dimensions of the specimen were given in Figure 3.10 [42]. After that, E_x modulus of specimens is obtained by using biaxial video extensometer. Finally, G_{12} is calculated by using Equation 3.1 [43].

$$G_{12} = \frac{1}{\frac{4}{E_{45}} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{2\nu_{12}}{E_1}} \tag{3.1}$$

In Equation 3.1, E_1 and E_2 describe the modulus of the fiber direction and the perpendicular of the fiber direction, respectively. ν_{12} is the poison ratio in plane 1-2. The test results are given in Table 3.4 for all specimens.

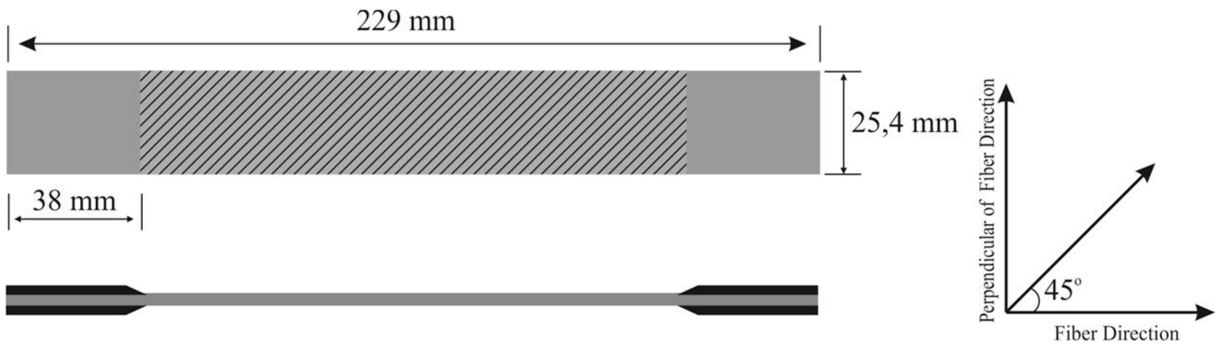


Figure 3.10 The dimensions of shear test specimens (G_{12})

Table 3.4 The shear properties of woven E-glass/epoxy specimens

Specimen Number	G_{12} (MPa)
1	3292
2	3792
3	3671
4	3987
5	3650
6	3773
7	3850
Avarage	**3708**

3.4. Experimental Set Up of Lateral Buckling

In this thesis, U-Test Tensile Testing Machine in Department of Mechanical Engineering, Uşak University was used to investigate the lateral buckling of woven E-glass/epoxy laminated composite plates with delaminations. The test machine has 50 kN load capacity. Lateral buckling tests were carried out by using compression feature of tensile test machine at velocity of 1 mm/min. To provide fixed end boundary condition for specimens, we designed a lateral buckling test fixture which made of steel (Figure 3.11). All lateral buckling tests were performed at room temperature.

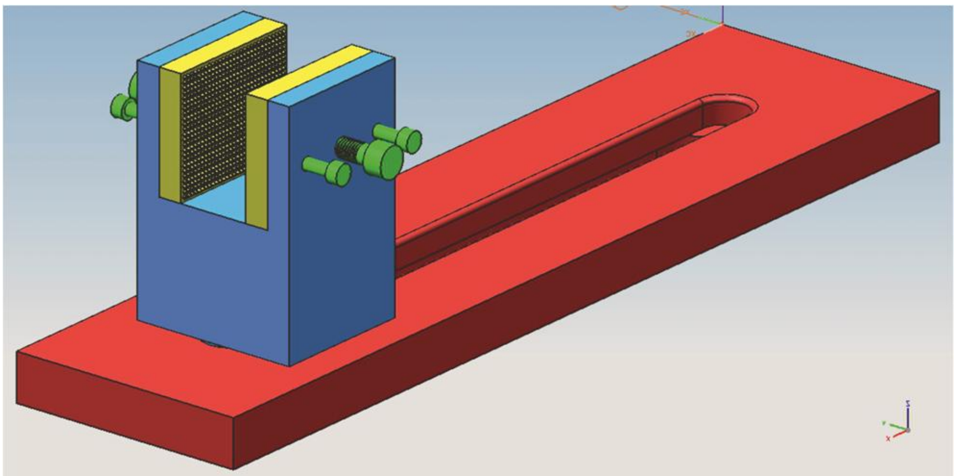


Figure 3.11 Lateral buckling test fixtures

The load-deflection curve is drawn by software which compatible works with the test machine. By the help of load-deflection curves, we determined critical lateral buckling load of specimens.

3.5. Lateral Buckling Tests Results

By using load-deflection curve obtained at the end of lateral buckling tests, critical buckling load of specimens were determined. When examine afore study in literature, three different methods stand out about to determine critical buckling load. These are;

- Membrane Strain Method
- Vertical Displacement Method
- Southwell Plot Method

In Vertical displacement method, a graph is drawn between the axial displacement of the test specimen and the applied load which are obtained from the experimental buckling load test data. The critical buckling load is obtained by taking the compressive load at the intersection of the first two tangent lines of the curve (Figure 3.12) [44].

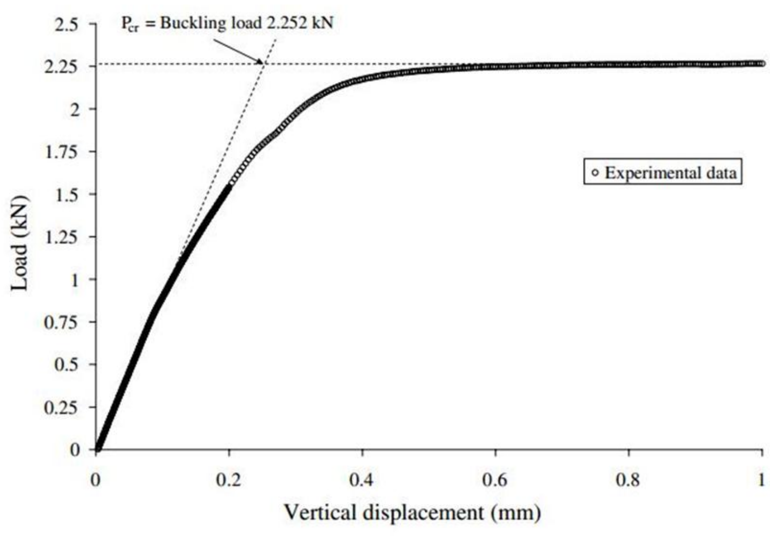


Figure 3.12 Determine the critical buckling load using vertical displacement method [44]

In Membrane Strain method, a graph is drawn between the average strain of the two strain gauges that are mounted longitudinally on the opposite sides and bonded at the center of the test specimens, and the applied load. The experimental buckling load is obtained when there is a distinct change in the slope of the curve, which is obtained by taking the intersection of the first two tangent lines of it (Figure 3.13) [44].

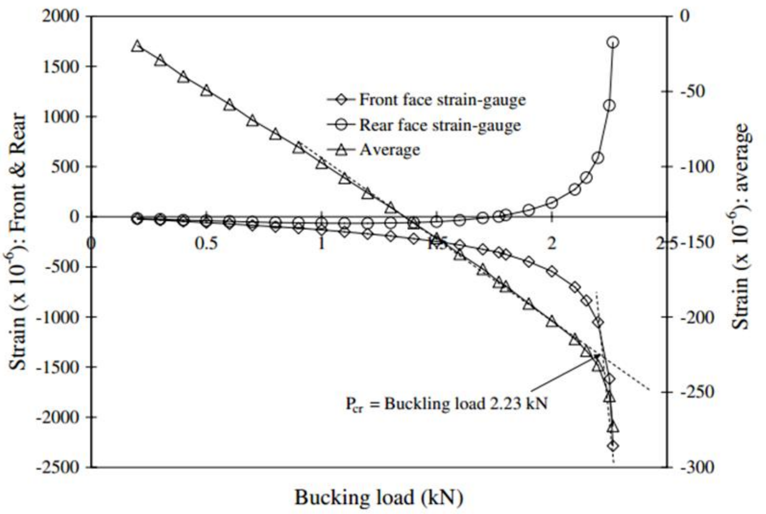


Figure 3.13 Determine critical buckling load with using membrane strain method [44]

In this study we use Southwell Plot Method to determine the experimental critical lateral buckling load. Southwell method is a plotting technique, which is used for estimating the critical load and the initial geometric imperfections of a column by using its experimental load and deflection data at loads smaller than the buckling load. According to this method, the lateral deflection to load ratio plot of a column approaches to a straight line, whose inverse slope and abscissa-intercept are the critical load and the initial lateral imperfection of the column, respectively. Since the experimental measurements at loads smaller than the buckling load are needed, the method eliminates the need for testing a column to failure [45]. An example figure for Southwell Plot Method was given in Figure 3.14.

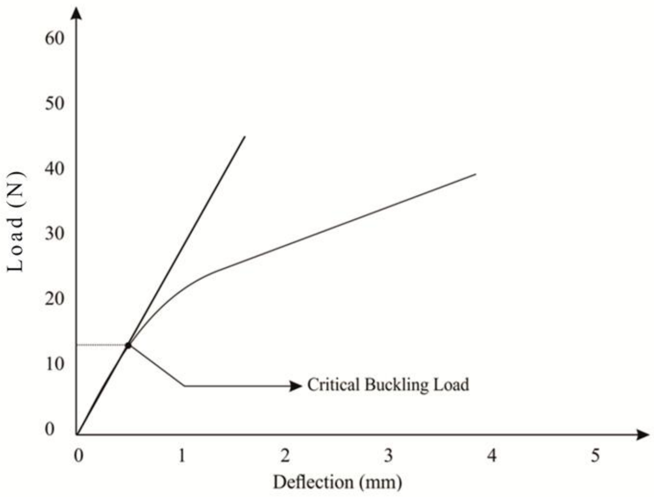


Figure 3.14 Determine critical buckling load with using Southwell Plot Method

Application of lateral load and supporting conditions of test specimens were given in Figure 3.15. Lateral buckling specimens can be sustained until crosshead of machine displaced 6 mm as vertically.

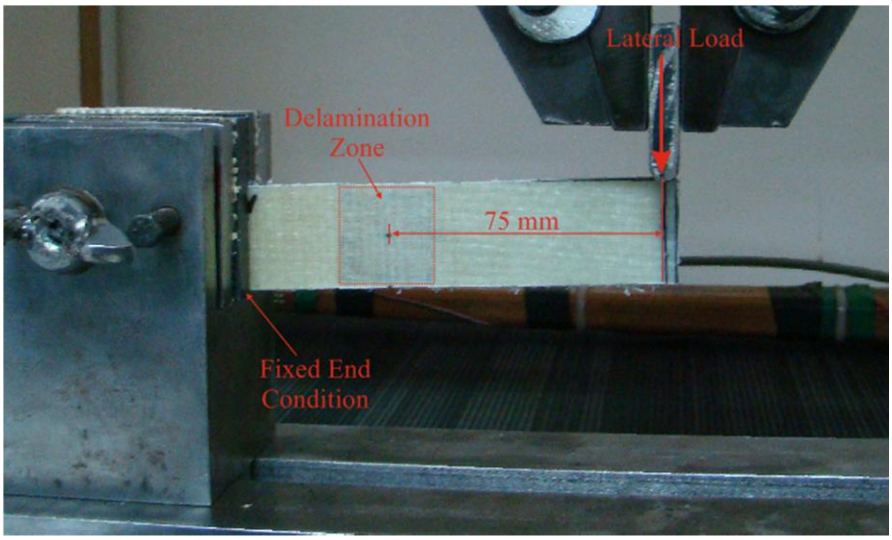


Figure 3.15 The lateral buckling test conditions

During lateral buckling tests, specimens bended and after that they buckled because of lateral load (Figure 3.16).

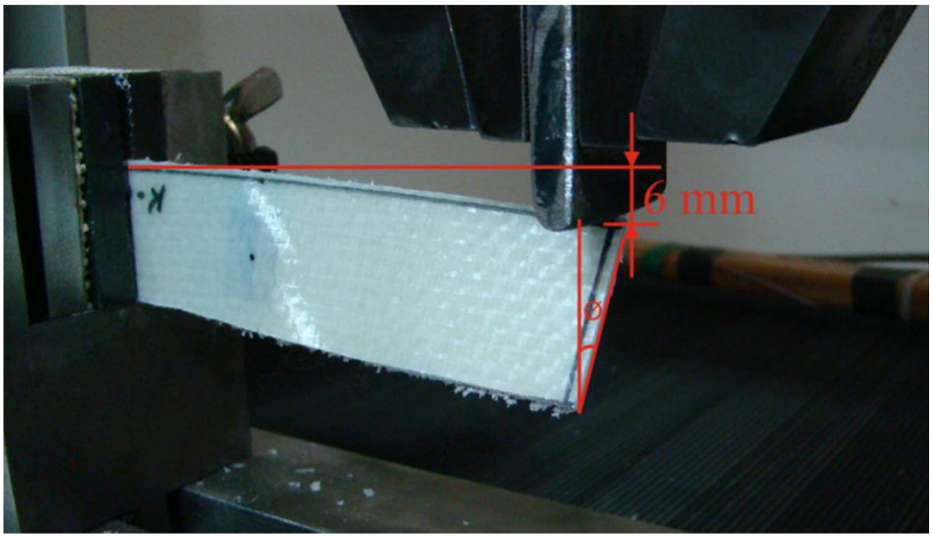


Figure 3.16 Behavior of test specimens under lateral load

Load-deformation curve of test specimens, which have fixed delamination area as 600 mm^2, were given in Figure 3.17-3.24 with critical buckling values, respectively.

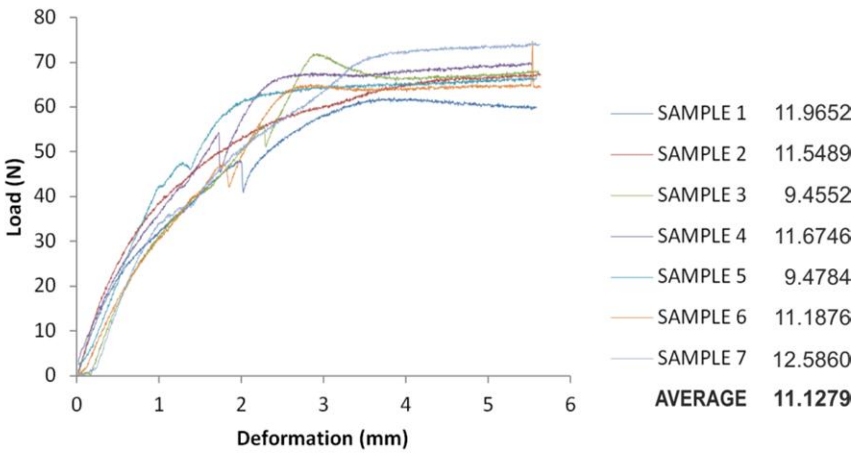


Figure 3.17 Load-deformation curves of laminated composite plate with square delamination having fixed area for a/b=1

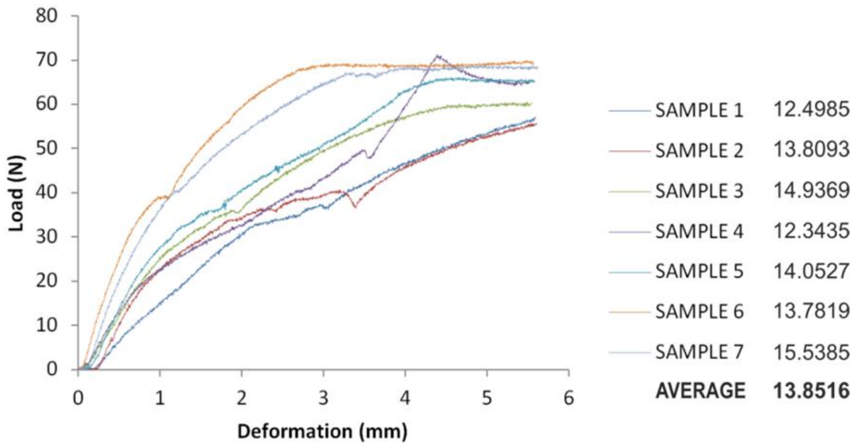


Figure 3.18 Load-deformation curves of laminated composite plate with rectangular delamination having fixed area for a/b=2

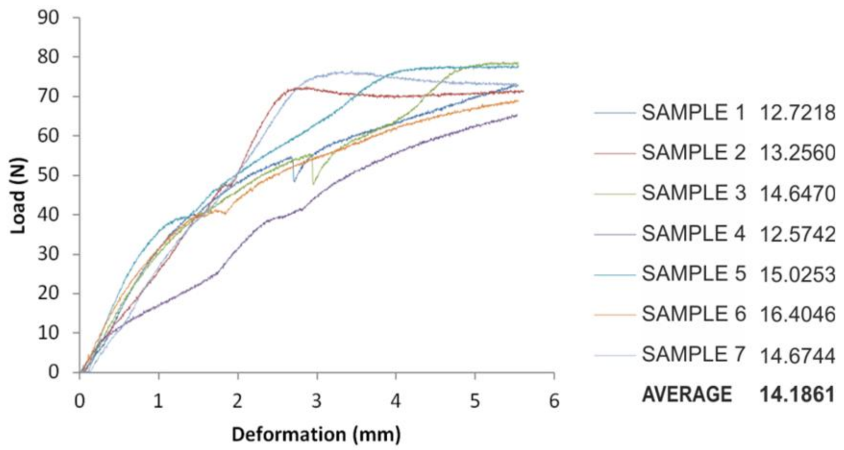


Figure 3.19 Load-deformation curves of laminated composite plate with rectangular delamination having fixed area for a/b=3

