

DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED
SCIENCES

FAILURE ANALYSIS OF COMPOSITE BOLTED
JOINTS UNDER CORROSIVE EFFECTS

by
Emre ÇIPLAK

July, 2009
İZMİR

FAILURE ANALYSIS OF COMPOSITE BOLTED JOINTS UNDER CORROSIVE EFFECTS

**A Thesis Submitted to the
Graduate School of Natural and Applied Sciences of Dokuz Eylül University
In Partial Fulfillment of the Requirements for the Degree of Master of Science
in Mechanical Engineering, Mechanics Program**

**by
Emre ÇIPLAK**

**July, 2009
İZMİR**

Ms. Sc. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled “**FAILURE ANALYSIS OF COMPOSITE BOLTED JOINTS UNDER CORROSIVE EFFECTS**” completed by **EMRE ÇIPLAK** under supervision of **PROF. DR. ONUR SAYMAN** 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.

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Emre ÇIPLAK

FAILURE ANALYSIS OF COMPOSITE BOLTED JOINTS UNDER CORROSIVE EFFECTS

ABSTRACT

In this study the effect of water absorption and corrosive sea water on the failure response of an angle ply glass fiber reinforced-epoxy composite oriented as $[0/0/90/45]_s$ has been experimentally investigated. Two geometric parameters were chosen for failure response of the bolted-joint composite laminates. Those were the edge distance-to-hole diameter ratio (E/D) and the plate width-to-hole diameter ratio (W/D), which were selected from 1 to 5 and from 2 to 5.

The specimens were first tested for unimmersed condition, afterwards another group of specimens were immersed into sea water for 200 days. The experiments were performed using some parameters for the pinned and bolted specimens. The specimens were tested under pre-load moments as, 0 and 3 Nm and 6 Nm. The experiments have not been stopped until a failure occurs on specimens. Interpretations have been made by relying on the bearing strength and displacement diagram.

Tables include failure loads with their failure type obtained as a result of the experiments and tables show the comparison failure load for unimmersed and immersed specimens under preload moments are given. The results point out that immersion of the composite specimens into the sea water under preload moments can cause a notable decrease on the failure load.

Keywords: Sea water absorption; Glass fibres; Failure response; Mechanical testing, Immersing, Composite bolted joint, Composite pinned joint.

KOROZİF ETKİLER ALTINDA KOMPOZİT CİVATALI BAĞLANTILARIN HASAR ANALİZİ

ÖZ

Bu çalışmada su absorpsiyonu ve deniz suyu korozyonunun $[0/0/90/45]_s$ yönlenme açılı ve fiberglas takviyeli epoksi kompozitin hasar tepkisi üzerindeki etkisi deneysel olarak araştırılmıştır. Cıvatalı kompozit bağlantı tabakalarının hasar tepkisi için iki geometrik parametre seçilmiştir. Bu parametreler sırasıyla 1'den 5'e kadar ve 2'den 5'e kadar değişen, delik merkezinin tabaka kenarına olan uzaklığının delik çapına oranı (E/D) ve tabaka kalınlığının delik çapına oranı (W/D) şeklindedir.

İlk olarak suda bekletilmemiş durumdaki numuneler, daha sonra ise suda 200 gün boyunca bekletilen numune grubu test edildi. Pimli ve cıvatalı bağlantılar için deneyler bazı parametreleri kullanarak yapıldı. Numuneler 0, 3 Nm ve 6 Nm değerindeki önmomentler altında test edildi. Deneyler numuneler üzerinde hasar oluşuncaya kadar sürdürüldü. Deneyler sonunda çıkartılan yatak mukavemeti – uzama diyagramları üzerinden yorumlar yapılmıştır.

Deneylerin sonucu olarak elde edilen hasar yüklerini ve çeşitlerini içeren tablolar ile suda bekletilen ve bekletilmeyen ön moment uygulanmış numuneler için hasar karşılaştırmalarını gösteren tablolar verilmiştir. Sonuçlar ön moment uygulanmış kompozit numunelerin deniz suyunda bekletilmesinin hasar yükü üzerinde dikkate değer bir düşüşe neden olduğunu göstermektedir.

Anahtar Sözcükler: Deniz suyu absorpsiyonu; Cam lifi; Hasar tepkisi; Mekanik deney, Suyu daldırmak, Kompozit cıvatalı bağlantı, Kompozit pimli bağlantı.

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CHAPTER ONE

INTRODUCTION

Composite materials have been increasingly used in aircraft and space structures. They offer many advantages over conventional metallic materials due to their comparatively high strength to weight and stiffness to weight ratios. These kinds of applications usually require the joining of composite to composites or to metals. Generally, the joining methods of composite structures are classified into two kinds, mechanical and adhesive. Mechanically fastening with a pin or bolt is commonly used because of their low cost, simplicity and ease of assembly and disassembly.

Bolted and pinned joints are commonly used in fiber reinforced composite structures. Some reviews have been presented on the mechanics of mechanically fastened joints in polymer matrix reinforced composite structures (Camanho, & Matthews, 1997). Failure modes and strength of pinned and bolted joints are the main important points (Dano, Gendron, & Picard, 2000), (Lin, & Lin, 1999).

An unskilled design of the joints in the case of mechanical fasteners often causes a reduction of load capability of the composite structure even though the composite materials possess high strength. Thus many review papers on mechanical joints and specifically pin and bolt loaded holes have been conducted in the past.

A major goal of pinned joints research is to find out the influence of various parameters on the bearing of joints (Whitworth, Othieno, & Barton, 2003). Okutan and Karakuzu (2003) have investigated the effects of parameters on the pin-loaded glass-epoxy laminated composite. Okutan, Aslan and Karakuzu (2001) have studied the effects of woven fiber, specimen width-to-hole diameter (W/D) and the ratio of edge distance to hole diameter (E/D) on the bearing strength of woven laminated composites. They have tested single-hole pin-loaded specimens for their tensile response. They have observed failure propagation and failure type on the specimens. Okutan et al. (2001) have investigated the failure strength of pin-loaded woven fiber-

glass reinforced epoxy laminates experimentally and have observed the effects of changing the geometric parameters were observed.

Ataş (2009) has examined experimentally the bearing strength of pinned joints in woven fabric composites with small weaving angles under some parameters. Four different stacking sequences are chosen for comparison, considering ratios $W/D = 3, 4$ and $E/D = 1, 2, 3$. It is concluded that using layers with identical orientations may result in undesirable severe damage modes and small load carrying capacities in mechanically fastened joints of woven fabric composites with small weaving angles. Pierron et al. (2000) have investigated the behavior of woven glass fiber epoxy pinned joints, both numerically and experimentally, by giving attention to some parameters, clearance, friction and non-linear material behavior. Particular attention was paid to account for the influence of the clearance which has been shown to be very significant. Failure analysis has been performed in pinned and bolted aluminum and fiber glass-epoxy sandwich composite plates (İçten, & Sayman, 2003), (Sayman & Ahishalı, 2008). In the study of Sayman and Ahishalı (2008) parametric studies were performed by experiments to find out the effects of joint geometry and preload moment on the failure strength and failure mode. The preload moments chosen (M) were 0, 3 and 6 Nm while the end distance to hole diameter (E/D) and width to diameter (W/D) ratios were chosen as 1—5 and 2—5, respectively.

Sen et al. (2008) have examined the failure analysis of bolted joints with clearance in composite laminates under preload moments. Two different geometrical parameters those are the edge distance-to-hole diameter ratio (E/D) and plate width-to-hole diameter ratio (W/D) were considered. For this purpose, E/D ratio was selected from 1 to 5, whereas W/D ratio was chosen from 2 to 5. Due to determining material parameters effect, laminated plates were stacked as three different groups which were $[0^\circ/0^\circ/45^\circ/-45^\circ]_s$, $[0^\circ/0^\circ/45^\circ/45^\circ]_s$ and $[0^\circ/0^\circ/30^\circ/30^\circ]_s$, symmetrically. In addition, the preload moments were applied as 0, 3 and 6 Nm, since an important target of that study was to observe the changing of failure mechanism under various preloads. The experiments were also performed under a clearance, for this reason the diameters of the bolt and the circular bolt hole were fixed 5 and 6 mm, respectively.

Persson and Madenci (1998) have performed an experimental and analytical study of the effect of the elliptical shape of pins and holes on the failure mode and stress distribution around pin-loaded composite laminates. Specimens exhibiting either net-section or bearing failure modes were considered. Measured and computed strain values at specific points were compared in order to establish the fidelity of the analysis method.

Choi et al. (2008) have investigated the failure load of a mechanically fastened composite joint subjected to a clamping force. They have tested and predicted the failure area using failure area index [FAI] method. The FAI method can predict the failure loads of mechanically fastened composite joints, relying on one reference experiment for a particular stacking sequence. From the tests and analyses in that work, the failure load of a mechanically fastened composite joint subjected to a clamping force could be predicted within 23% via the FAI method.

Tong (2000) has investigated the effect of the relative positions of the bolt and the washer on the bearing failure behavior of bolted composite joints with various lateral constraints. Two extreme diametral fit positions, with a positive or negative bolt hole-to-washer clearance, have been considered.

Several researchers have highlighted the importance of width (W), end distance (E), hole diameter (D) and laminate thickness (t) on the joint strength. Kretsis and Matthews (1985) showed, using E glass fiber-reinforced plastic and carbon fiber-reinforced plastic, that as the width of the specimen decreases, there is a point where the mode of failure changes from one of bearing to one of tension. A similar behavior between the end distance and the shear out mode of failure was found. Chamis (1990) has reported on the variation of joint strength with respect to geometric shapes and laminate strengths.