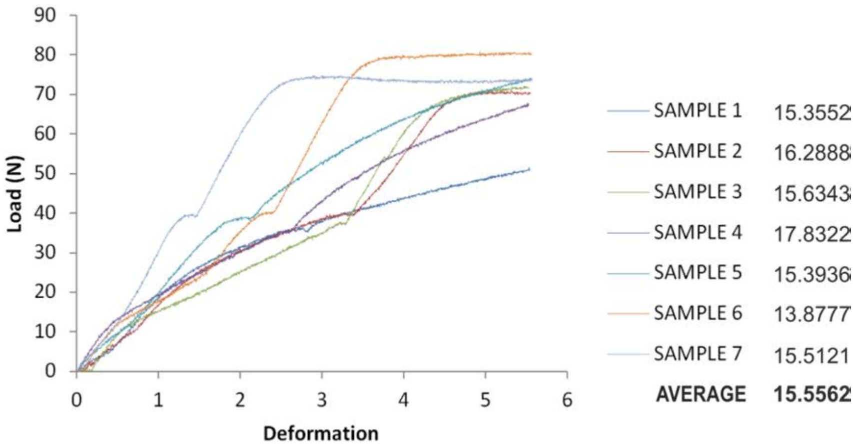


Figure 3.20 Load-deformation curves of laminated composite plate with rectangular delamination having fixed area for a/b=4

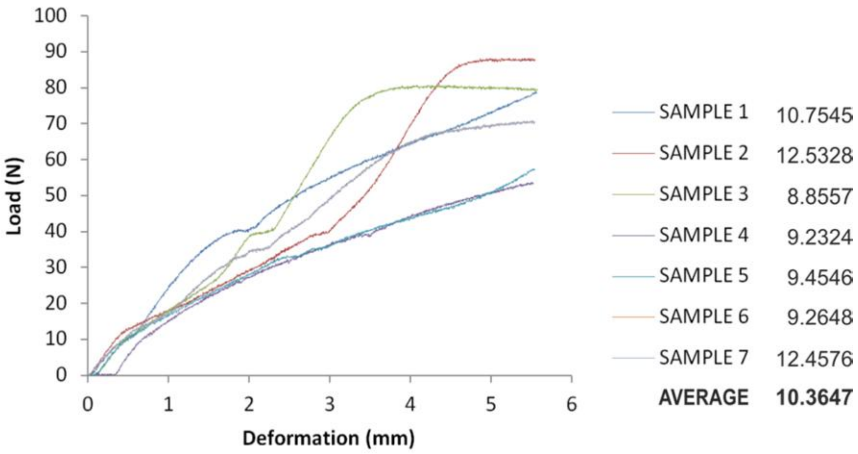


Figure 3.21 Load-deformation curves of laminated composite plate with circular delamination having fixed area for a/b=1

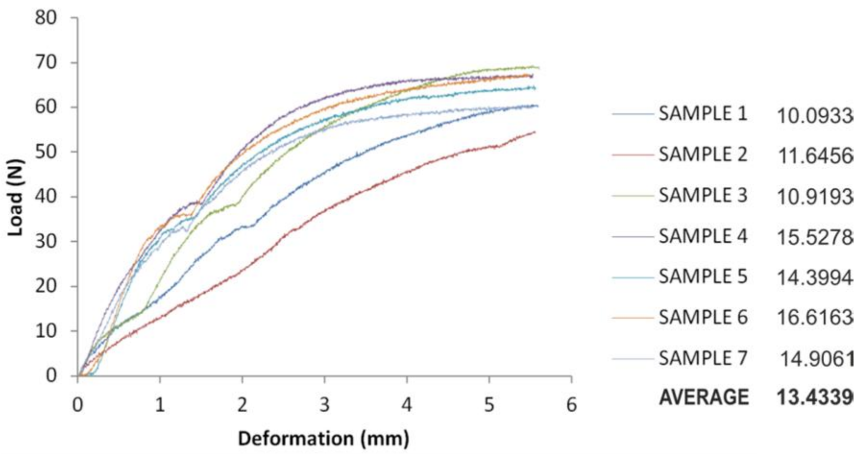


Figure 3.22 Load-deformation curves of laminated composite plate with elliptical delamination having fixed area for a/b=2

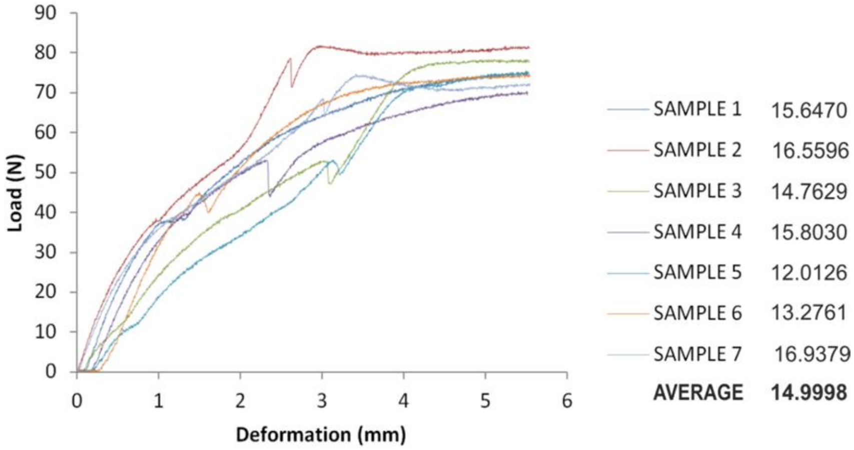


Figure 3.23 Load-deformation curves of laminated composite plate with elliptical delamination having fixed area for a/b=3

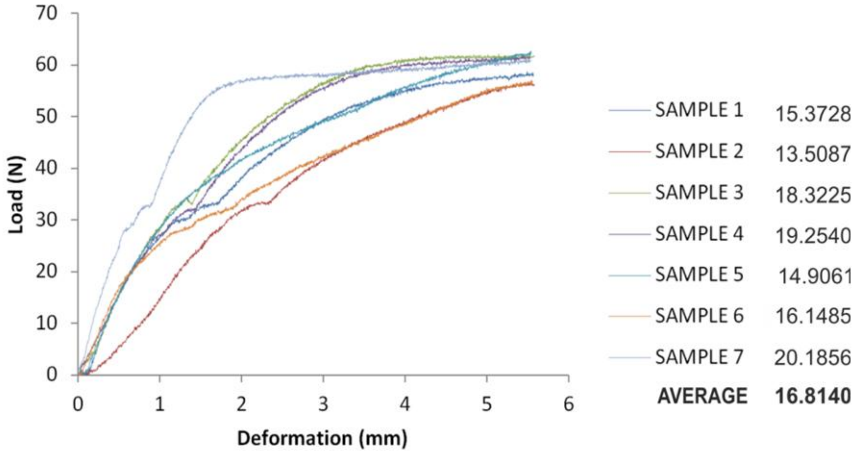


Figure 3.24 Load-deformation curves of laminated composite plate with elliptical delamination having fixed area for a/b=4

Load-deformation curve of test specimens, which have delamination with fixed a/b aspect ratio, were given in Figure 3.25-3.38 with critical buckling values, respectively.

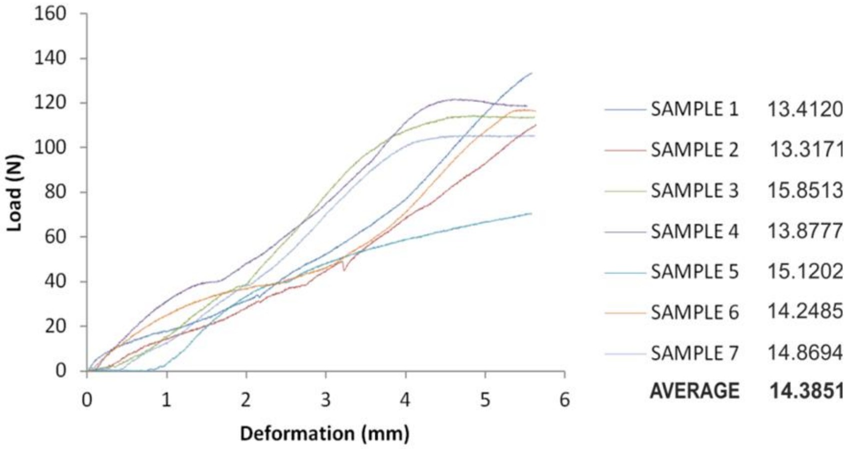


Figure 3.25 Load-deformation curves of laminated composite plate with rectangular delamination having fixed a/b aspect ratio for a/b=0.5

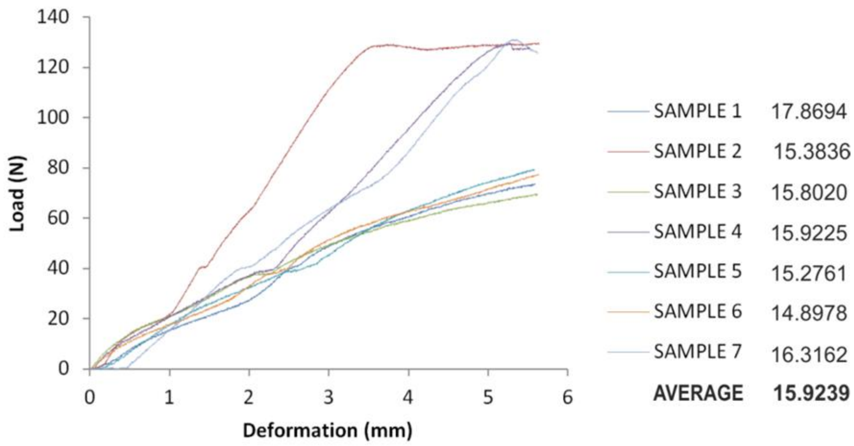


Figure 3.26 Load-deformation curves of laminated composite plate with rectangular delamination having fixed a/b aspect ratio for a/b=0.6

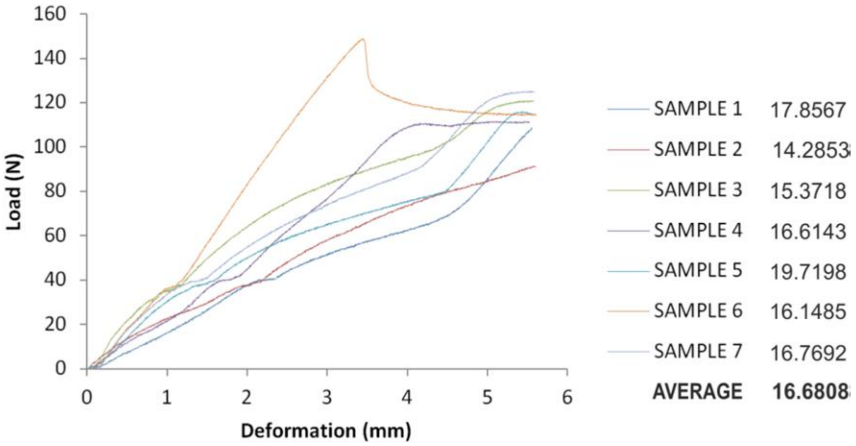


Figure 3.27 Load-deformation curves of laminated composite plate with rectangular delamination having fixed a/b aspect ratio for a/b=0.75

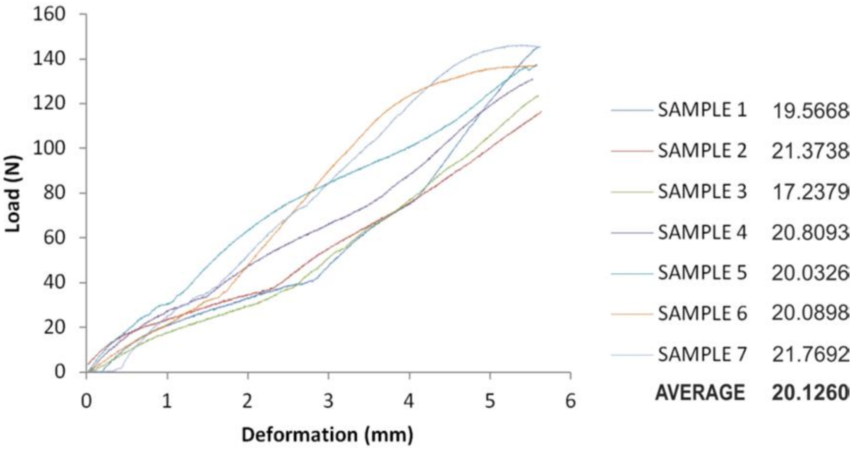


Figure 3.28 Load-deformation curves of laminated composite plate with square delamination for having fixed a/b aspect ratio a/b=1

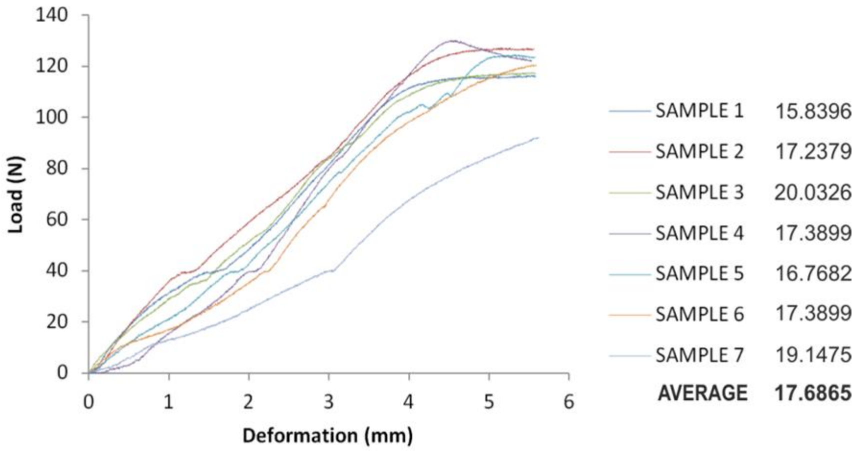


Figure 3.29 Load-deformation curves of laminated composite plate with rectangular delamination for having fixed a/b aspect ratio a/b=1.3

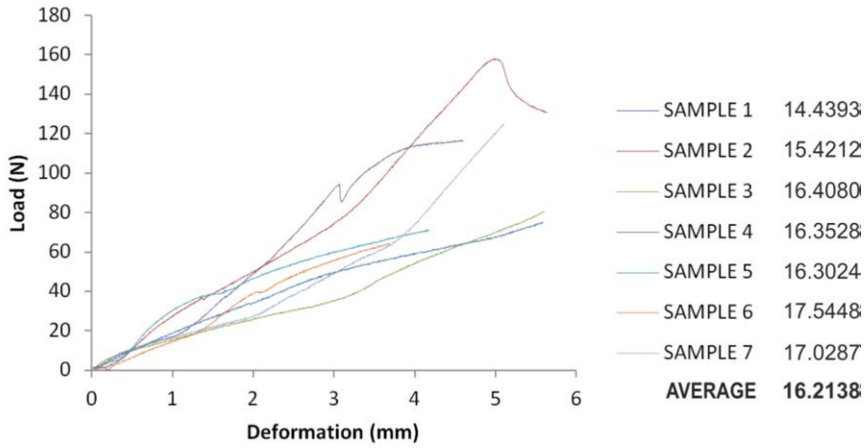


Figure 3.30 Load-deformation curves of laminated composite plate with rectangular delamination having fixed a/b aspect ratio for a/b=1.6

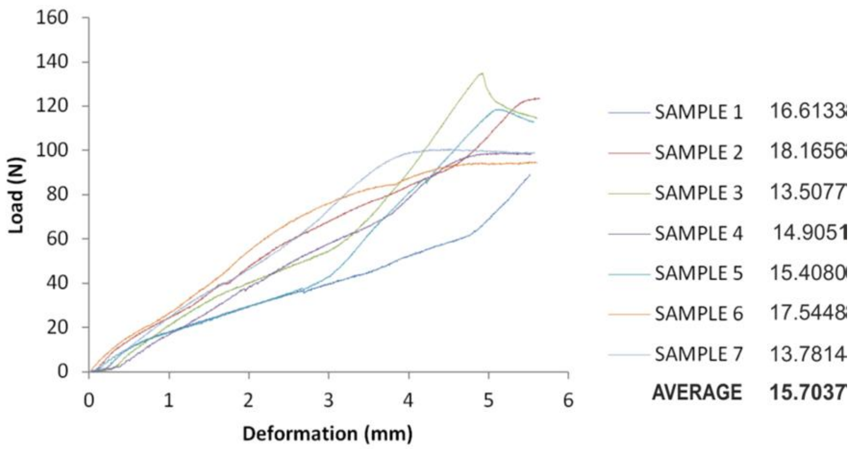


Figure 3.31 Load-deformation curves of laminated composite plate with rectangular delamination having fixed a/b aspect ratio for a/b=2