Review papers on the strength of mechanically fastened joints in fiber reinforced plastics have been written by Godwin and Matthews (1980). Effects of material

properties, fastener parameters and design parameters have been summarized and discussed. These parameters are very important for the strength of mechanically fastened joints in composite laminate.

In this study, the influence of sea water on the failure response of fiber glass-epoxy composite pinned and bolted joints has been investigated experimentally. A preload moment has been applied to the bolted joints as 3 and 6 Nm. The lateral forces are measured by using strain gauges.

CHAPTER TWO

INTRODUCTION TO COMPOSITE MATERIALS

2.1 Definition & Background

A composite material is made by combining two or more materials to give a unique combination of properties. The above definition is more general and can include metals alloys, plastic co-polymers, minerals, and wood. Fiber-reinforced composite materials differ from the above materials in that the constituent materials are different at the molecular level and are mechanically separable. In bulk form, the constituent materials work together but remain in their original forms. The final properties of composite materials are better than constituent material properties.

The concept of composites was not invented by human beings; it is found in nature. An example is wood, which is a composite of cellulose fibers in a matrix of natural glue called lignin. The shell of invertebrates, such as snails and oysters, is an example of a composite. Such shells are stronger and tougher than man-made advanced composites. Scientists have found that the fibers taken from a spider's web are stronger than synthetic fibers. In India, Greece, and other countries, husks or straws mixed with clay have been used to build houses for several hundred years. Mixing husk or sawdust in a clay is an example of a particulate composite and mixing straws in a clay is an example of a shortfiber composite. These reinforcements are done to improve performance.

The main concept of a composite is that it contains matrix materials. Typically, composite material is formed by reinforcing fibers in a matrix resin as shown in Figure 2.1. The reinforcements can be fibers, particulates, or whiskers, and the matrix materials can be metals, plastics, or ceramics.

The reinforcements can be made from polymers, ceramics, and metals. The fibers can be continuous, long, or short. Composites made with a polymer matrix have

become more common and are widely used in various industries. They can be thermoset or thermoplastic resins.

The reinforcing fiber or fabric provides strength and stiffness to the composite, whereas the matrix gives rigidity and environmental resistance. Reinforcing fibers are found in different forms, from long continuous fibers to woven fabric to short chopped fibers and mat. Each configuration results in different properties. The properties strongly depend on the way the fibers are laid in the composites. All of the above combinations or only one form can be used in a composite. The important thing to remember about composites is that the fiber carries the load and its strength is greatest along the axis of the fiber. Long continuous fibers in the direction of the load result in a composite with properties far exceeding the matrix resin itself. The same material chopped into short lengths yields lower properties than continuous fibers, as illustrated in Figure 2.2. Depending on the type of application (structural or nonstructural) and manufacturing method, the fiber form is selected. For structural applications, continuous fibers or long fibers are recommended; whereas for nonstructural applications, short fibers are recommended. Injection and compression molding utilize short fibers, whereas filament winding, pultrusion, and roll wrapping use continuous fibers.

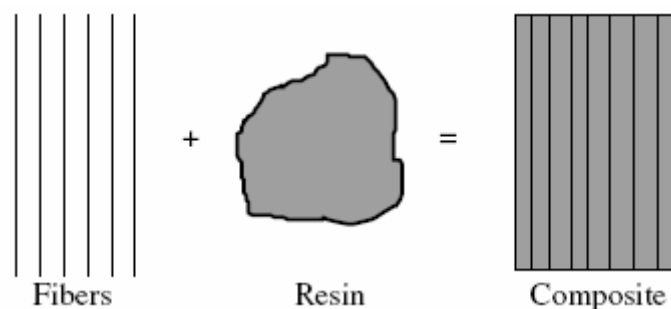


Figure 2.1 Formation of a composite material using fibers and resin.

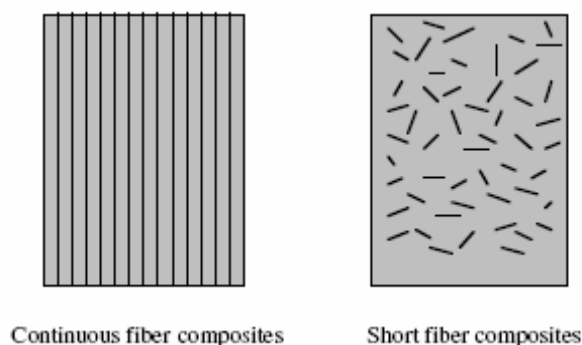


Figure 2.2 Continuous fiber and short fiber composites.

2.2 Classification of Composite Materials

It's known that composites have two (or more) chemically distinct phases on a microscopic scale, separated by a distinct interface, and it is important to be able to specify these constituents. The constituent that is continuous and is often, but not always, present in the greater quantity in the composite is termed the matrix. The normal view is that it is the properties of the matrix. That is improved upon when incorporating another constituent to produce a composite. A composite may have a ceramic, metallic or polymeric matrix. The mechanical properties of these classes of material differ considerably. As a generalization, polymers have low strengths and Young's moduli, ceramics are strong, stiff and brittle, and metals have intermediate strengths and moduli, together with good ductilities, i.e. they are not brittle.

The second constituent is known to as the reinforcing phase, or reinforcement, as it enhances or reinforces the mechanical properties of the matrix. In most cases the reinforcement is harder, stronger and stiffer than the matrix, although there are some exceptions; for example, ductile metal reinforcement in a ceramic matrix and rubber like reinforcement in a brittle polymer matrix. At least one of the dimensions of the reinforcement is small, say less than 500 μm and sometimes only of the order of a micrometer. The geometry of the reinforcing phase is one of the major parameters in determining the effectiveness of the reinforcement; in other words, the mechanical properties of composites are a function of the shape and dimensions of the reinforcement. We usually describe the reinforcement as being either fibrous or

particulate. Figure 2.3 represents a commonly employed classification scheme for composite materials which utilizes this designation for the reinforcement (Fig. 2.3 - Block A)

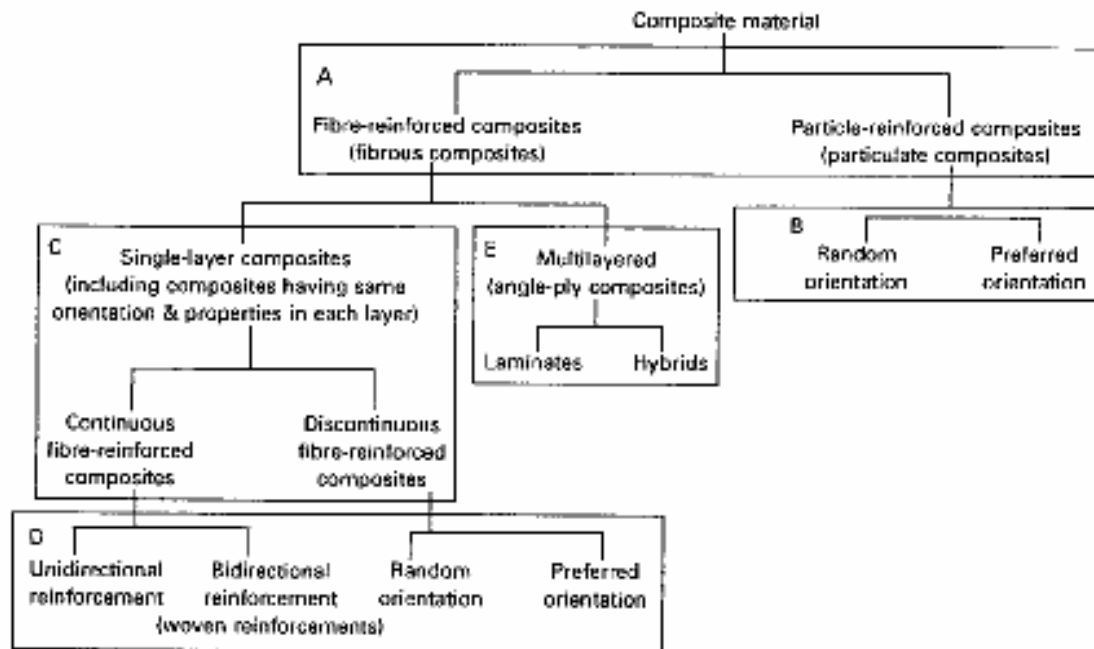


Figure 2.3 Classification of Composite Materials

Particulate reinforcements have dimensions that are approximately equal in all directions the shape of the reinforcing particles may be spherical, cubic, platelet or any regular or irregular geometry. The arrangement of the particulate reinforcement may be random or with a preferred orientation, and this characteristic is also used as a part of the classification scheme (Fig 2.3 Block B). In the majority of particulate reinforced composites the orientation of the particles is considered, for practical purposes, to be random.

A fibrous reinforcement is characterized by its length being much greater than its cross-section dimensions. However, the ratio of length to a cross-section dimension, known as the aspect ratio, can vary considerably. In single-layer composites long fibres with high aspect ratios give what are called continuous fibre-reinforced composites, whereas discontinuous fibre composites are fabricated using short fibres

of low aspect ratio (Fig 2.3 Block C). The orientation of the discontinuous fibres may be random or preferred. The frequently encountered preferred orientation in the case of a continuous fibre composite is termed unidirectional and the corresponding random situation can be approximated to by bidirectional woven reinforcement (Figure 2.3 Block D).

Multilayered composites are another category, and commonly used form, of fibre reinforced composites. These are classified as either laminates or hybrids (Fig 2.3 Block E). Laminates are sheet constructions which are made by stacking layers (also called plies or laminate and usually unidirectional) in a specified sequence. The layers are often in the form of 'prepreg' (fibres pre-impregnated with partly cured resin) which are consolidated in an autoclave. A laminate may have between 4 and 400 layers and the fibre orientation changes from layer to layer in a regular manner through the thickness of the laminate, e.g. a 0/90/0 stacking sequence results in a cross-ply composite.

Hybrids are composites with mixed fibres and are becoming commonplace. The fibres may be mixed within a ply or layer by layer, and these composites are designed to benefit from the different properties of the fibres employed. For example, a mixture of glass and carbon fibres incorporated into a polymer matrix gives a relatively inexpensive composite, owing to the low cost of glass fibres, but with mechanical properties enhanced by the excellent stiffness of carbon.

2.3 The Matrix and Reinforcement

Most composites are designed to exploit an improvement in mechanical properties. Even for composites produced essentially for their physical properties, the mechanical properties can play an important role during component manufacture and service. The strengths of fibres are generally much higher than those of their monolithic counterparts owing to the presence of defects in the latter.

There are of course many properties other than strength that should be taken into account when selecting a reinforcement. In the case of fibres the flexibility is important as it determines whether the fibers may be easily woven or not, and influences the choice of method for composite manufacture. The flexibility of a fibre depends on Young's modulus and the diameter of the fibre, decreasing as diameter increases.

Clearly, single fibres, because of their small cross-section dimensions, are not directly usable in structural applications. This problem may be overcome by embedding the fibres in a material to hold the fibres apart, to protect the surface of the fibres, and to facilitate the production of components. The embedding material is the matrix. The amount of reinforcement that can be incorporated in a given matrix is limited by a number of factors. For example with particulate-reinforced metals the reinforcement content is usually kept to less than 40 vol% (0.4 volume fraction) owing to processing difficulties and increasing brittleness at higher contents. On the other hand, the processing methods for fibre-reinforced polymers are capable of producing composites with a high proportion of fibres, and the upper limit of about 70 vol% (0.7 volume fraction) is set by the need to avoid fibre-fibre contact, which results in fibre damage.

Finally the fact that the reinforcement is bonded to the matrix means that any loads applied to a composite are carried by both constituents. As in most cases the reinforcement is the stiffer and stronger constituent, it is the principal load-bearer. The matrix is said to have transferred the load to the reinforcement.

2.4 Functions of Fibers and Matrix

A composite material is formed by reinforcing plastics with fibers. To develop a good understanding of composite behavior, one should have a good knowledge of the roles of fibers and matrix materials in a composite. The important functions of fibers and matrix materials are discussed below.

The main functions of the fibers in a composite are:

- To carry the load. In a structural composite, 70 to 90% of the load is carried by fibers.
- To provide stiffness, strength, thermal stability, and other structural properties in the composites.
- To provide electrical conductivity or insulation, depending on the type of fiber used.

A matrix material fulfills several functions in a composite structure, most of which are vital to the satisfactory performance of the structure. Fibers in and of themselves are of little use without the presence of a matrix material or binder. The important functions of a matrix material include the following:

- The matrix material binds the fibers together and transfers the load to the fibers. It provides rigidity and shape to the structure.
- The matrix isolates the fibers so that individual fibers can act separately. This stops or slows the propagation of a crack.
- The matrix provides a good surface finish quality and aids in the production of net-shape or near-net-shape parts.
- The matrix provides protection to reinforcing fibers against chemical attack and mechanical damage (wear).
- Depending on the matrix material selected, performance characteristics such as ductility, impact strength, etc. are also influenced. A ductile matrix will increase the toughness of the structure. For higher toughness requirements, thermoplastic-based composites are selected.
- The failure mode is strongly affected by the type of matrix material used in the composite as well as its compatibility with the fiber.

2.5 Special Features of Composites

Composites have been routinely designed and manufactured for applications in which high performance and light weight are needed. They offer several advantages over traditional engineering materials as discussed below.

- Composite materials provide capabilities for part integration. Several metallic components can be replaced by a single composite component.
- Composite structures provide in-service monitoring or online process monitoring with the help of embedded sensors. This feature is used to monitor fatigue damage in aircraft structures or can be utilized to monitor the resin flow in an RTM (resin transfer molding) process. Materials with embedded sensors are known as “smart” materials.
- Composite materials have a high specific stiffness (stiffness-to-density ratio). Composites offer the stiffness of steel at one fifth the weight and equal the stiffness of aluminum at one half the weight.
- The specific strength (strength-to-density ratio) of a composite material is very high. Due to this, airplanes and automobiles move faster and with better fuelefficiency. The specific strength is typically in the range of 3 to 5 times that of steel and aluminum alloys. Due to this higher specific stiffness and strength, composite parts are lighter than their counterparts.
- The fatigue strength (endurance limit) is much higher for composite materials. Steel and aluminum alloys exhibit good fatigue strength up to about 50% of their static strength. Unidirectional carbon/epoxy composites have good fatigue strength up to almost 90% of their static strength.
- Composite materials offer high corrosion resistance. Iron and aluminum corrode in the presence of water and air and require special coatings and alloying. Because the outer surface of composites is formed by plastics, corrosion and chemical resistance are very good.
- Composite materials offer increased amounts of design flexibility. For example, the coefficient of thermal expansion (CTE) of composite structures can be made zero by selecting suitable materials and lay-up sequence.

Because the CTE for composites is much lower than for metals, composite structures provide good dimensional stability.

- Net-shape or near-net-shape parts can be produced with composite materials. This feature eliminates several machining operations and thus reduces process cycle time and cost.
- Complex parts, appearance, and special contours, which are sometimes not possible with metals, can be fabricated using composite materials without welding or riveting the separate pieces. This increases reliability and reduces production times. It offers greater manufacturing feasibility.
- Composite materials offer greater feasibility for employing design for manufacturing (DFM) and design for assembly (DFA) techniques. These techniques help minimize the number of parts in a product and thus reduce assembly and joining time. By eliminating joints, high-strength structural parts can be manufactured at lower cost. Cost benefit comes by reducing the assembly time and cost.
- Composites offer good impact properties, as shown in Figures 2.4 and 2.5. Figure 2.4 shows impact properties of aluminum, steel, glass/epoxy, kevlar/epoxy, and carbon/epoxy continuous fiber composites. Glass and Kevlar composites provide higher impact strength than steel and aluminum. Figure 2.5 compares impact properties of short and long glass fiber thermoplastic composites with aluminum and magnesium. Among thermoplastic composites, impact properties of long glass fiber nylon 66 composite (NylonLG60) with 60% fiber content, short glass fiber nylon 66 composite (NylonSG40) with 40% fiber content, long glass fiber polypropylene composite (PPLG40) with 40% fiber content, short glass fiber polypropylene composite (PPSG40) with 40% fiber content, long glass fiber PPS composite (PPSLG50) with 50% fiber content, and long glass fiber polyurethane composite (PULG60) with 60% fiber content are described. Long glass fiber provides three to four times improved impact properties than short glass fiber composites.
- Noise, vibration, and harshness (NVH) characteristics are better for composite materials than metals. Composite materials dampen vibrations and

order of magnitude better than metals. These characteristics are used in a variety of applications, from the leading edge of an airplane to golf clubs.

- By utilizing proper design and manufacturing techniques, cost-effective composite parts can be manufactured. Composites offer design freedom by tailoring material properties to meet performance specifications, thus avoiding the over-design of products. This is achieved by changing the fiber orientation, fiber type, and/or resin systems.

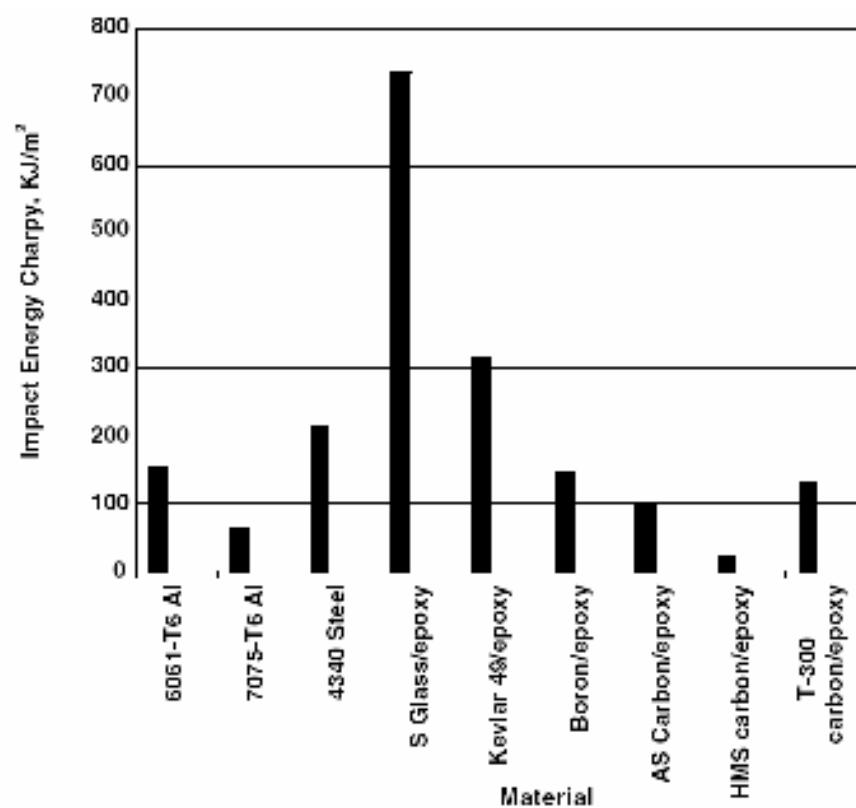


Figure 2.4 Impact properties of various engineering materials.

Unidirectional composite materials with about 60% fiber volume fraction are used.