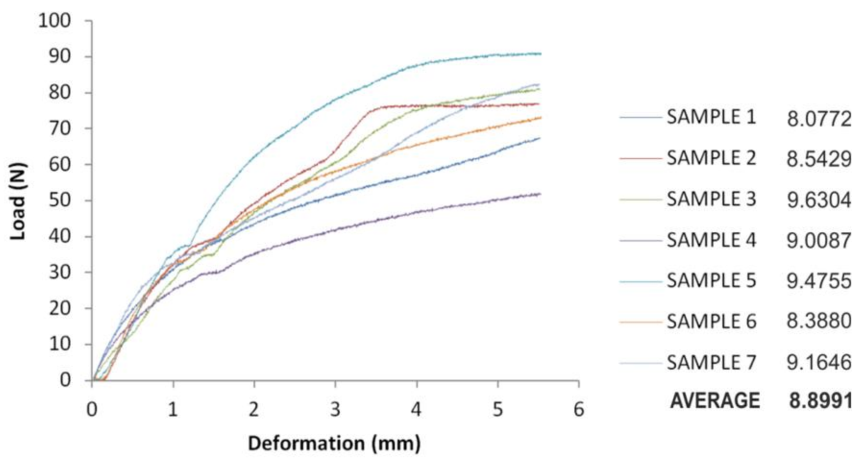


Figure 3.32 Load-deformation curves of laminated composite plate with elliptical delamination having fixed a/b aspect ratio for a/b=0.5

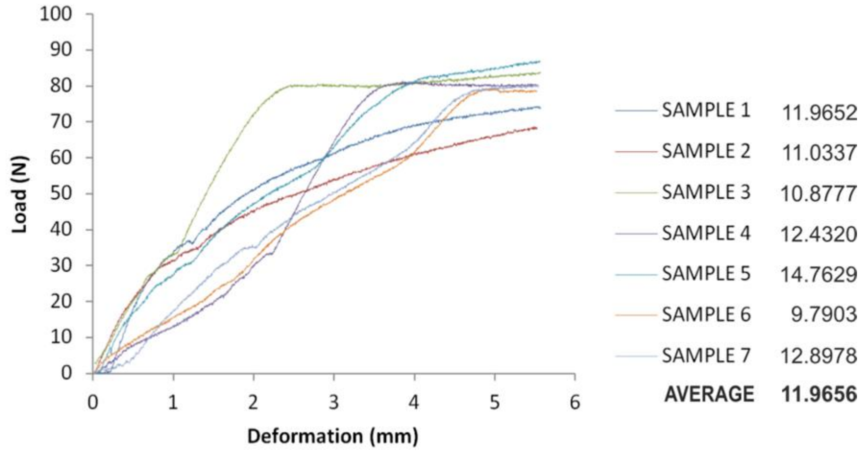


Figure 3.33 Load-deformation curves of laminated composite plate with elliptical delamination having fixed a/b aspect ratio for a/b=0.6

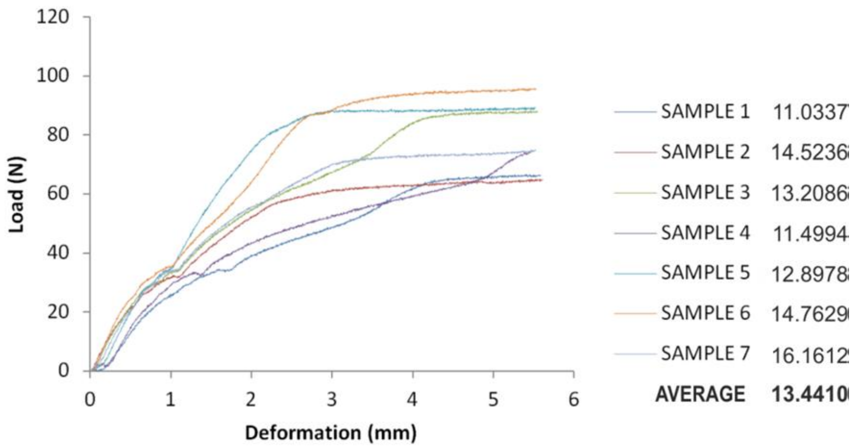


Figure 3.34 Load-deformation curves of laminated composite plate with elliptical delamination having fixed a/b aspect ratio for a/b=0.75

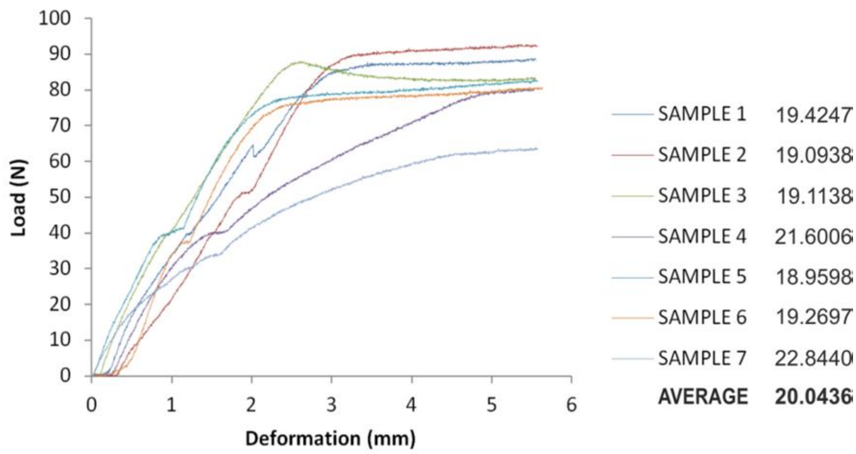


Figure 3.35 Load-deformation curves of laminated composite plate with circular delamination having fixed a/b aspect ratio for a/b=1

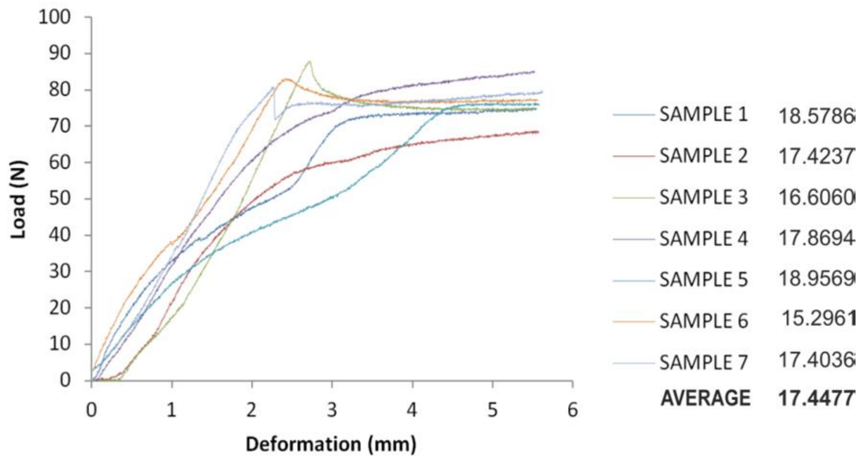


Figure 3.36 Load-deformation curves of laminated composite plate with elliptical delamination having fixed a/b aspect ratio for a/b=1.3

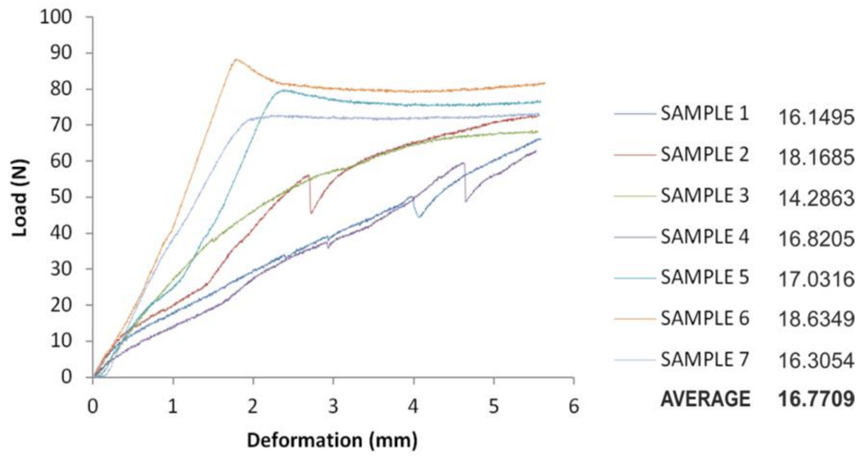


Figure 3.37 Load-deformation curves of laminated composite plate with elliptical delamination having fixed a/b aspect ratio for a/b=1.6

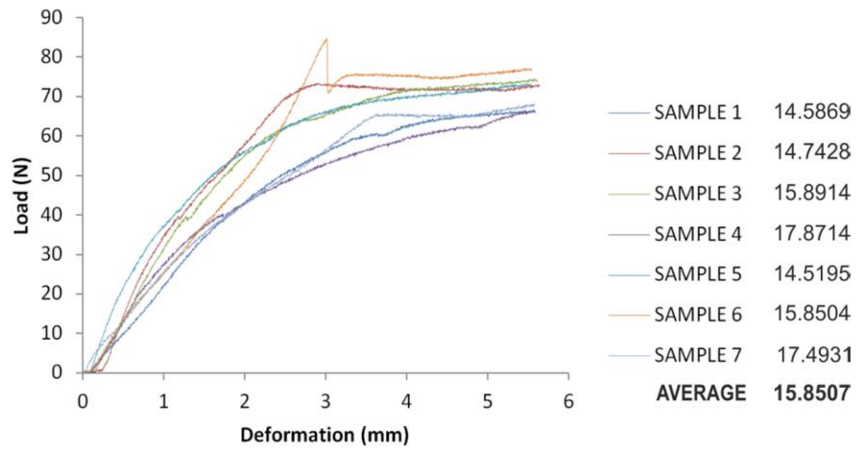


Figure 3.38 Load-deformation curves of laminated composite plate with elliptical delamination having fixed a/b aspect ratio for a/b=2

Load-deformation curve of lateral test specimens without delamination, were given in Figure 3.39 with critical buckling values.

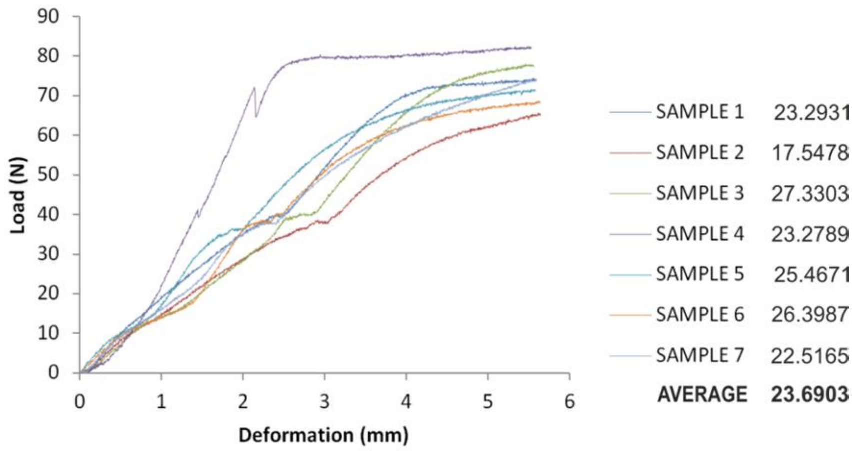


Figure 3.39 Load-deformation curves of laminated composite plate without delamination

CHAPTER FOUR: WEIBULL ANALYSIS

4.1. Introduction

The Weibull distribution is named after its originator, the Swedish physicist Waloddi Weibull, who in 1939 used it to model the distribution of the breaking strength of materials and in 1951 for a wide range of other applications. Weibull analysis is common used in data analysis which concerned life time and statistical model in engineering in order to create reliability model. Some of that are given below;

- Plotting the data and interpreting the plot
- Failure forecasting and prediction
- Evaluating corrective action plans
- Engineering change substantiation
- Maintenance planning and cost effective replacement strategies
- Spare parts forecasting
- Warranty analysis and support cost predictions
- Calibration of complex design systems, i.e., CAD\CAM, finite element analysis, etc.
- Recommendations to management in response to service problems

In the recent past, Weibull analysis underlies reliability studies which are in engineering field. The number of studies, concerned with this issue is increasing, with come into prominence modeling of mechanical properties of materials. For the Weibull distribution, there are two popular forms as named two and three parameter Weibull analysis. The distribution function of the three-parameter Weibull distribution is given as [46];

$$F(x;a,b,c) = 1 - \exp\left[-\left(\frac{x-a}{b}\right)^{c}\right] \rightarrow a \geq 0, b \geq 0, c \geq 0 \qquad (4.1)$$

where a, b, and c are the location, scale, and shape parameters respectively. If a=0 in Equation 4.1, the distribution function of the two parameter Weibull distribution is acquired. The three-parameter Weibull distribution is suitable for situations in which an extreme value cannot take values less than a.

In the context of study, the two-parameter Weibull distribution, which can be used in lateral buckling studies, will be considered. The distribution function in this case can then be written as follows:

$$F(x;b,c) = 1 - \exp\left[-\left(\frac{x}{b}\right)^{c}\right] \rightarrow b \geq 0, c \geq 0 \qquad (4.2)$$

F(x; b, c), represents the probability that the lateral buckling load is equal to or less than x. Using the equality *F(x; b, c)+R(x; b, c)=1*, the reliability *R(x; b, c),* that is, the probability that the bearing strength is at least x, is defined as [43];

$$R(x;b,c) = \exp\left[-\left(\frac{x}{b}\right)^{c}\right] \rightarrow b \geq 0, c \geq 0 \qquad (4.3)$$

The parameters b and c of the distribution function *F(x; b, c)* are estimated from observations. The methods usually employed in estimation of these parameters are method of linear regression, method of maximum likelihood, and method of moments. This method is based on transforming Equation 4.2 into $1-F(x;\ b,\ c)=exp[-(x/(b)^{c}]$ and taking double logarithms of both sides. Hence, a linear regression model in the form *Y=mX+r* is acquired;

$$\ln\left[\ln\left(\frac{1}{1-F(x;b,c)}\right)\right] = c\ln(x) - c\ln(b) \qquad (4.4)$$

F(x; b, c) is an unknown in Equation 4.4 and therefore it is estimated from observed values; order *n* observations from smallest to largest, and let x_i denote the i^{th} smallest observation (i=1 corresponds to the smallest and i=n corresponds to the largest). Then a good estimator of $F(x_i; b, c)$ is the median rank of x_i:

$$F'(x_i; b, c) = \frac{i - 0.3}{n + 0.4} \tag{4.5}$$

When linear regression, based on least squares method, is applied to the paired values;

$$(X, Y) = \left(\ln(x_i), \ln\left[\frac{1}{1 - F'(x_i; b, c} \right] \right) \tag{4.6}$$

for the model in Equation 4.4, the parameter estimates for *b* and *c* are obtained.

Among these methods, use of linear regression goes back to the days when computers were not available: the linear regression line was fitted manually with the help of Weibull graph papers. Linear regression is still common among practitioners, and will be used for parameter estimation in this study. However, today software programs with statistical abilities such as MS Excel, SPSS^{TM} and Microcal Origin have replaced Weibull graph papers [48].

4.2. Results of Weibull Analysis

In this study, the two-parameter Weibull distribution, which can be used in lateral buckling studies, will be considered. We benefited from Weibull++8 which designed ReliaSoft Corporation. ReliaSoft's Weibull 8++ software tool is the industry standard in life data analysis (Weibull analysis) for thousands of companies worldwide. The software performs life data analysis utilizing multiple lifetime distributions (including all forms of the Weibull distribution), with a clear and concise interface geared toward reliability engineering. Built by reliability engineers for reliability engineers, this package continues to raise the bar for statistical analysis software for reliability applications. The screen of Weibull 8++ is given in Figure 4.1.

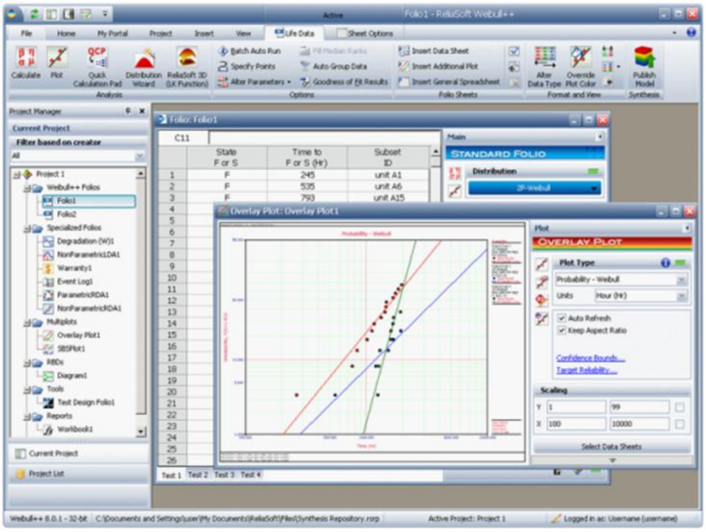
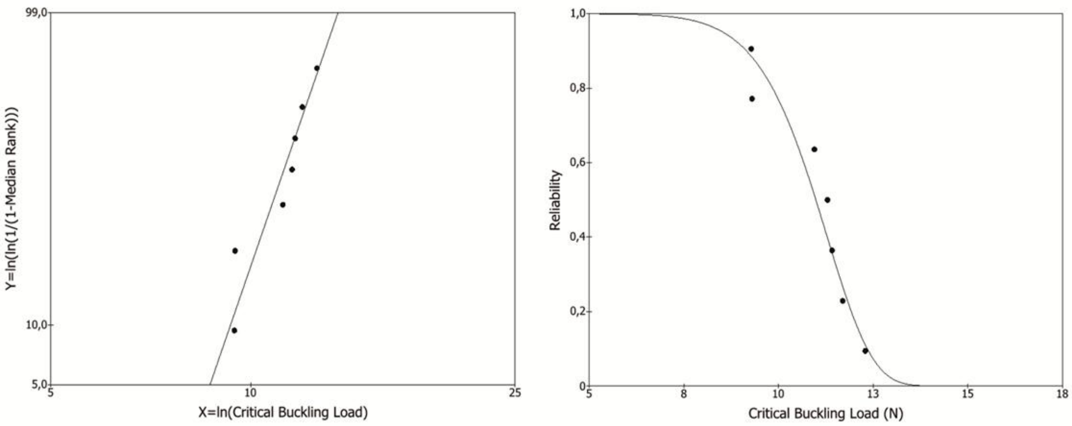


Figure 4.1 The mainscreen of ReliaSoft Weibull 8++

Weibull 8++ provides the most comprehensive toolset available for reliability life data analysis, calculated results, plots and reporting. The software supports all data types and all commonly used product lifetime distributions (including the Weibull model and the mixed Weibull model as well as the Exponential, Lognormal, Normal, Generalized Gamma, Gamma, Logistic, Loglogistic, Gumbel, Bayesian-Weibull and Competing Failure Modes).The software is also packed with tools for related reliability analyses, such as warranty data analysis, degradation data analysis, non-parametric data analysis, recurrent event data analysis and reliability test design.

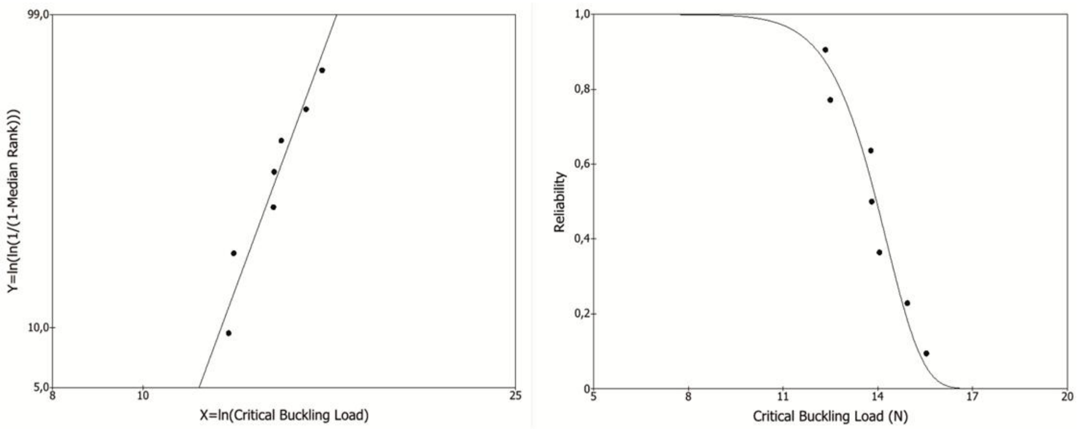
Weibull analysis were performed using with critical buckling load values of test specimens, which given in Chapter three. Result of Weibull analysis, regression line and Weibull distribution curve were obtained.

Regression line and Weibull distribution curve of specimens, which have fixed delamination area, were given in Figure 4.2-4.9.



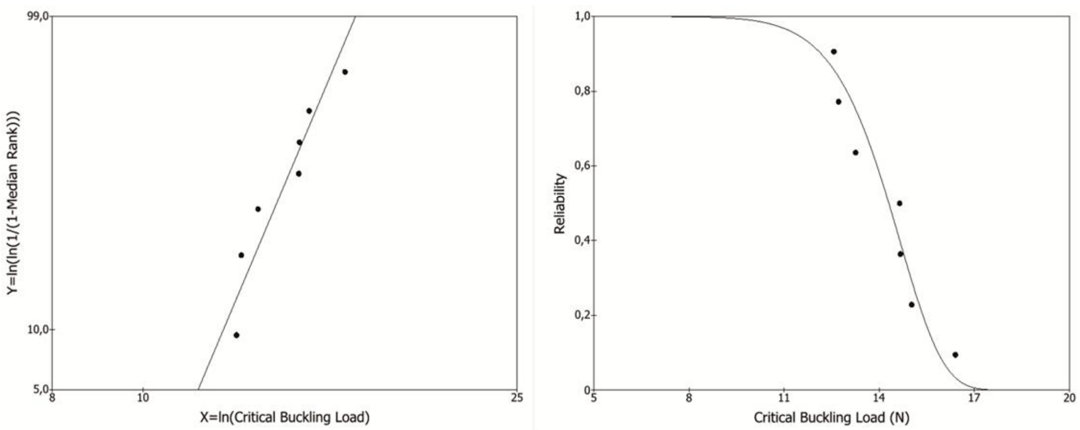
(a) (b)

Figure 4.2 Statistical graphs of the lateral test specimens with square delamination having fixed area for a/b=1 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.3 Statistical graphs of the lateral test specimens with rectangular delamination having fixed area for a/b=2 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.4 Statistical graphs of the lateral test specimens with rectangular delamination having fixed area for a/b=3 (a) regression line and (b) Weibull distribution

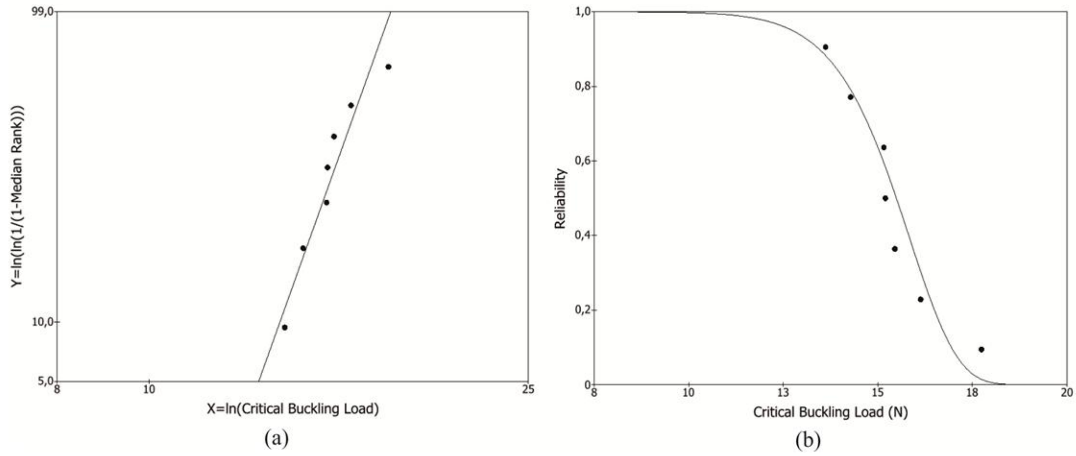


Figure 4.5 Statistical graphs of the lateral test specimens with rectangular delamination having fixed area for a/b=4 (a) regression line and (b) Weibull distribution

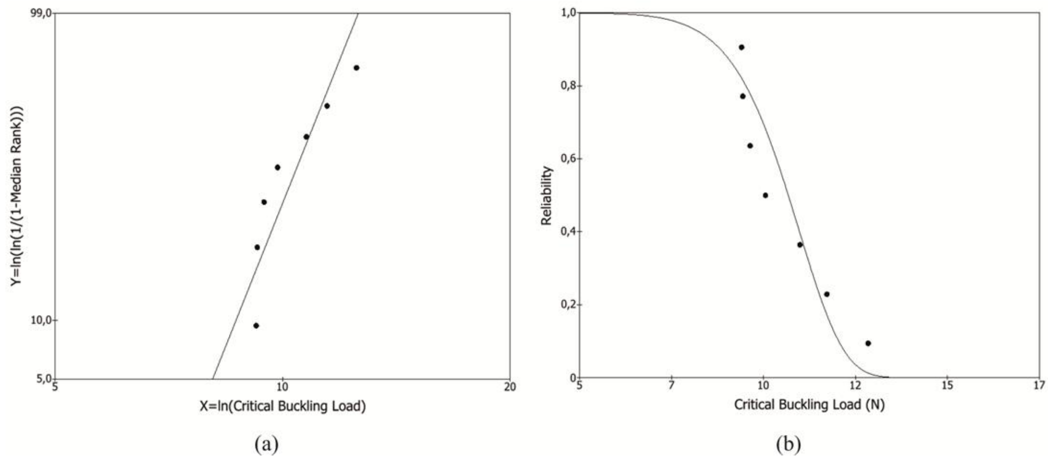


Figure 4.6 Statistical graphs of the lateral test specimens with circular delamination having fixed area for a/b=1 (a) regression line and (b) Weibull distribution

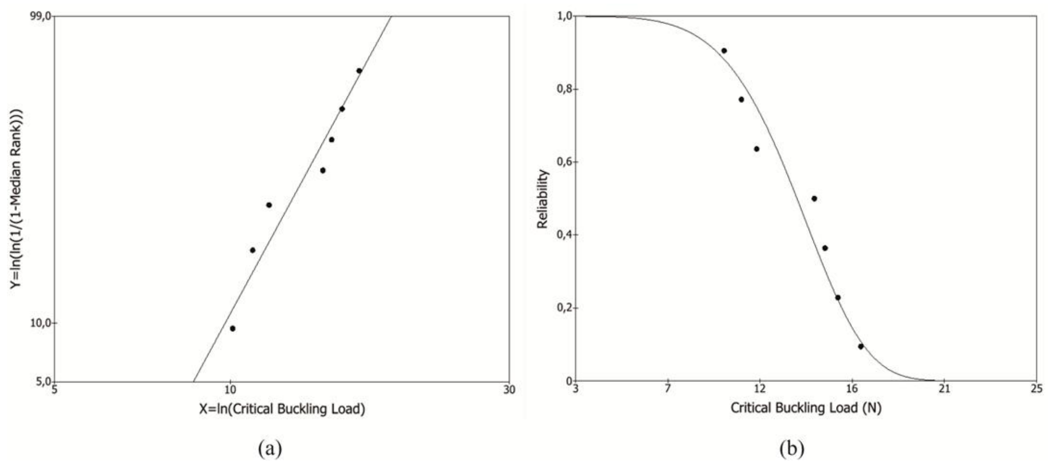


Figure 4.7 Statistical graphs of lateral test specimens with elliptical delamination having fixed area for a/b=2 (a) regression line and (b) Weibull distribution

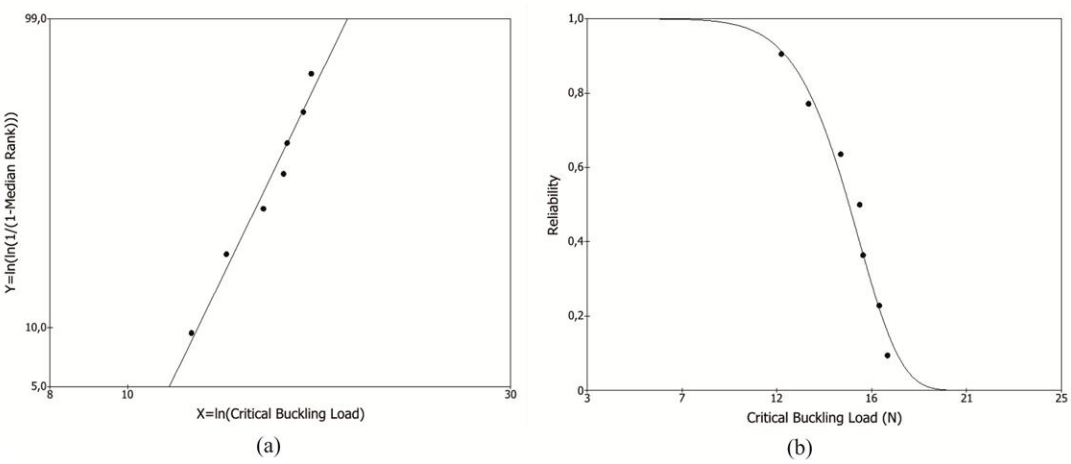


Figure 4.8 Statistical graphs of lateral test specimens with elliptical delamination having fixed area for a/b=3 (a) regression line and (b) Weibull distribution

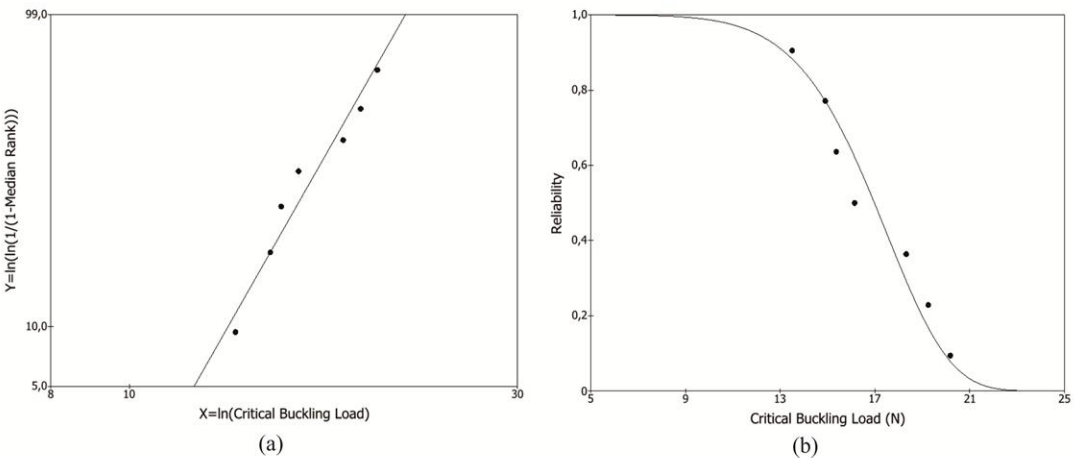
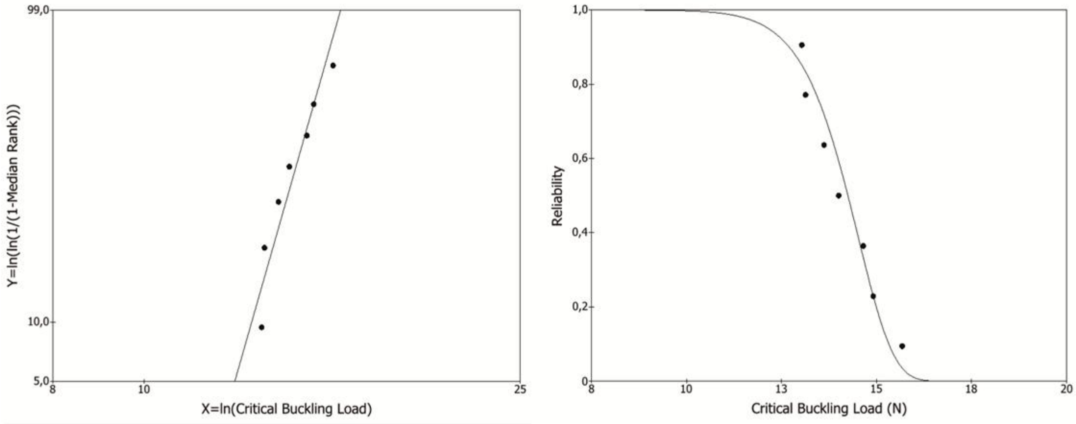


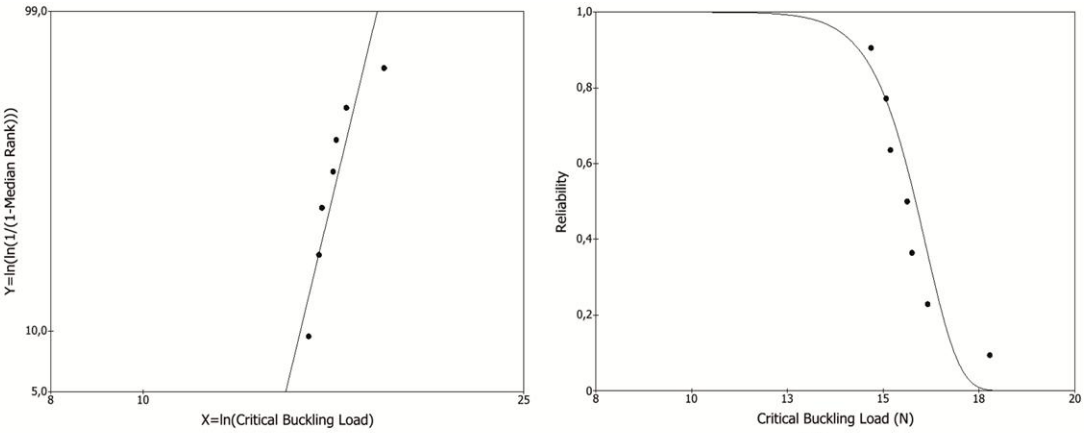
Figure 4.9 Statistical graphs of the lateral test specimens with elliptical delamination having fixed area for a/b=4 (a) regression line and (b) Weibull distribution

Regression line and Weibull distribution curve of specimens, which have delamination with fixed a/b aspect ratio, were given in Figure 4.10-4.23.