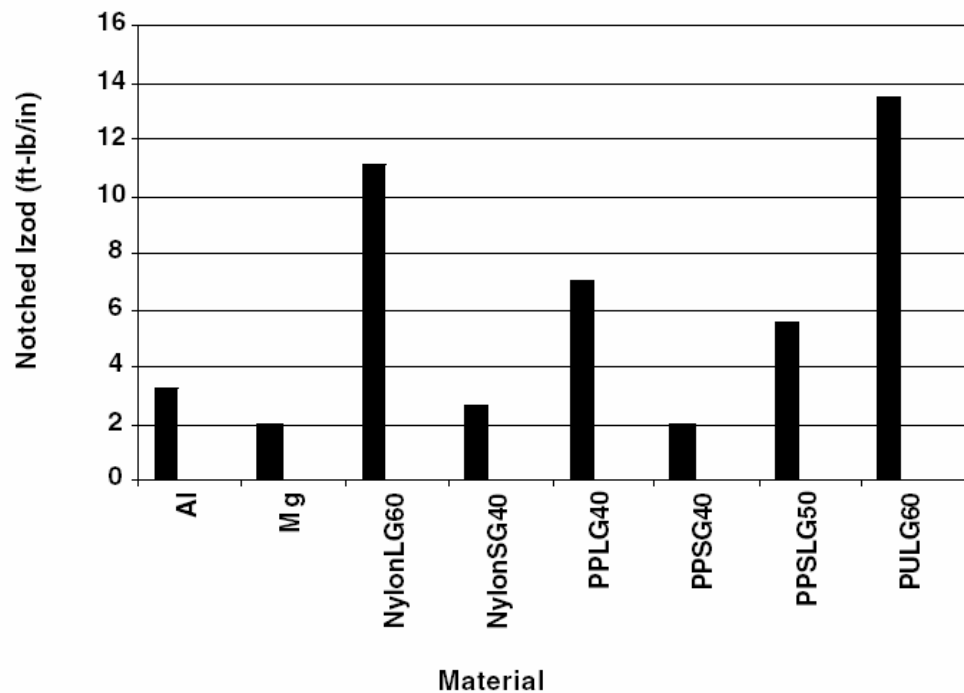


Figure 2.5 Impact properties of long glass (LG) and short glass (SG) fibers reinforced thermoplastic composites. Fiber weight percent is written at the end in two digits.

- Glass-reinforced and aramid-reinforced phenolic composites meet FAA and JAR requirements for low smoke and toxicity. This feature is required for aircraft interior panels, stow bins, and galley walls.
- The cost of tooling required for composites processing is much lower than that for metals processing because of lower pressure and temperature requirements. This offers greater flexibility for design changes in this competitive market where product lifetime is continuously reducing.

2.6 Drawbacks of Composites

Although composite materials offer many benefits, they suffer from the following disadvantages:

- The materials cost for composite materials is very high compared to that of steel and aluminum. It is almost 5 to 20 times more than aluminum and steel on a weight basis. For example, glass fiber costs \$1.00 to \$8.00/lb; carbon fiber costs \$8 to \$40/lb; epoxy costs \$1.50/lb; glass/epoxy prepreg costs \$12/lb; and carbon/epoxy prepreg costs \$12 to \$60/lb. The cost of steel is \$0.20 to \$1.00/lb and that of aluminum is \$0.60 to \$1.00/lb.
- In the past, composite materials have been used for the fabrication of large structures at low volume (one to three parts per day). The lack of high-volume production methods limits the widespread use of composite materials. Recently, pultrusion, resin transfer molding (RTM), structural reaction injection molding (SRIM), compression molding of sheet molding compound (SMC), and filament winding have been automated for higher production rates. Automotive parts require the production of 100 to 20,000 parts per day. For example, Corvette volume is 100 vehicles per day, and Ford-Taurus volume is 2000 vehicles per day. Steering system companies such as Delphi Saginaw Steering Systems and TRW produce more than 20,000 steering systems per day for various models. Sporting goods items such as golf shafts are produced on the order of 10,000 pieces per day.
- Classical ways of designing products with metals depend on the use of machinery and metals handbooks, and design and data handbooks. Large design databases are available for metals. Designing parts with composites lacks such books because of the lack of a database.
- The temperature resistance of composite parts depends on the temperature resistance of the matrix materials. Because a large proportion of composites uses polymer-based matrices, temperature resistance is limited by the plastics' properties. Average composites work in the temperature range -40 to $+100^{\circ}\text{C}$. The upper temperature limit can range between $+150$ and $+200^{\circ}\text{C}$ for high temperature plastics such as epoxies, bismaleimides, and PEEK. Table 2.1 shows the maximum continuous-use temperature for various polymers.

- Solvent resistance, chemical resistance, and environmental stress cracking of composites depend on the properties of polymers. Some polymers have low resistance to solvents and environmental stress cracking.
- Composites absorb moisture, which affects the properties and dimensional stability of the composites.

Table 2.1 Maximum Continuous-Use Temperatures for Various Thermosets and Thermoplastics

Materials	Maximum Continuous-Use Temperature (°C)
Thermosets	
Vinylester	60–150
Polyester	60–150
Phenolics	70–150
Epoxy	80–215
Cyanate esters	150–250
Bismaleimide	230–320
Thermoplastics	
Polyethylene	50–80
Polypropylene	50–75
Acetal	70–95
Nylon	75–100
Polyester	70–120
PPS	120–220
PEEK	120–250
Teflon	200–260

2.7 Composites Markets

There are many reasons for the growth in composite applications, but the primary impetus is that the products fabricated by composites are stronger and lighter. Today, it is difficult to find any industry that does not utilize the benefits of composite materials. The largest user of composite materials today is the transportation industry, having consumed 1.3 billion pounds of composites in 2000. Composite materials have become the materials of choice for several industries.

In the past three to four decades, there have been substantial changes in technology and its requirement. This changing environment created many new needs and opportunities, which are only possible with the advances in new materials and their associated manufacturing technology.

In the past decade, several advanced manufacturing technology and material systems have been developed to meet the requirements of the various market segments. Several industries have capitalized on the benefits of composite materials. The vast expansion of composite usage can be attributed to the decrease in the cost of fibers, as well as the development of automation techniques and high-volume production methods. For example, the price of carbon fiber decreased from \$150.00/lb in 1970 to about \$8.00/lb in 2000. This decrease in cost was due to the development of low-cost production methods and increased industrial use.

Broadly speaking, the composites market can be divided into the following industry categories: aerospace, automotive, construction, marine, corrosion resistant equipment, consumer products, appliance/business equipment, and others. U.S. composite shipments in the above markets are shown in Figure 2.6 for the years 1999 and 2000 (projected).

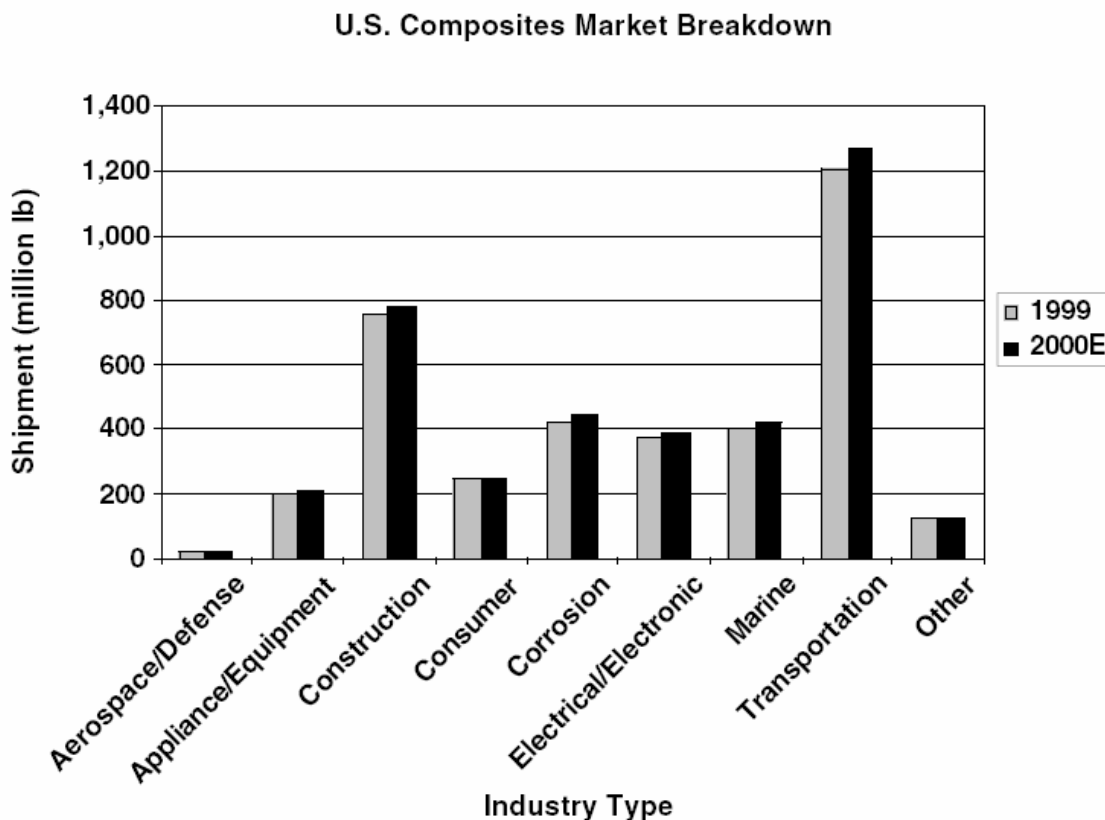


Figure 2.6 Composite shipments in various industries in 1999 and those projected for 2000.

2.7.1 The Aerospace Industry

The aerospace industry was among the first to realize the benefits of composite materials. Airplanes, rockets, and missiles all fly higher, faster, and farther with the help of composites. Glass, carbon, and Kevlar fiber composites have been routinely designed and manufactured for aerospace parts. The aerospace industry primarily uses carbon fiber composites because of their high-performance characteristics. The hand lay-up technique is a common manufacturing method for the fabrication of aerospace parts; RTM and filament winding are also being used.