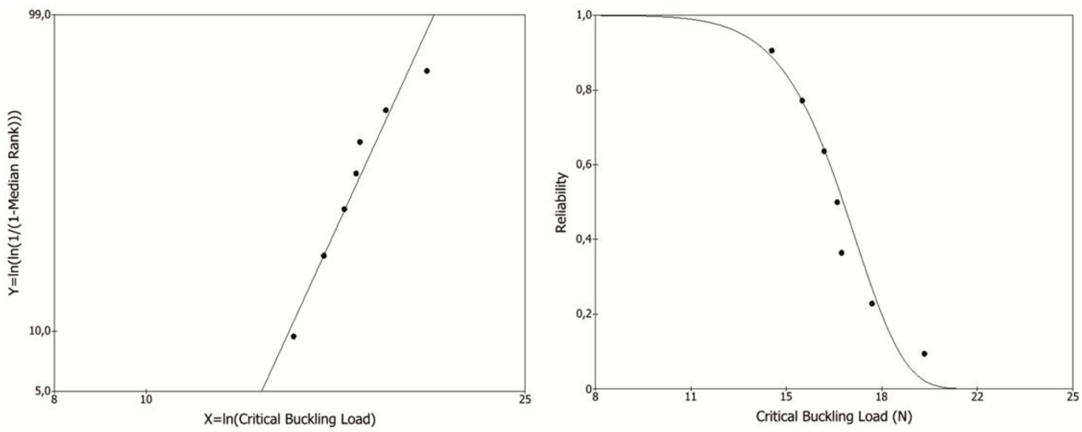
(a) (b)

Figure 4.10 Statistical graphs of the lateral test specimens with rectangular delamination having fixed a/b aspect ratio for a/b=0.5 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.11 Statistical graphs of the lateral test specimens with rectangular delamination having fixed a/b aspect ratio for a/b=0.6 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.12 Statistical graphs of lateral test specimens with rectangular delamination having fixed a/b aspect ratio for a/b=0.75 (a) regression line and (b) Weibull distribution

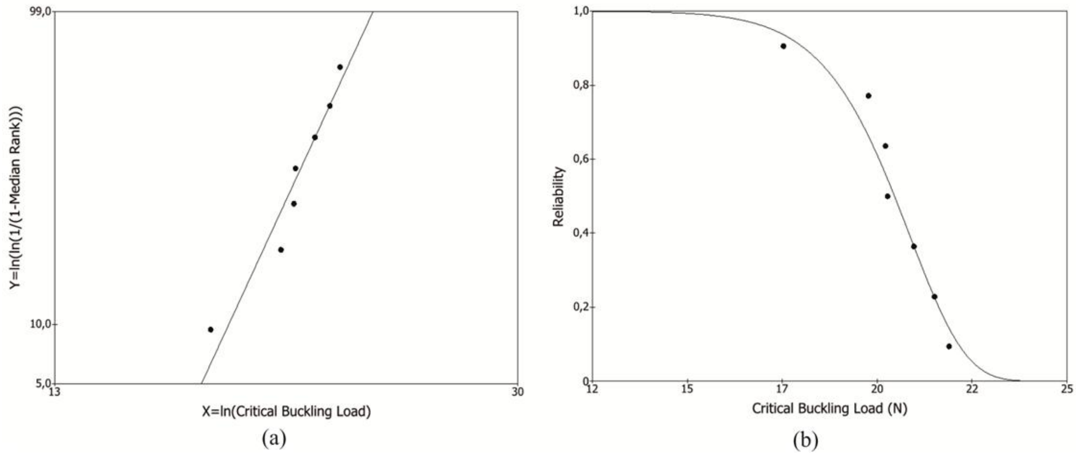


Figure 4.13 Statistical graphs of lateral test specimens with square delamination having fixed a/b aspect ratio for a/b=1 (a) regression line and (b) Weibull distribution

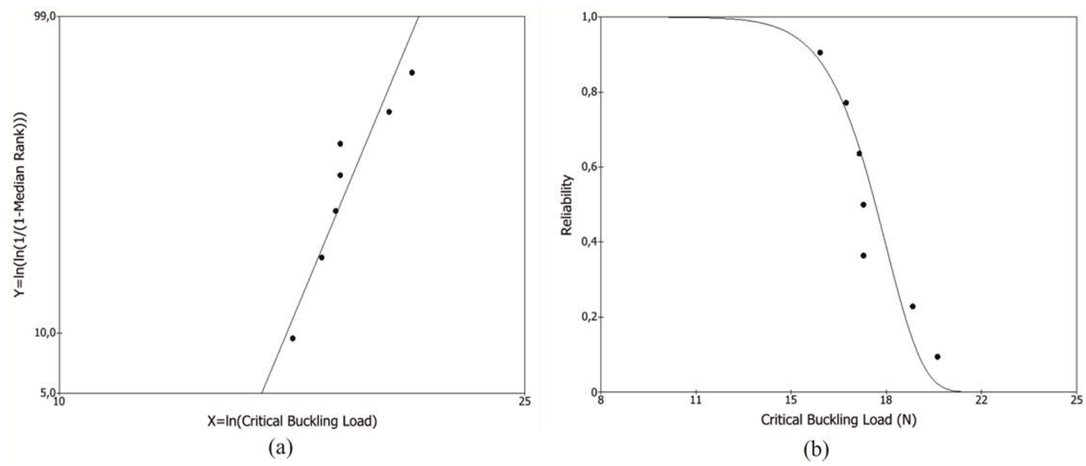


Figure 4.14 Statistical graphs of the lateral test specimens with rectangular delamination having fixed a/b aspect ratio for a/b=1.3 (a) regression line and (b) Weibull distribution

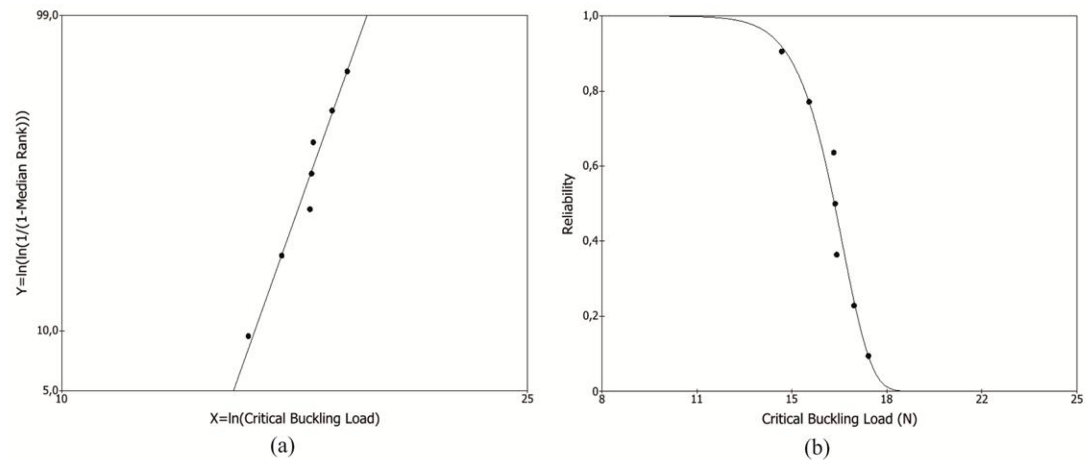
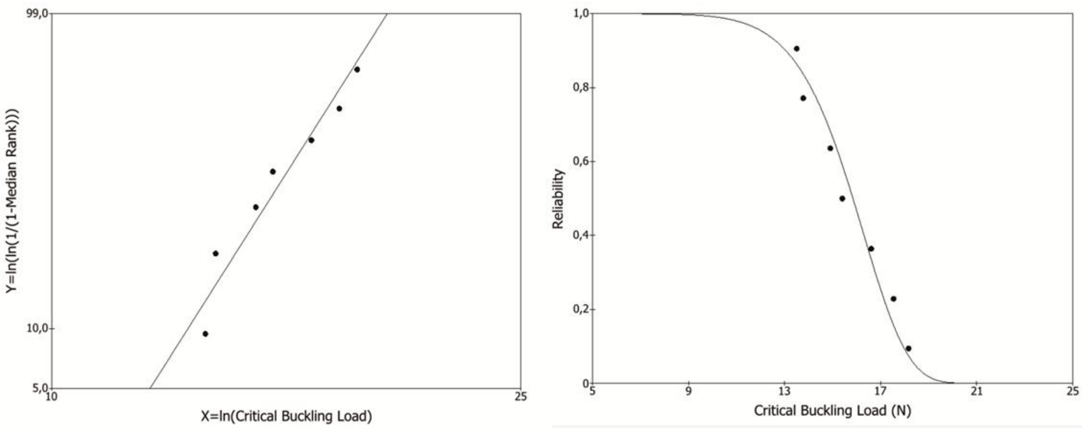
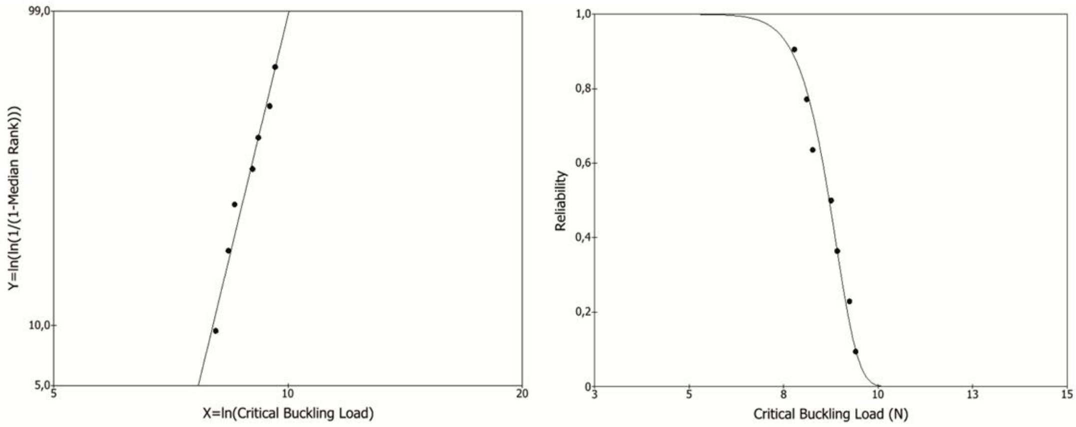


Figure 4.15 Statistical graphs of the lateral test specimens with rectangular delamination having fixed a/b aspect ratio for a/b=1.6 (a) regression line and (b) Weibull distribution



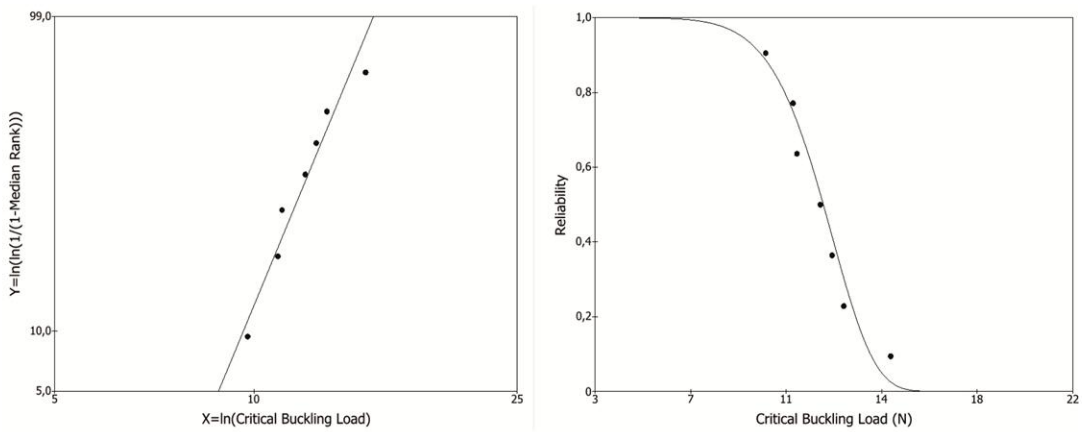
(a) (b)

Figure 4.16 Statistical graphs of the lateral test specimens with rectangular delamination having fixed a/b aspect ratio for a/b=2 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.17 Statistical graphs of the lateral test specimens with elliptical delamination having fixed a/b aspect ratio for a/b=0.5 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.18 Statistical graphs of the lateral test specimens with elliptical delamination having fixed a/b aspect ratio for a/b=0.6 (a) regression line and (b) Weibull distribution

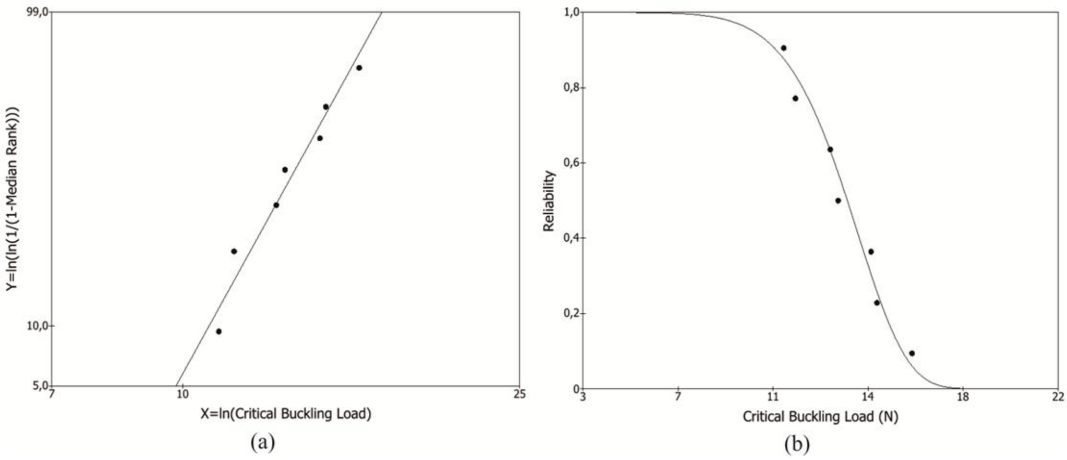


Figure 4.19 Statistical graphs of the lateral test specimens with elliptical delamination having fixed a/b aspect ratio for a/b=0.75 (a) regression line and (b) Weibull distribution

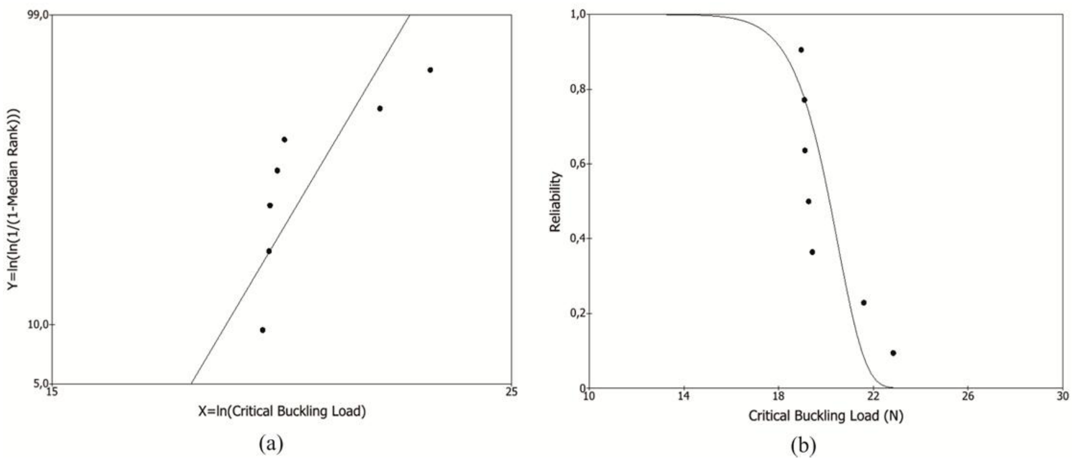


Figure 4.20 Statistical graphs of lateral test specimens with circular delamination having fixed a/b aspect ratio for a/b=1 (a) regression line and (b) Weibull distribution

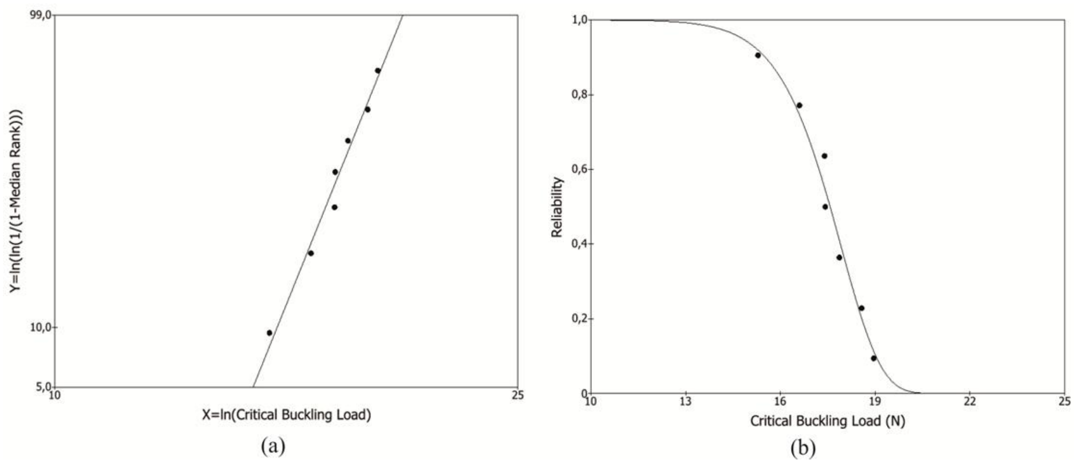
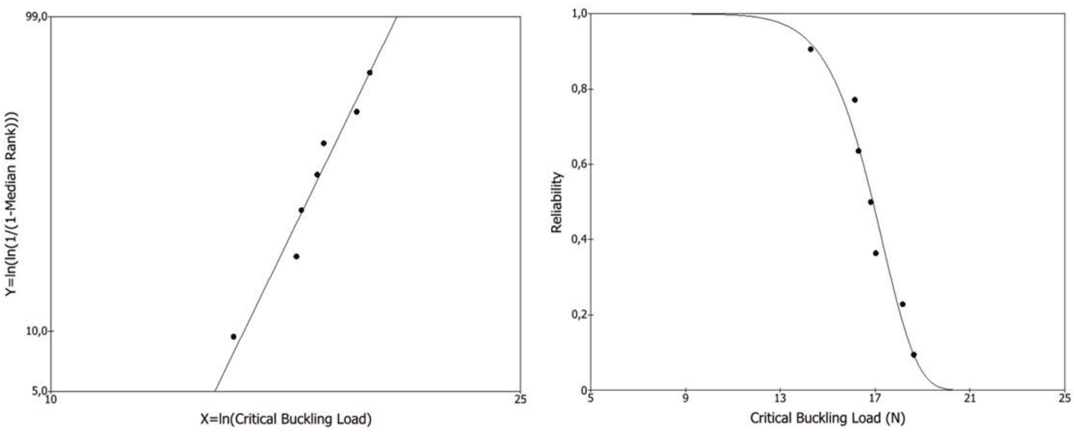
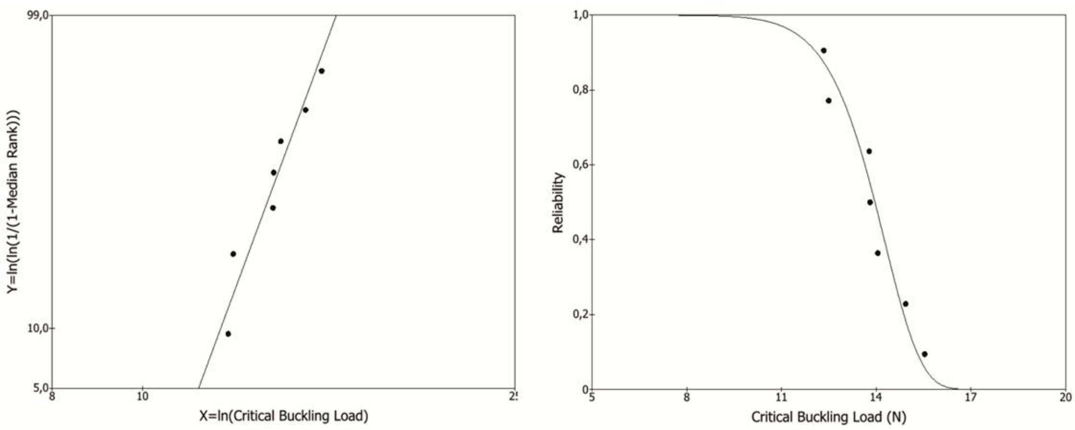


Figure 4.21 Statistical graphs of the lateral test specimens with elliptical delamination having fixed a/b aspect ratio for a/b=1.3 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.22 Statistical graphs of the lateral test specimens with elliptical delamination having fixed a/b aspect ratio for a/b=1.6 (a) regression line and (b) Weibull distribution



(a) (b)

Figure 4.23 Statistical graphs of the lateral test specimens with elliptical delamination having fixed a/b aspect ratio for a/b=2 (a) regression line and (b) Weibull distribution

Regression line and Weibull distribution curve of specimens without delamination were given in Figure 4.24.

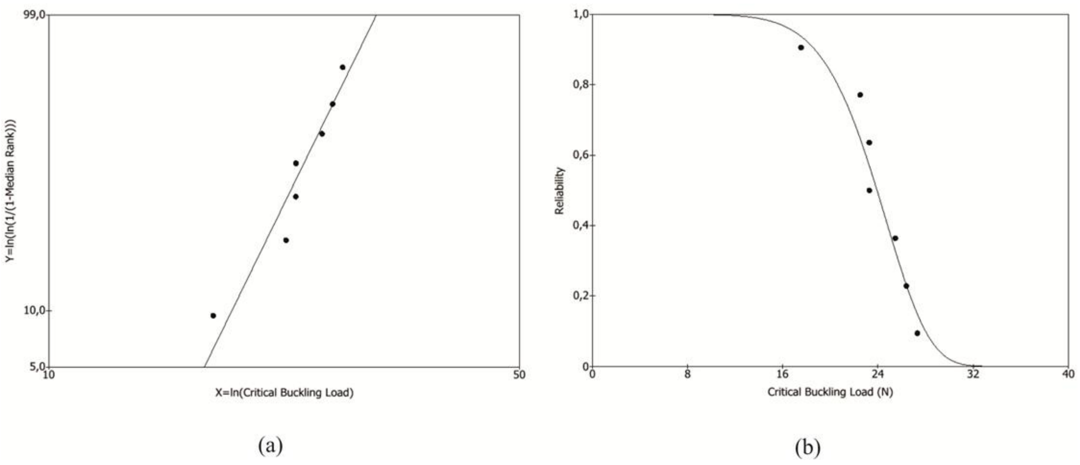


Figure 4.24 Statistical graphs of the lateral test specimens without delamination (a) regression line and (b) Weibull distribution

Composite materials are generally used in important engineering applications. One of these is woven E-glass/epoxy laminated composite and lateral buckling strength variation in of this composite has been modeled with using Weibull distribution. The aim of study is rejection of assumption that the lateral buckling strength of laminated composite materials is taken as an average of experimental results. In this context Weibull distribution allows researchers to describe the lateral buckling strength of a laminated composite material in terms of a reliability function. Also Weibull distribution curve provides an opinion about necessary mechanical properties with certain confidence to the end user.

In this master thesis; Weibull distributions graphs, which have 95% reliability coefficient, were performed. On the graphs, x-axis defines critical bucking value for lateral load, and y-axis define reliability coefficient. In order to determine reliability of critical buckling load of test specimen, value on y-axis corresponds to x-axis which obtained from experimental test, is assigned. As an example, if investigate Figure 4.24b, reliability of 30 N is approximately 5% or reliability of 25 N is approximately 95%.

CHAPTER FIVE: FINITE ELEMENT ANALYSIS of LATERAL BUCKLING

5.1. Introduction

The finite element method (FEM) or finite element analysis (FEA), is based on the idea of building a complicated object with simple block, or dividing a complicated object into small and manageable pieces. Applications range from deformation and stress analysis of automotive, aircraft, building, and bridge structures to field analysis of heat flux, fluid flow, magnetic flux, seepage, and other flow problems. With the advances in computer technology and CAD systems, complex problems can be modeled with relative ease. Several alternative configurations can be tested on a computer before the first prototype is built. All of this suggests that we need to keep pace with these developments by understanding the basic theory, modeling techniques, and computational aspects of the FEM. In this method, a complex region is discretized into simple geometric shapes called finite elements. The material properties and the governing relationships are considered over these elements and expressed in terms of unknown values at element corners. An assembly process, duly considering the loading and constraints, results in a set of equations. Solution of these equations gives us the approximate behavior of the continuum [49].

In this chapter, lateral critical buckling load of specimens were determined as numerical with using Ansys 12.

5.2. Finite Element Model for Lateral Buckling

The applied steps for FEA of lateral buckling were explained below.

At the beginning, analysis method is selected as structural for lateral buckling analysis. Then Layered 46 which suit for laminated composite model was selected as element type. After that number for layer of composite model was entered eight and fiber orientation angle was assumed entered $[(0/90)_4]_S$ due to woven structure and thickness of each layer are sized as 0.1875 mm. Degree of freedom is adjusted to deformation model during analysis on x, y, z coordinate axis.

The test specimens for used lateral buckling tests are orthotropic structure. We entered orthotropic mechanical properties of laminated composite material that determined in Chapter three. These mechanical properties values were given in Table 5.1.

Table 5.1 The mechanical properties of woven glass/epoxy composite

Measured				**Assumed**		
E_1 (MPa)	E_2 (MPa)	G_{12} (MPa)	ν_{12}	E_3=0.6E_2 (MPa)	G_{13}= G_{23}=0.6G_{12} (MPa)	ν_{13}= ν_{23}=0.6ν_{12}
26289	17596	3708	0.25	10558	2225	0.15

The value of E_3, ν_{13}, ν_{23}, G_{13}, and G_{23} which belong to mechanical properties of composite material could not be determined lack of necessary equipment. Because of that, these values were determined with using formulation given below as theorical [50].

$$E_3=E_2=0.6E_1 \tag{5.1}$$

$$\nu_{13}=\nu_{23}=0.6\nu_{12} \tag{5.2}$$

$$G_{13}=G_{23}=0.6G_{12} \tag{5.3}$$

After all of these processes, the next step is composing of numerical model. For this, firstly a rectangular area, sized 120x30 mm, was created. Then created area extruded 0.75 mm to create first volume. After that created volume was reflected on z direction. Final of these processes we obtain two separated volume. Each of these volumes has four layers. The laminated composite model that has eight layers was acquired with gluing of these two separated volumes. But, in the course of gluing process, the field that be delamination area, did not glue. By this way, delamination damage, which occurred result of not to glue of two layers to one another or separate of two layers from one another, was modeled. In Figure 5.1, green field was symbolized glued volumes and blue field was symbolized not to glue volumes or delamination area.

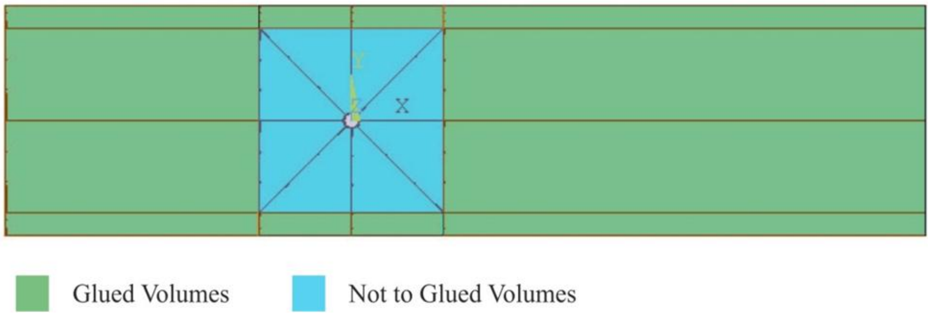
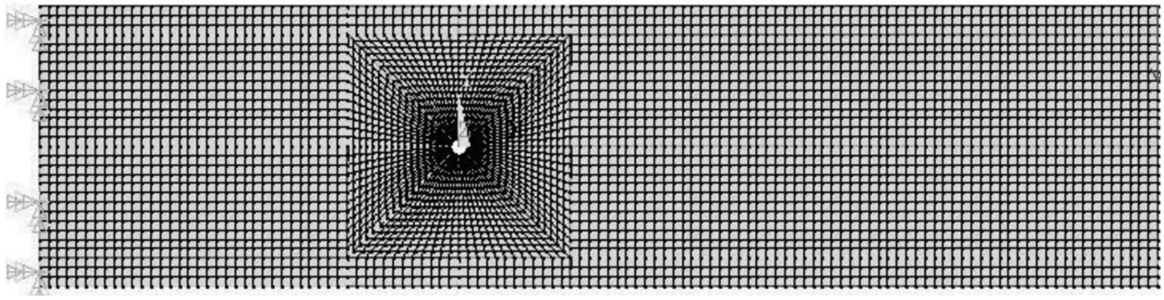


Figure 5.1 Glued and not to glued volumes

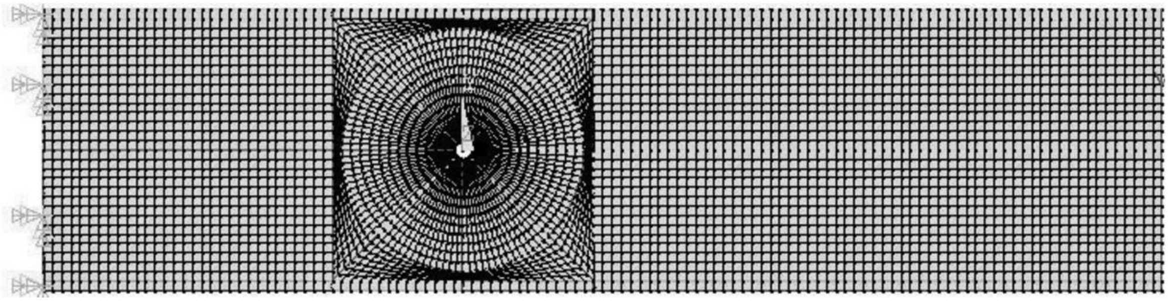
In fact, experimental specimens don't have a hole in the middle of delamination area. But we put a hole on the numerical model to observe the separation in laminated composite specimen under lateral buckling load. We selected diameter of hole as very little not to affect lateral buckling strength.

The basics of the finite element analysis depend to divide numerical model to small piece which named meshing process in Ansys. If divided element size is as small as we select, we get closer results to experimental study. Hence, we selected mesh size 1 mm that is the smallest size for mesh. We used mapped method for mesh to obtain a smoothly mesh.

Next step is describing boundary conditions after mesh process. The numerical model was supported on the one side as fixed end. Lateral force was applied on negative y direction of other one side. Figure 5.2 illustrate the state of mesh, boundary conditions, and applied of lateral load for numerical model with rectangular and circular delamination.



(a)



(b)

Figure 5.2 Meshing, boundary condition and loading style for numerical model with (a) square and (b) circular delamination

In order to achieve lateral buckling analysis, two different solvers were used in Ansys 12.1. These are nonlinear analysis and eigenvalue analysis, respectively. While static solution have done for nonlinear analysis, eigenvalue analysis is used to obtain critical buckling load for laminated composite specimen loaded laterally.

5.3. FEM Results of Lateral Buckling

After nonlinear analysis and eigenvalue analysis were applied on numerical model respectively, we can see results of lateral buckling analysis from General Post Processing. The critical lateral buckling value of laminated composite with delaminations which has different shape and size was given in Table 5.2 and 5.3.

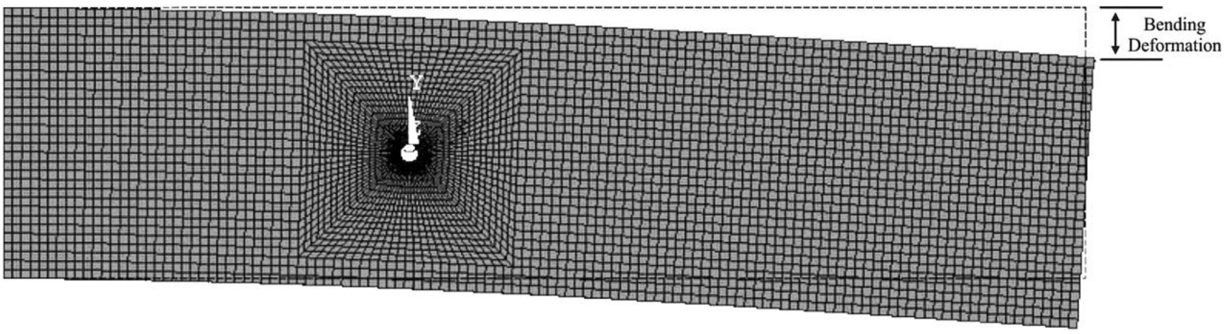
Table 5.2 The critical lateral buckling load of specimens with delaminations having fixed area

Aspect Ratio (a/b)	**Critical Lateral Buckling Load (N)**	
	Square Delamination	Circular Delamination
1	11.5393	9.6750
2	14.2481	13.1000
3	14.7741	14.9750
4	16.1250	15.8000

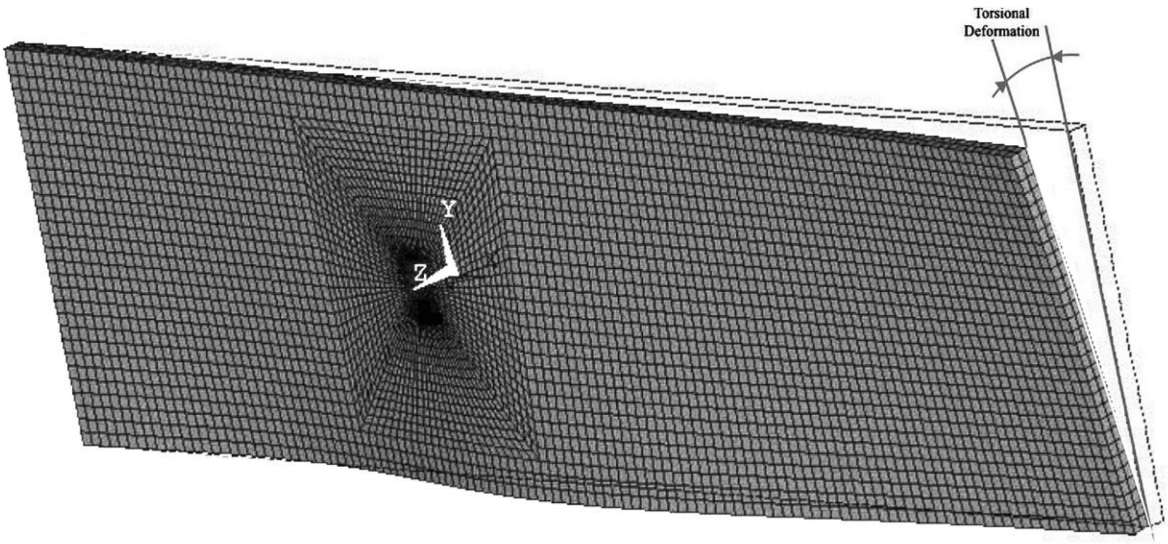
Table 5.3 Critical buckling load of laminated composites with delamination having fixed a/b aspect ratio

Aspect Ratio (a/b)	**Critical Lateral Buckling Load (N)**	
	Square Delamination	Circular Delamination
0.5	14.0384	9.3684
0.6	15.6014	11.3835
0.75	17.0448	13.8045
1	19.5102	19.4805
1.3	18.4733	16.8312
1.6	16.7990	16.1039
2	15.4006	15.2468

In finite element analysis, when we look at the behavior of numerical model under lateral load, deformation movements have good agreement with experimental behavior. As in experiment, bending and torsional deformations were acquired on numerical model (Figure 5.3- 5.4).