In 1999, the aerospace industry consumed 23 million pounds of composites, as shown in Figure 2.7. Military aircrafts, such as the F-11, F-14, F-15, and F-16, use composite materials to lower the weight of the structure. The composite components

used in the above-mentioned fighter planes are horizontal and vertical stabilizers, wing skins, fin boxes, flaps, and various other structural components as shown in Table 2.2. Typical mass reductions achieved for the above components are in the range of 20 to 35%. The mass saving in fighter planes increases the payload capacity as well as the missile range.

Figure 2.7.a, Figure 2.7.b and Figure 2.7.c show the typical composite structures used in commercial aircraft and Figure 2.8.a and Figure 2.8.b shows the typical composite structures used in military aircraft. Composite components used in engine and satellite applications are shown in Figures 2.9 and 2.10, respectively.

Table 2.2 Composite Components in Aircraft Applications

Composite Components	
F-14	Doors, horizontal tails, fairings, stabilizer skins
F-15	Fins, rudders, vertical tails, horizontal tails, speed brakes, stabilizer skins
F-16	Vertical and horizontal tails, fin leading edge, skins on vertical fin box
B-1	Doors, vertical and horizontal tails, flaps, slats, inlets
AV-8B	Doors, rudders, vertical and horizontal tails, ailerons, flaps, fin box, fairings
Boeing 757	Spoilers, horizontal stabilizers, wings
Boeing 737	Doors, rudders, elevators, ailerons, spoilers, flaps, fairings
Boeing 767	Doors, rudders, elevators, ailerons, spoilers, fairings

Commercial Aircraft Composite Structures

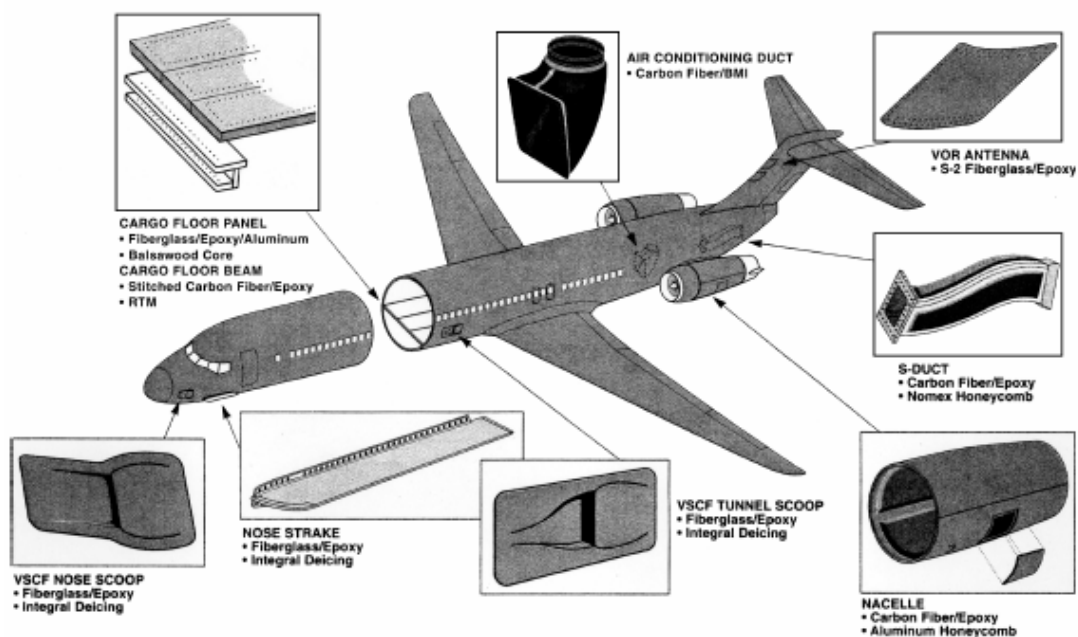


Figure 2.7.a Typical composite structures used in commercial aircraft.

Major monolithic CFRP and thermoplastics application

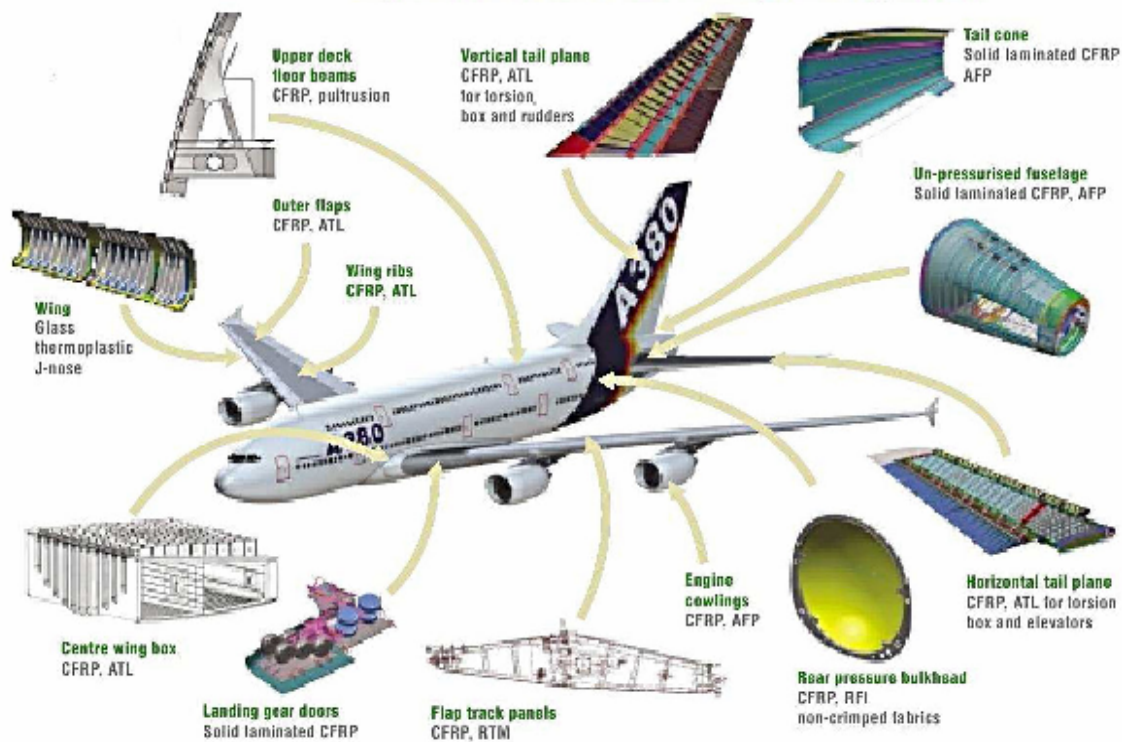


Figure 2.7.b Major composite parts on the Airbus A380.

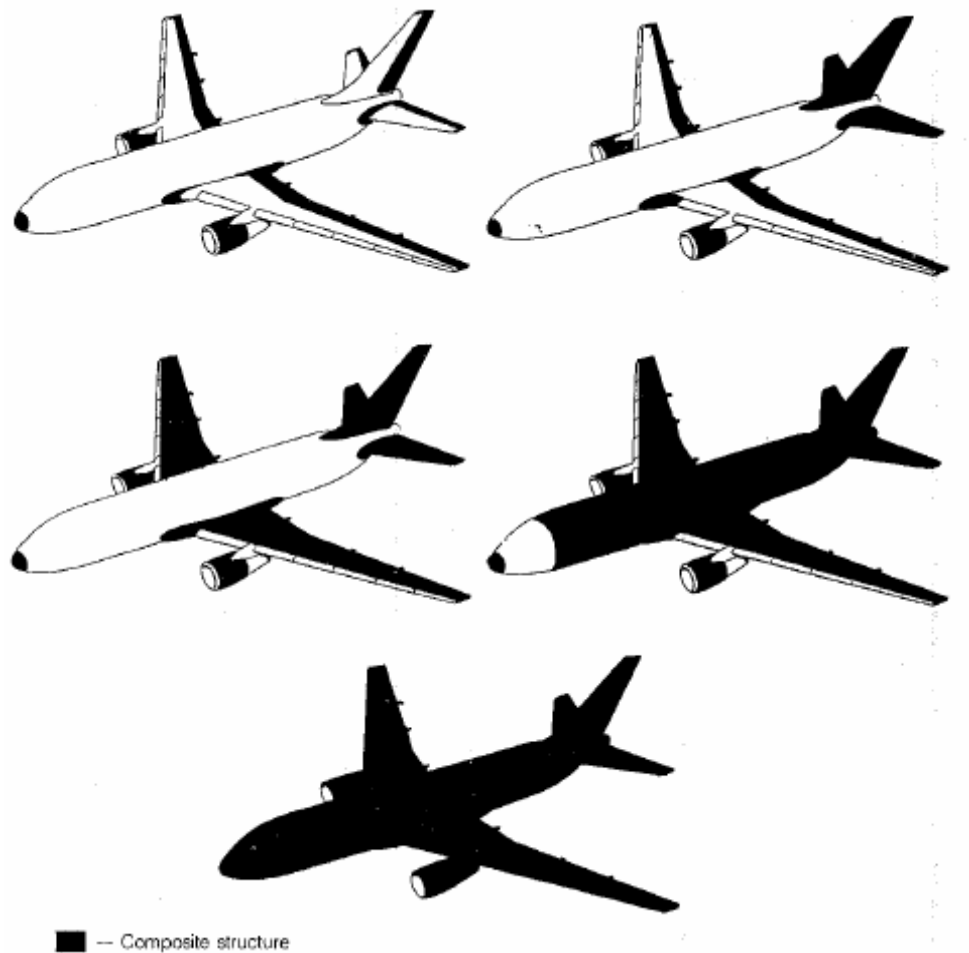


Figure 2.7.c The progressive use of composites on commercial transport airframes

The major reasons for the use of composite materials in spacecraft applications include weight savings as well as dimensional stability. In low Earth orbit (LEO), where temperature variation is from -100 to $+100^{\circ}\text{C}$, it is important to maintain dimensional stability in support structures as well as in reflecting members. Carbon epoxy composite laminates can be designed to give a zero coefficient of thermal expansion. Typical space structures are tubular truss structures, face sheets for the payload bay door, antenna reflectors, etc. In space shuttle composite materials provide weight savings of 2688 lb per vehicle.