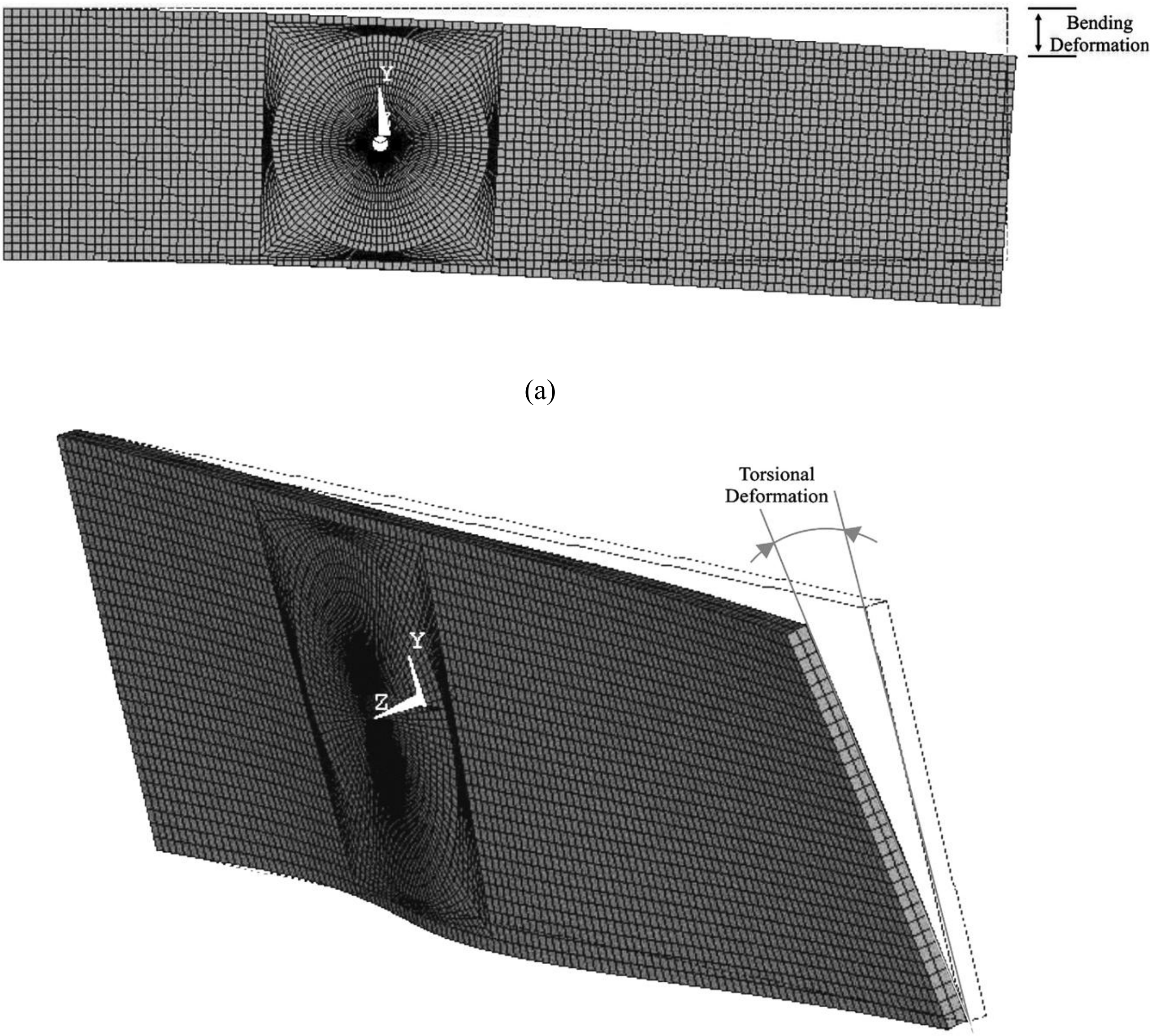
(a)



(b)

Figure 5.3 Bending (a) and torsional (b) deformation of numerical model for square delamination

When amount of bending deformation reach to maximum level which laminated composite specimens can resist under lateral load, torsional deformation was seen on specimens. This behavior was observed in both experiment and numerical study.

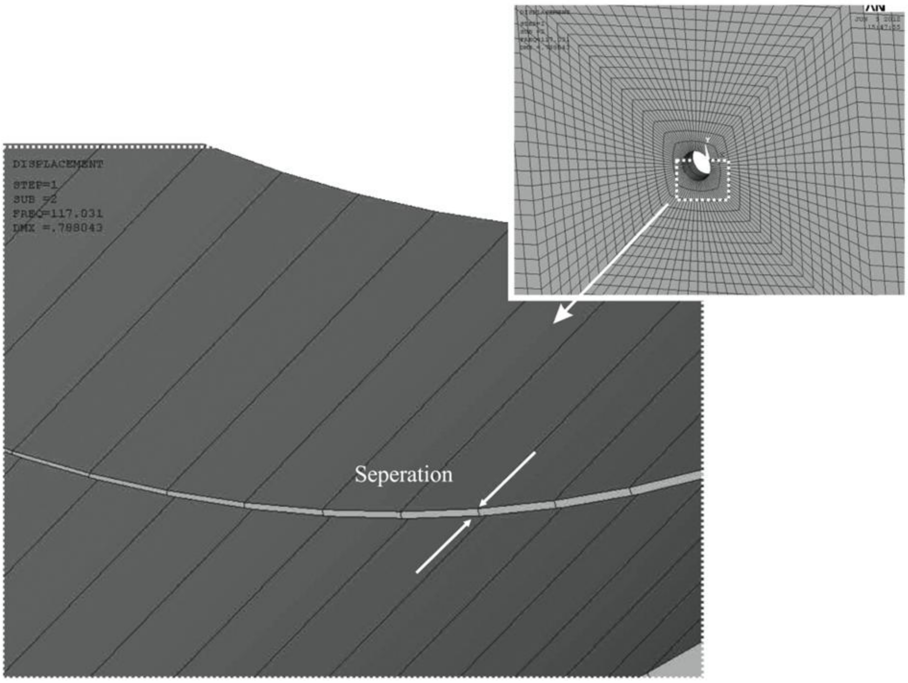


(a)

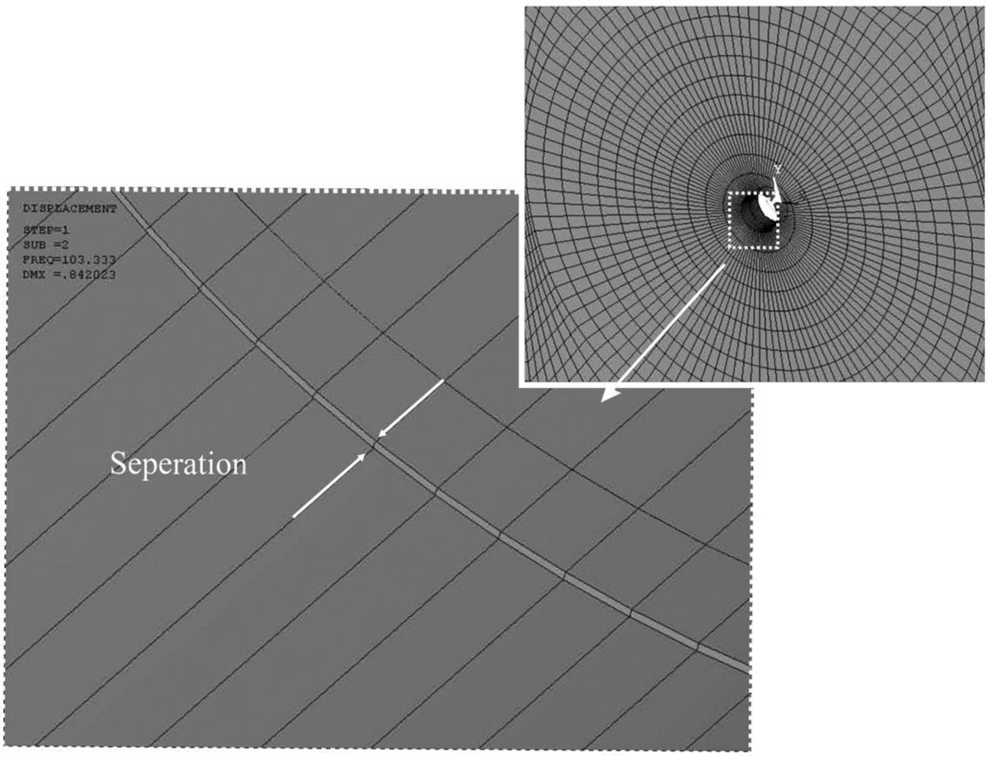
(b)

Figure 5.4 Bending (a) and torsional (b) deformation of numerical model for circular delamination

During lateral buckling, shear stress occurred between layers. With this shear stress, layers are forced to slide on each other. This strain inspires to separation which take place between layers. This separation is named as delamination in literature. The layers of our delaminated composite specimens forced to separate with one such strain. In order to observe whether there is a separation between layers, we generated a very small hole at the middle of delamination area in numerical study. We choose small diameter size for hole, because a hole with big diameter decrease cross sectional area that bear lateral load, as a result of this, results of experimental and numerical studies cannot be equal. When we look at the results of numerical analysis, a separation between layers was seen. Some of the screen shots were given in Figure 5.5.



(a)



(b)

Figure 5.5 Separation on numerical model for (a) square and (b) circular delaminations

In order to find out the effect of the shape and size of delaminations on the critical lateral buckling strength, experimental results of specimens with delamination were compared with the experimental results of specimens without delaminations. To make same comparison in the numerical study, a numerical model which does not include delamination was generated. State of the mesh, boundary conditions and loading style was showed in Figure 5.6.

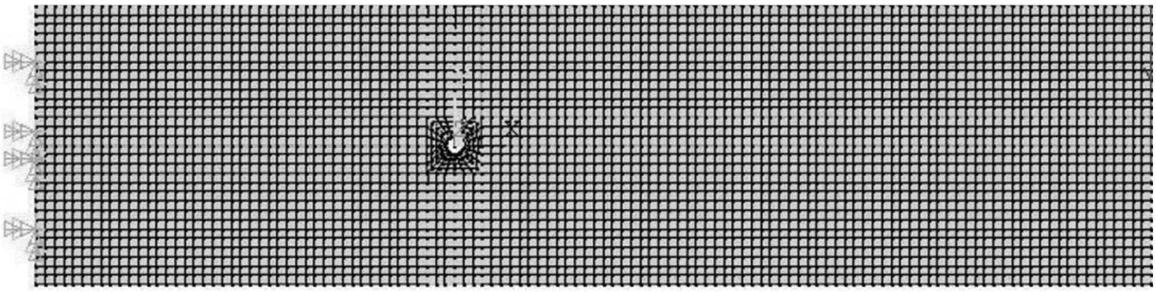
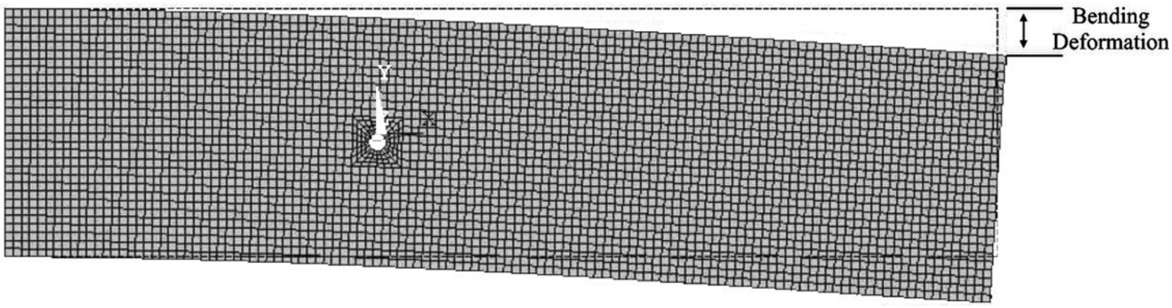
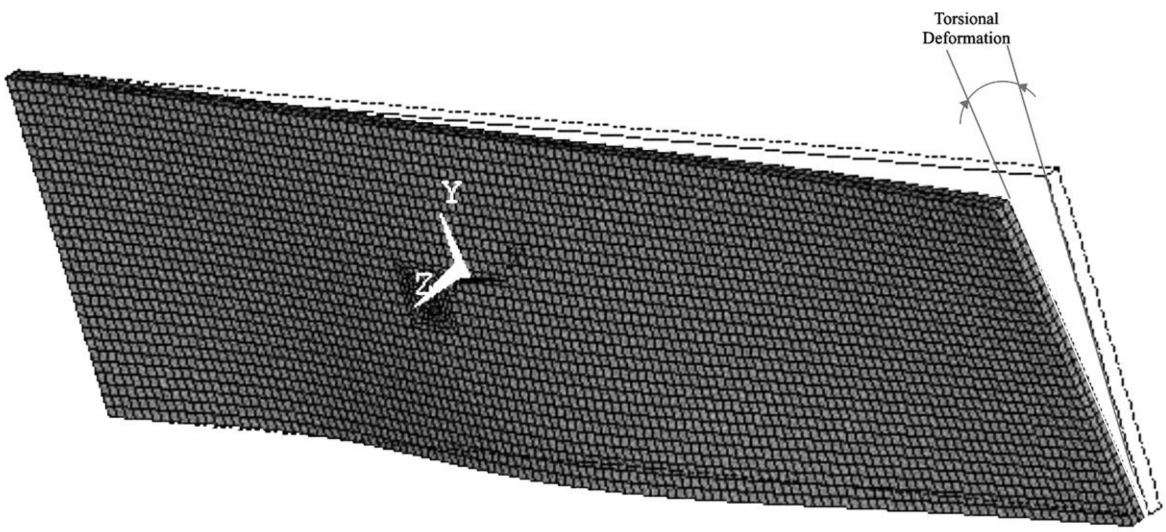


Figure 5.6 Meshing, boundary condition and loading style for numerical model without delaminations

As a result, numerical model without delamination indicated same behavior with experimental model without delamination under lateral load. The value of critical buckling load was obtained **25.1523 N** from numerical study. Bending and torsional deformations of numerical model were given in Figure 5.7.



(a)



(b)

Figure 5.7 (a) Bending and (b) torsional deformation of numerical model without delaminations

It must be noted that, any separation was observed between layers owing to not to have delamination. So that, it was proved that delamination damage cause separation between layers under lateral load. In Figure 5.8 was shown that there is not separation between layers, for specimen without delamination.

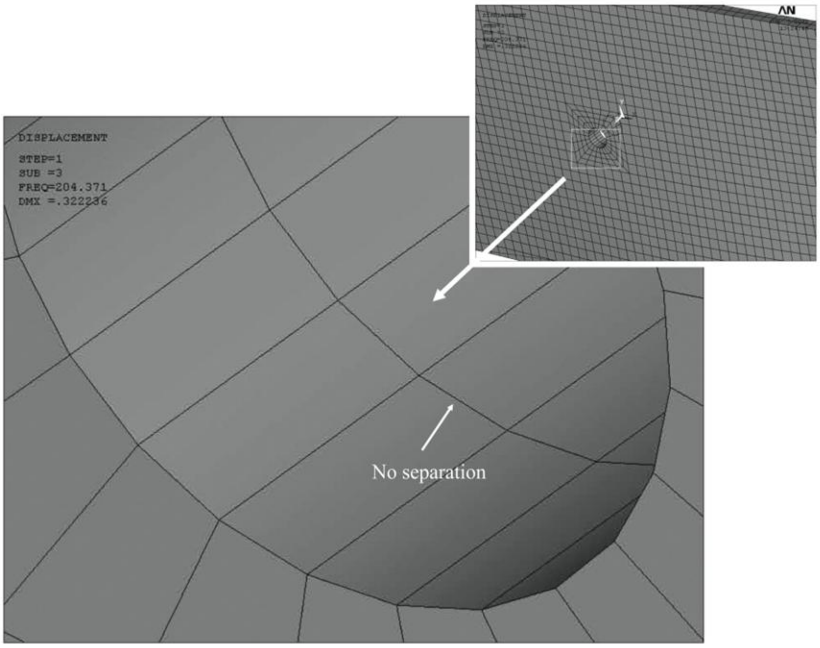


Figure 5.8 No separation on numerical model without delamination

CHAPTER SIX: RESULTS and CONCLUSIONS

In this thesis, the critical lateral buckling load of laminated composites with delamination which has different shape and size, were investigated experimentally, statically and numerically. In order to find out the effect of delamination on lateral behavior of woven E-glass/epoxy composites, delamination shape and size were classified in two different categories which diversified in twenty two series. For statistical study; Weibull distribution analyses were performed by using experimental lateral buckling results.

In the first category we investigated the effect of four different aspect ratio (a/b=1, 2, 3 and 4) on delamination having fixed area. Stiffness and strength of laminated composites increased with increasing of aspect ratio for delamination having fixed area. Although the delamination area of specimens have same size, the lateral buckling strength of specimens were different because of they have delamination with different a/b aspect ratio. The critical lateral buckling load increase by increasing *a* and decreasing *b* for obtaining same delamination area.

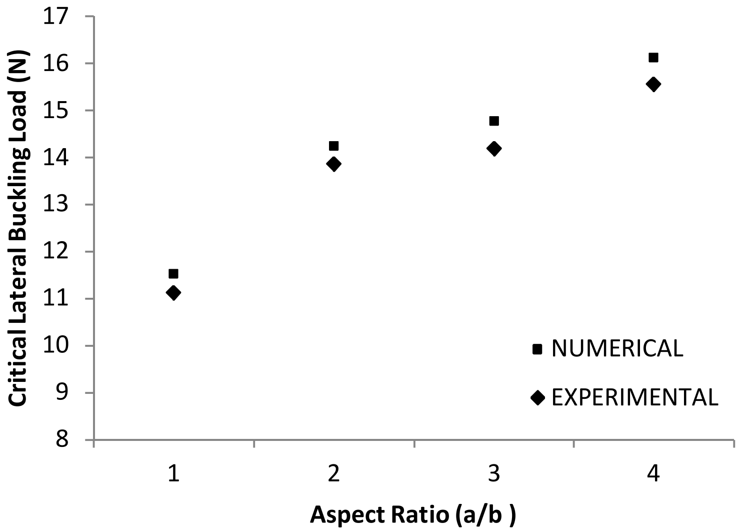
The critical lateral buckling loads obtained from experiment and numerical study, were given in Table 6.1. Error is also given for seeing deviation in numerical results from experimental results. The values of strength reduction were acquired by comparing experimental results of specimen with delamination and without delamination.

Table 6.1 The experimental and numerical critical lateral buckling loads of woven glass/epoxy composite having fixed delamination area

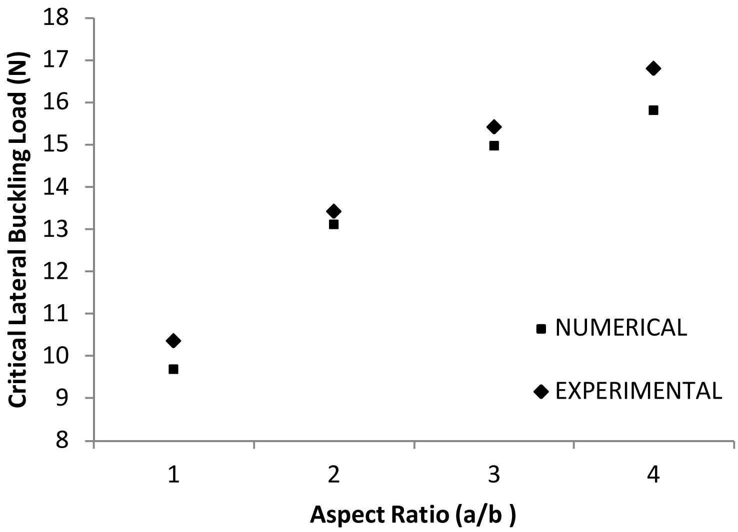
Delamination Shape	Aspect Ratio (a/b)	Experimental (N)	Numerical (N)	Error (%)	Reduction in Exp. (%)
Without	-	23.6903	25.1023	5.96	-
Square	1	11.1279	11.5393	3.70	53.03
	2	13.8516	14.2481	2.86	41.53
	3	14.1861	14.7741	4.15	40.12
	4	15.5562	16.1250	3.66	34.34
Circular	1	10.3647	9.6750	6.65	56.25
	2	13.4349	13.1000	2.49	43.29
	3	15.4227	14.9750	2.90	34.90
	4	16.8140	15.8000	6.03	29.03

The maximum critical lateral buckling load was obtained when a/b aspect ratio is 4 for both square and circular delamination. When experimental results of specimens with delamination compared with experimental results of specimens without delamination; it observed that, the critical lateral buckling load was reduced in the range of approx. 34-53% and 29-56% for square and circular delaminations respectively.

Finite element results of numerical model with delamination having fixed area have good agreement with experimental results. The values of error were 2-6.7% in the range of approx. and that showed numerical model is suit to simulate experimental model. The experimental and numerical results were given in Figure 6.1 as comparatively.



(a)



(b)

Figure 6.1 Comparison with experimental and numerical results of specimens with (a) square and (b) circular delaminations having fixed area

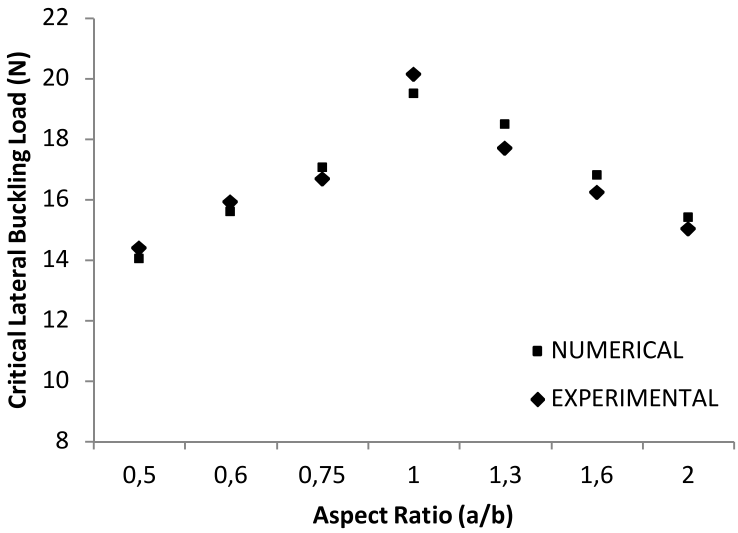
In the second category, we investigated the effect of seven fixed aspect ratio (a/b=0.5, 0.6, 0.75, 1, 1.3, 1.6 and 2) on different sized area. The critical lateral buckling load increased with increasing a/b ratio from 0.5 to 1. When a/b aspect ratio reached 1, by changing of a/b aspect ratio from 1 to 2, the critical lateral buckling load reduced gradually. So the maximum lateral buckling load was obtained when a/b aspect ratio is 1 both square and circular delaminations.

As in the first category, existence of delamination between layers reduced the critical lateral buckling load in the range of approx. 15-40% for specimens having square delamination. For the specimen having circular delamination, reductions in the critical lateral buckling loads are obtained among approx. 15-63% i.e., the critical lateral buckling load is effected by the circular delamination more than by square delamination. All the experimental and numerical results were given in Table 6.2 for second category.

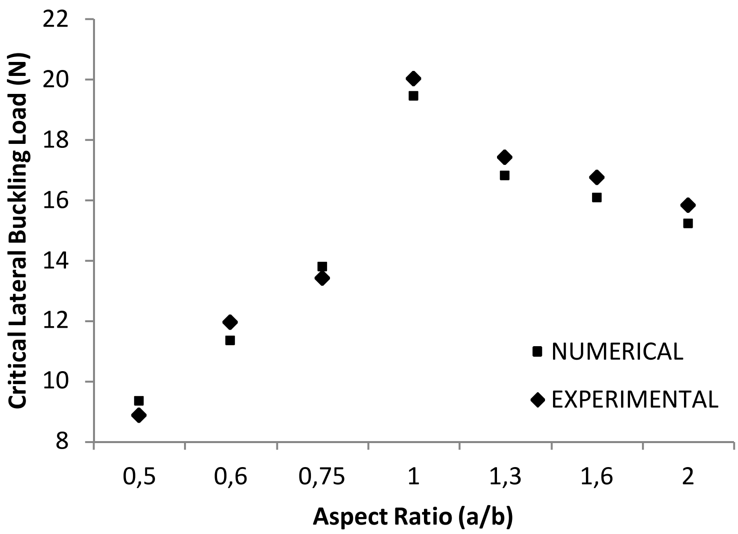
Table 6.2 The experimental and numerical critical lateral buckling loads of woven glass/epoxy composite having fixed a/b aspect ratio

Delamination Shape	**Aspect Ratio (a/b)**	**Experimental (N)**	**Numerical (N)**	**Error (%)**	**Reduction in Exp. (%)**
Without	-	23.6903	25.1023	5.96	-
Square	0.5	14.3851	14.0384	2.41	39.28
	0.6	15.9239	15.6014	2.03	32.78
	0.75	16.6808	17.0448	2.18	29.59
	1	20.1260	19.5102	3.06	15.05
	1.3	17.6865	18.4733	4.45	25.34
	1.6	16.2138	16.7990	3.61	31.56
	2	15.0370	15.4006	2.42	36.53
Circular	0.5	8.8981	9.3684	5.29	62.44
	0.6	11.9656	11.3835	4.87	49.49
	0.75	13.4410	13.8045	2.70	43.26
	1	20.0436	19.4805	2.81	15.39
	1.3	17.4477	16.8312	3.53	26.35
	1.6	16.7709	16.1039	3.98	29.21
	2	15.8507	15.2468	3.81	33.09

It can be seen from Table 6.2, that the numerical results are so close to experimental results. The range of error values changed between approx. 2-6%. This is acceptable error values for finite element analysis. The experimental and numerical results were given in Figure 6.2 as comparatively.



(a)



(b)

Figure 6.2 Comparison with experimental and numerical results of specimens with (a) square and (b) circular delaminations having fixed a/b aspect ratio

In conclusion, that observed from experimental and numerical studies, size and shape of delamination affected critical lateral buckling load of specimens. Delamination caused to reduce amount of cross-sectional area which is exposed to lateral load. Thus, test specimens and numerical models was buckled on load which is lower than their can endure.

Although specimens have same size delamination area, experimental and numerical results showed that specimens, which have larger load bearing cross-sectional area, have higher critical lateral buckling load.

6.1. Recommendations for Further Research

The following recommendations may be listed to shine a light for further research.

- The critical lateral buckling load of laminated composite having different material such as carbon/epoxy or kevlar/epoxy may be investigated.
- The effect of fiber orientation and the number of layers or thickness of plates on the critical lateral buckling load may be investigated.
- The lateral buckling behavior of laminated composites with and without delamination may be studied under low and high velocity.
- The effect of one or more delamination which located in different interfaces on critical lateral buckling load may be investigated.
- The lateral buckling behavior of laminated composites under different temperature and pressure may be investigated.

REFERENCES

[1] Sapkas, A., Kollar, L.P., "Lateral-torsional buckling of composite beams", International Journal of Solids and Structures, 39, 2939-2963, 2002

[2] Lee, J., "Lateral buckling analysis of thin-walled laminated composite beams with monosymmetric sections", Engineering Structures, 28, 1997-2009, 2006

[3] Kim, N., Shin, D.K., Kim, M.Y., "Exact lateral buckling analysis for thin-walled composite beam under end moment", Engineering Structures, 29, 1739-1751, 2007

[4] Lopatin, A.V., Morozov, E.V., "Buckling of a composite cantilever circular cylindrical shell subjected to uniform external lateral pressure", Composite Structures, 94, 553-562, 2012

[5] Lee, J., Kim, S.E., Hong, K., "Lateral buckling of I-section composite beams", Engineering Structures, 24, 955-964, 2002

[6] Machado, S.P., Cortinez, V.H., "Lateral buckling of thin-walled composite bisymmetric beams with prebuckling and shear deformation", Engineering Structures, 27, 1185-1196, 2005

[7] Lee, J., Kim, S.E., "Lateral buckling analysis of thin-walled laminated channel-section beams", Composite Structures, 56, 391-399, 2002

[8] Attard, M.M., Kim, M.Y., "Lateral buckling of beams with shear deformations - A hyperelastic formulation", International Journal of Solids and Structures, 47, 2825-2840, 2010

[9] Japon, J.L.M., Bardudo, I.H.S., "Nonlinear plastic analysis of steel arches under lateral buckling", Journal of Constructional Steel Research, 67, 1860-1863, 2011

[10] Pi, Y.L, Put, B.M., Trahair, N.S., “Lateral buckling strengths of cold-formed Z-section beams”, Thin-Walled Structures, 34, 65-93, 1999

[11] Wang, Q., Li, W.Y., “Lateral buckling of thin-walled members with shear lag using spline finite member element method”, Computers and Structures, 75, 81-91, 2000

[12] Pi, Y.L., Trahair, N.S., “Inelastic lateral buckling strength and design of steel arches”, Engineering Structures, 22, 993-1005, 2000

[13] Ascione, L., Giordano, A., Spedea, S., “Lateral buckling of pultruded FRP beams”, Composites: Part B, 42, 819-824, 2011

[14] Trahair, N.S., “Lateral buckling of monorail beams”, Engineering Structures, 30, 3213-3218, 2008

[15] Wang, Q., Li, W.Y., “A closed form Approximate solution of lateral buckling of doubly symmetric thin-walled members considering shear lag”, International Journal of Mechanic Science, 39, 523-535, 1997

[16] Vaz, M.A., Patel, M.H., “Lateral buckling of bundled pipe systems”, Marine Structures, 12, 21-40, 1999

[17] Ohga, M., Wijenayaka, A.S., Croll, J.G.A., “Lower bound buckling strength of axially loaded sandwich cylindrical shell under lateral pressure”, Thin-Walled Structures, 44, 800-807, 2006

[18] Mohebkhah A., “Lateral buckling resistance of inelastic I-beams under off-shear center loading”, Thin-Walled Structures, 49, 431-436, 2011

[19] Mohri, F., Bouzeria, C., Ferry, M.P., “Lateral buckling of thin-walled beam-column elements under combined axial and bending loads”, Thin-Walled Structures, 46, 290–302, 2008

[20] Eryiğit, E., Zor, M., Arman, Y., "Hole effects on lateral buckling of laminated cantilever beams", Composites: Part B, 40, 174-179, 2002

[21] Gui, L., Li, Z., "Delamination buckling of stitched laminates", Composites Science and Technology, 61, 629-636, 2001

[22] Hu, N., Fukunaga, H., Sekine, H., Kouchakzadeh, M.A., "Compressive buckling of laminates with an embedded delaminations", Composites Science and Technology, 59, 1247-1260, 1999

[23] Cappello, F., Tumino, D., "Numerical analysis of composite plates with multiple delaminations subjected to uniaxial buckling load", Composites Science and Technology, 66, 264-272, 2006

[24] Kim, H.J., Hong, C.S., "Buckling and post buckling behavior of composite laminates with a delaminations", Composites Science and Technology, 57, 557-564, 1997

[25] Aslan, Z., Şahin, M., "Buckling behavior and compressive failure of composite laminates containing multiple large delaminations" Composite Structures, 89, 382-390, 2009

[26] Toudeshky, H.H., Hosseini, S., Mohammadi, B., "Delamination buckling growth in laminated composites using layer wise interface element", Composite Structures, 92, 1846-1856, 2010

[27] Tafreshi, A., "Delamination buckling and postbuckling in composite cylindrical shells under combined axial compression and external pressure", Composite Structures, 72, 401-418, 2006

[28] Hwang, S.F., Liu, G.H., "Buckling behavior of composite laminates with multiple delaminations under uniaxial compression", Composite Structures, 53, 235-243, 2001

[29] Arman, Y., Zor, M., Aksoy, S., "Determination of critical delamination diameter of laminated composite plates under buckling loads", Composites Science and Technology, 66, 2945–2953, 2006

[30] Ashby, M.F., "Technology in the 1990s: Advanced Materials and Predictive Design," Philosophical Transactions of the Royal Society of London, 322, 393-407, 1987

[31] Staab, G.H., "Laminar Composites (1st Edition)", Butterworth-Heinemann Publication, United States of America, 1999

[32] Richardson, T., "Composites: A Design Guide", Industrial Press Inc., New York, 1987

[33] Internet: Scribd, 2011, "Composite materials", http://www.scribd.com/doc/71522291/19/, 25 March 2012

[34] Internet: Wikipedia the Free Encyclopedia, 2011, "Buckling", http://en.wikipedia.org/wiki/Buckling, 20 December 2011

[35] Pekbey, Y. "Buckling of economical composite bars", PhD Thesis, Dokuz Eylül University, İzmir, 2005

[36] Arman, Y. "Circular delamination effects on buckling behavior of the laminated composites plates with circular hole", Master Science Thesis, Dokuz Eylül University, İzmir, 2003

[37] Ye, J., "Laminated composite plates and shells 3D modelling", Springer England, 2003

[38] “Standards and literature references for composite materials, standard test method for tensile properties of fiber-resin composites D 3039-76”, American Society for Testing and Materials, Philadelphia P.A., 1990

[39] Aktaş, M. “Temperature effect on impact behavior of laminated composite plates”, PhD Thesis, Dokuz Eylül University, İzmir, 2007

[40] Carlson, L.A., Pipes, R.B., “Experimental characterization of advanced composite materials (2nd Edition)”, Technomic Publishing Company, USA, 1997

[41] “Standard and literature references for composite materials, standard test method for compressive properties of unidirectional or cross-ply fiber-resin composites D 3410-87”, American Society for Testing and Materials, Philadelphia PA, 1990

[42] Daniel, I.M., Ishai, O., “Engineering Mechanics of Composite Materials (1st Edition)”, Oxford University New York Press, New York, 1990

[43] Jones, R.M., “Mechanics of composite materials (2nd Edition)”, McGraw-Hill, Tokyo, 1998

[44] Parlapalli, M.R., Soh, K.C., Shu, D.W., Ma, G., “Experimental investigation of delamination buckling of stitched composite laminates”, Composites: Part A, 38, 2024-2033, 2007

[45] Kalkan, İ., “Application of Southwell method on the analysis of lateral torsional buckling tests on reinforced concrete beams”, International Journal of Engineering Research & Development, 2 , 58-66, 2010

[46] Ghosh, A., “Fortran program for fitting Weibull distribution and generating samples”, Computers and Geosciences, 25, 729–738, 1999

[47] Dodson, B., “Weibull Analysis (1st Edition)”, American Society for Quality, 1994

[48] Aktaş, A., "Statistical analysis of bearing strength of glass-fiber composite materials", Journal of Reinforced Plastics and Composites, 26, 555-655, 2007

[49] Chandrupatla, T.R., Belegundu, A.D., "Introduction to finite element in engineering (3rd Edition)", Prentice Hall, New Jersey, 2002

[50] Datoo, M.H., "Mechanics of fibrous composites", Elsevier Science Publishers England, 1991