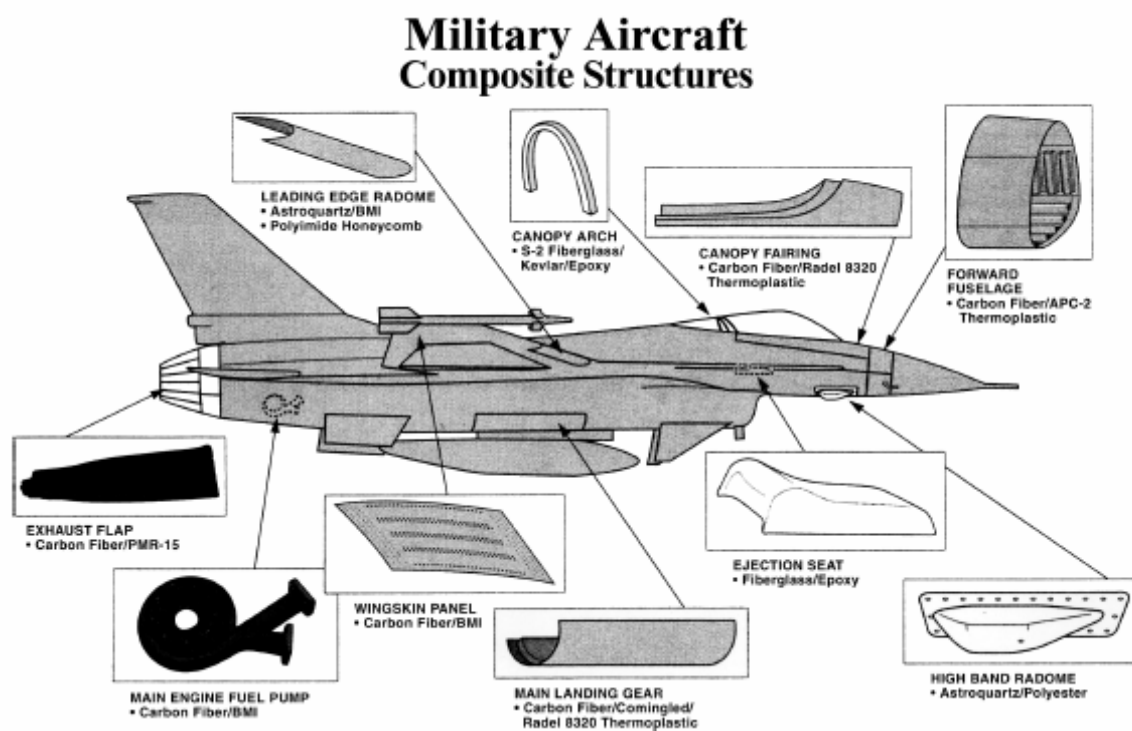


Figure 2.8.a Typical composite structures used in military aircraft

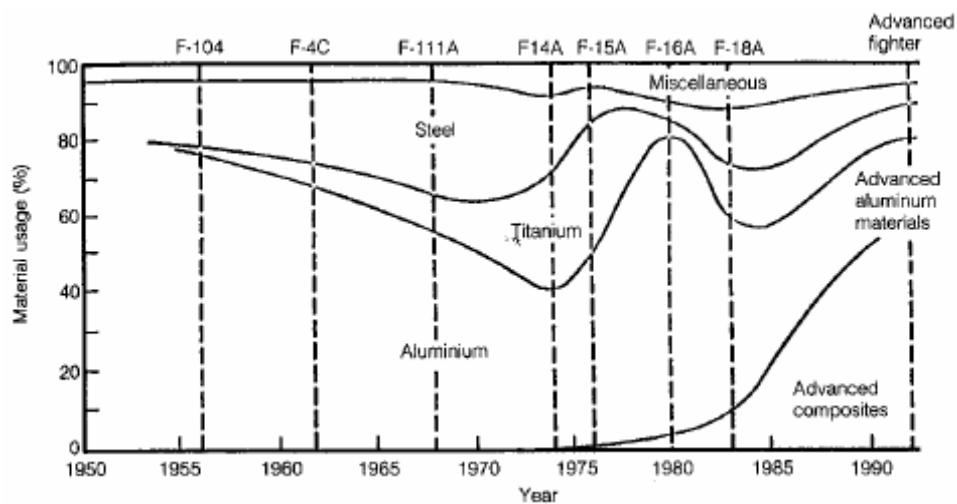


Figure 2.8.b Progress in using composite materials on military fighter aircraft

Engine Components

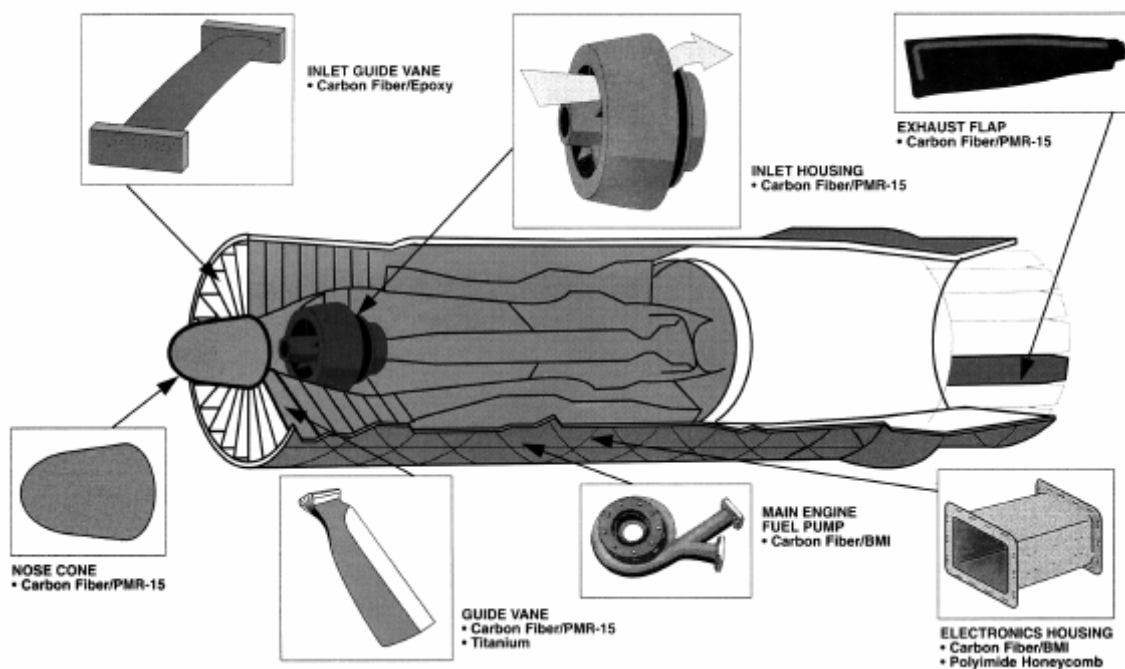


Figure 2.9 Composite components used in engine applications

Satellite Components

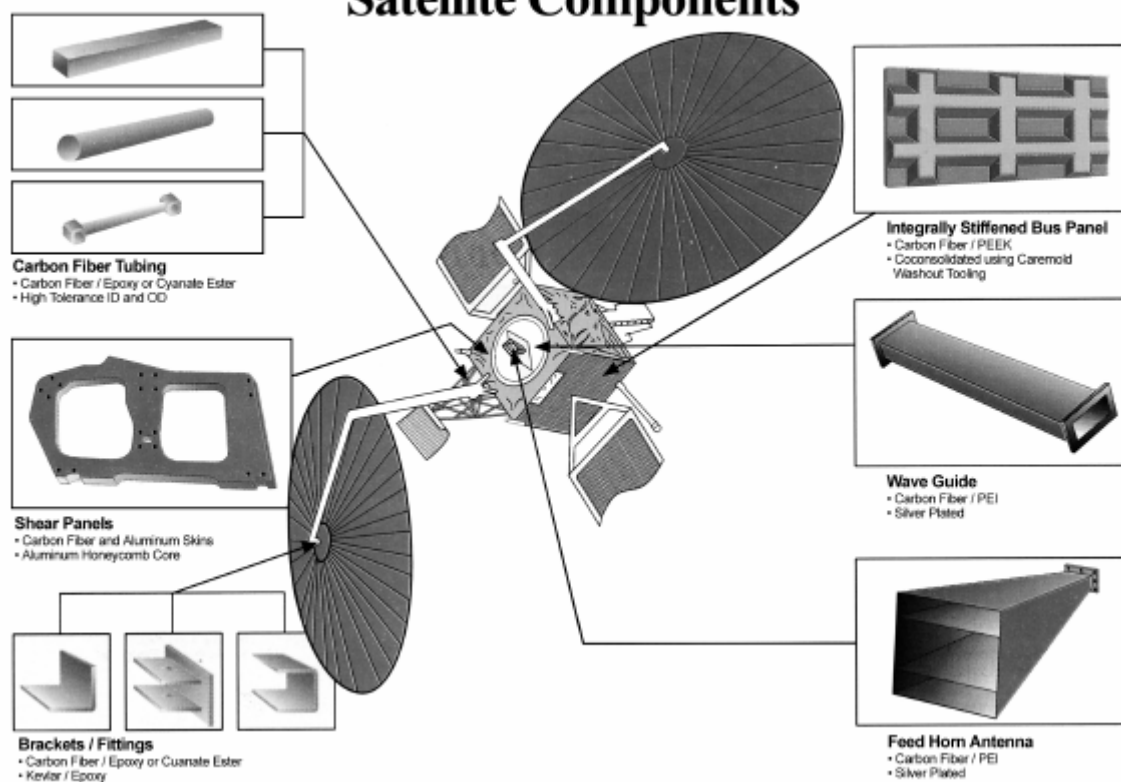


Figure 2.10 Composite components used in satellite applications

Passenger aircrafts such as the Boeing 747 and 767 use composite parts to lower the weight, increase the payload, and increase the fuel efficiency. The components made out of composites for such aircrafts are shown in Table 2.2

2.7.2 The Automotive Industry

Composite materials have been considered the “material of choice” in some applications of the automotive industry by delivering high-quality surface finish, styling details, and processing options. Manufacturers are able to meet automotive requirements of cost, appearance, and performance utilizing composites. Today, composite body panels have a successful track record in all categories — from exotic sports cars to passenger cars to small, medium, and heavy truck applications. In 2000, the automotive industry used 318 million pounds of composites.

Because the automotive market is very cost-sensitive, carbon fiber composites are not yet accepted due to their higher material costs. Automotive composites utilize glass fibers as main reinforcements. Table 2.3 provides a breakdown of automotive composite usage by applications, matrix materials, and manufacturing methods.



Figure 2.11 Composite applications in automotive industry

Table 2.3 Average use of composites in automobiles per year, 1988-1993

Applications	Usage (kg x106)	Matrix Material	Usage (kg x 106)	Manufacturing Process	Usage (kg x 106)
Bumper beam	42	Polyester (TS)	42	SMC (comp. mold)	40
Seat/load floor	14	Polypropylene	22	GMT (comp. mold)	20
Hood	13	Polycarbonate/PBT	10	Injection molding	13
Radiator support	4	Polyethylene	4	Ext. blow mold	5
Roof panel	4	Epoxy	4	Filament wound	3
Other	11	Other	7	Other	8
Total	89	Total	89	Total	89

2.7.3 The Sporting Goods Industry

Sports and recreation equipment suppliers are becoming major users of composite materials. The growth in structural composite usage has been greatest in highperformance sporting goods and racing boats. Anyone who has visited a sporting goods store can see products such as golf shafts, tennis rackets, snow skis, fishing rods, etc. made of composite materials. These products are light in weight and provide higher performance, which helps the user in easy handling and increased comfort.

2.7.4 Marine Applications

Composite materials are used in a variety of marine applications such as passenger ferries, power boats, buoys, etc. because of their corrosion resistance and light weight, which gets translated into fuel efficiency, higher cruising speed, and portability. The majority of components is made of glass-reinforced plastics (GRP) with foam and honeycomb as core materials. About 70% of all recreational boats are made of composite materials according to a 361-page market report on the marine industry. According to this report total annual domestic boat shipments in the United States was \$8.85 billion and total composite shipments in the boating industry worldwide is estimated as 620 million lbs in 2000.

Composites are also used in offshore pipelines for oil and gas extractions. The motivation for the use of GRP materials for such applications includes reduced handling and installation costs as well as better corrosion resistance and mechanical performance. Another benefit comes from the use of adhesive bonding, which minimizes the need for a hot work permit if welding is employed.

2.7.5 Consumer Goods

Composite materials are used for a wide variety of consumer good applications, such as sewing machines, doors, bathtubs, tables, chairs, computers, printers, etc. The majority of these components are short fiber composites made by molding technology such as compression molding, injection molding, RTM, and SRIM.

2.7.6 Construction and Civil Structures

The construction and civil structure industries are the second major users of composite materials. Construction engineering experts and engineers agree that the U.S. infrastructure is in bad shape, particularly the highway bridges. Some 42% of this nation's bridges need repair and are considered obsolete, according to Federal Highway Administration officials. The federal government has budgeted approximately \$78 billion over the next 20 years for major infrastructure rehabilitation. The driving force for the use of glass-and carbon-reinforced plastics for bridge applications is reduced installation, handling, repair, and life-cycle costs as well as improved corrosion and durability. It also saves a significant amount of time for repair and installation and thus minimizes the blockage of traffic. Composite usage in earthquake and seismic retrofit activities is also booming. The columns wrapped by glass/epoxy, carbon/epoxy, and aramid/epoxy show good potential for these applications.

2.7.7 Industrial Applications

The use of composite materials in various industrial applications is growing. Composites are being used in making industrial rollers and shafts for the printing industry and industrial drive shafts for cooling-tower applications. Filament winding shows good potential for the above applications. Injection molded, short fiber composites are used in bushings, pump and roller bearings, and pistons. Composites are also used for making robot arms and provide improved stiffness, damping, and response time.

2.8 Barriers in Composite Markets

The primary barrier to the use of composite materials is their high initial costs in some cases, as compared to traditional materials. Regardless of how effective the material will be over its life cycle, industry considers high upfront costs, particularly when the life-cycle cost is relatively uncertain. This cost barrier inhibits research into new materials. In general, the cost of processing composites is high, especially in the hand lay-up process. Here, raw material costs represent a small fraction of the total cost of a finished product. There is already evidence of work moving to Asia, Mexico, and Korea for the cases where labor costs are a significant portion of the total product costs. The recycling of composite materials presents a problem when penetrating a high-volume market such as the automotive industry, where volume production is in the millions of parts per year. With the new government regulations and environmental awareness, the use of composites has become a concern and poses a big challenge for recycling. (Matthews et al., 2000), (Mazumdar, 2002), (Chun, 1992)

CHAPTER THREE

EXPERIMENTAL STUDY

3.1 Production of the laminated composite plate

Composite laminate used in experiments was manufactured in Izoreel Firm, Izmir. It consists of glass fiber and epoxy resin. The weight of glass fiber per square meter is 509 gr/m². The fiber is oriented unidirectionally. Epoxy CY225 and hardener HY225 were chosen as 100/80 of mass ratio. The laminated plate was manufactured by sticking eight laminas together under a press and heating, symmetrically. The stacking sequence was [0/0/90/45]_s. At the end of the production process, the laminated plate had a nominal thickness of 2,8 mm. The volume fraction of the plate was calculated as 58 % after heating of the laminated plate in an electric oven at 600°C.

3.2 Material Properties

Laminated plate of eight unidirectional oriented layers was manufactured in order to measure its mechanical properties. Some mechanical tests were performed in order to measure the mechanical properties and constants of the laminate composite plate in Dokuz Eylül University Mechanics Laboratory by using INSTRON 1114 Universal Test Machine (Figure 3.8)

The elasticity modulus in the fiber direction, E_1 , and Poisson's ratio, ν_{12} , were measured in a rectangular test specimen by using strain gauges. To calculate E_1 and ν_{12} , a rectangular specimen is taken which's one of the fiber direction coincides with the loading direction. And two strain gauges were stuck on perpendicular directions; one in loading direction and other in the transverse direction. The composite plate was loaded incrementally by an Instron-1114 tensile test machine and the strains ε_1 and ε_2 were measured using an indicator. Then by using these strains E_1 , ν_{12} were calculated.

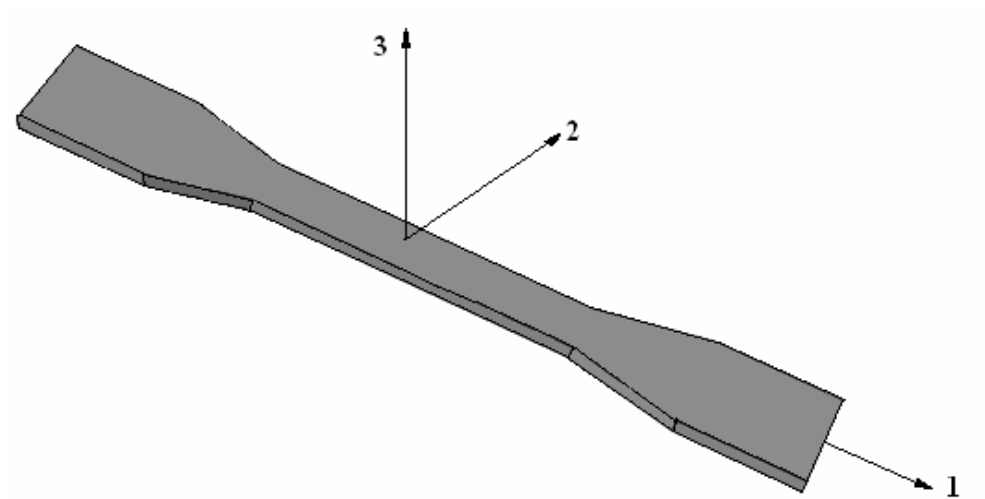


Figure 3.1 Principal directions in a test specimen.

To measure the elasticity modulus in the transverse direction, a test specimen was prepared and then loaded in the transverse direction; E_2 was calculated by a strain gauge stuck onto the specimen.

The ultimate strengths of the composite specimens were measured as X and Y in the directions of fiber and matrix.

To find X_t , a specimen which has the dimensions was loaded step by step to rupture by tensile test machine. (Fig. 3.2) It was calculated from the equation (3.1)

$$X_t = P_{ult} / A \quad (3.1)$$

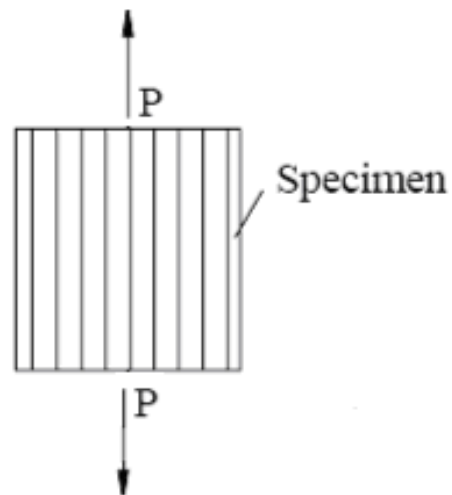


Figure 3.2 Longitudinal tension test

The similar test method was used to determine Y_t which is the tensile strength in transverse direction (Figure 3.3). The Y_t value was calculated by the equation (3.2).

$$Y_t = P_{ult} / A \quad (3.2)$$

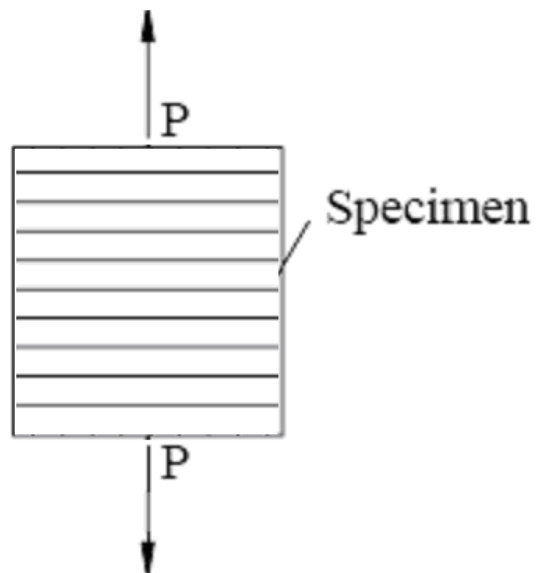


Figure 3.3 Transversal tension test

To find X_c , a specimen, whose fiber direction coincides with the loading direction was taken and it was subjected to compressive loading (Fig.3.4). X_c was also

calculated by dividing the ultimate force by the cross-sectional area of the specimen.
(Equation (3.3))

$$X_c = P_{ult} / A \quad (3.3)$$

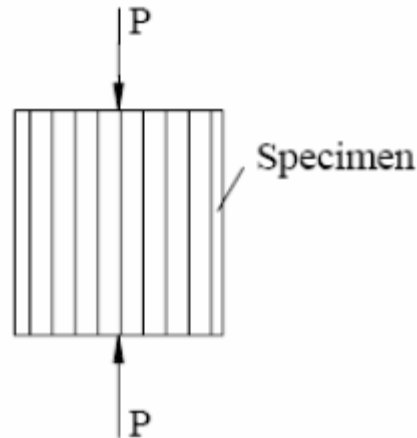


Figure 3.4 Longitudinal compression test

The similar test method was used to determine Y_t (Figure 3.5). The Y_t value was calculated by the equation (3.4).

$$Y_t = P_{ult} / A \quad (3.4)$$

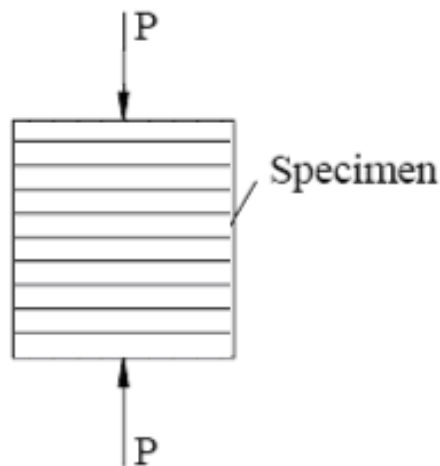


Figure 3.5 Transversal compression test

The Arcan Test Apparature was used for measuring the shear modulus and strength as shown in Figure 3.6. The compressive stresses in the fiber and matrix directions were measured by using the IITRI test method, since it prevents the buckling of the specimens under compressive forces before failure (Daniel, I. M. and Ishai, O., 1994). It eliminates the problem of line contact, since surface to surface contact can be obtained at all positions of the wedges. The mechanical properties of the composite laminate are given in Table 3.1.

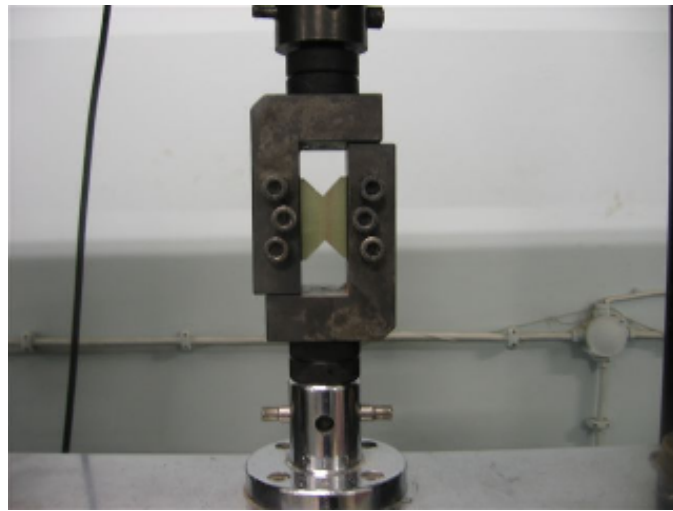


Figure 3.6 Arcan test fixture

Table 3.1. Mechanical properties of glass-epoxy laminated composite plate

E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}	X_t (MPa)	Y_t (MPa)	X_c (MPa)	Y_c (MPa)	S (MPa)	V_f (%)
41.7	14.5	4.1	0.28	1040	105	595	183	78	58

E_1 : Elastic modulus in fiber-direction

E_2 : Elastic modulus in transverse directions

G_{12} : Shear modulus in 1–2 planes

ν_{12} : Poisson's ratio

X_t : Tensile strength in fiber-direction

Y_t : Tensile strength in transverse direction

X_c : Compressive strength in fiber-direction

Y_c : Compressive strength in transverse direction

S : Shear strength

V_f : Fiber volume fraction

3.3 Problem Statement

The failure tests were applied in tension mode on a 20kN test capacity INSTRON 1114 Universal Test Machine (Figure 3.8) equipped with a chart to record the load-displacement relation of specimens at a cross-head speed of 1mm/min. To determine the effects of joint geometry and stacking sequence on the failure behavior, parametric studies were carried out experimentally. Two geometric parameters were chosen for failure response of the bolted-joint composite laminates. Those were the edge distance-to-hole diameter ratio (E/D) and the plate width-to-hole diameter ratio (W/D), which were selected from 1 to 5 and from 2 to 5, respectively, as shown in Figure 3.7.

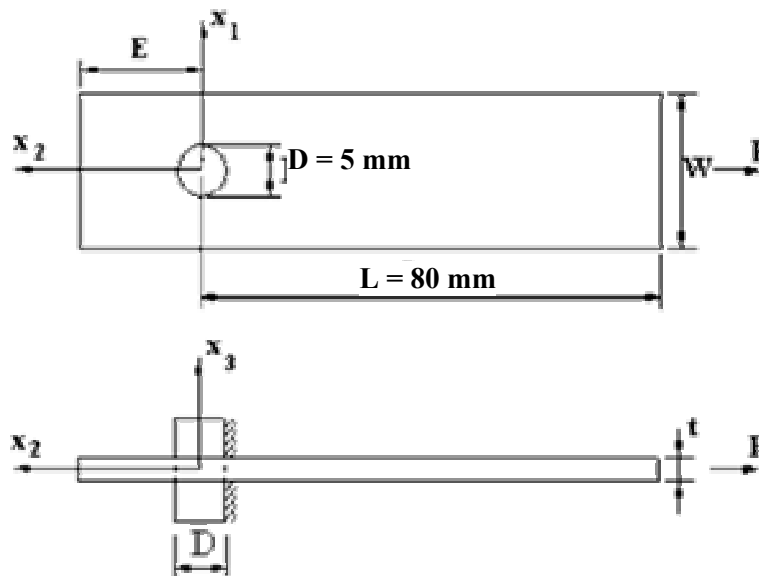


Figure 3.7 Geometry of the composite laminate specimen and pinned joints.

The main geometric parameters of the test plate can be defined as follows:

L - The distance from hole center to the plate edge.

D - Hole diameter.

E - Edge distance, the distance from the center of hole to the free edge.

W – Width of the plate.

E/D -Edge distance-to-hole diameter ratio.

W/D - Plate width-to-hole diameter ratio.

t – Thickness of the plate



Figure 3.8 INSTRON 1114 Universal Test Machine

The basic failure modes in mechanical fastened composite joints are cleavage, shear-out, net-tension and bearing (Mallick, P.K. 1993). The cleavage mode is generally observed in 0° oriented plates.

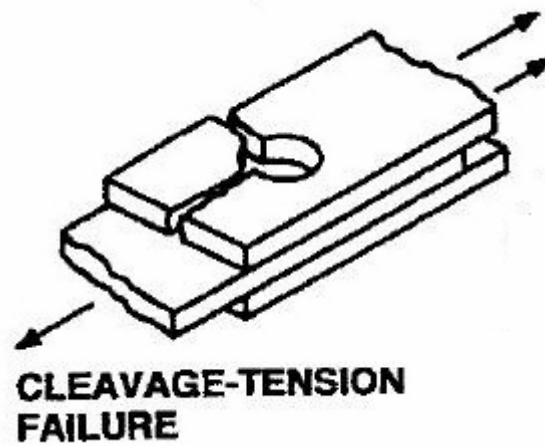


Figure 3.9 Cleavage failure mode of the pinned-joint configuration (Jones, 1999)

The shear-out mode occurs in plates with small (E/D) ratios.

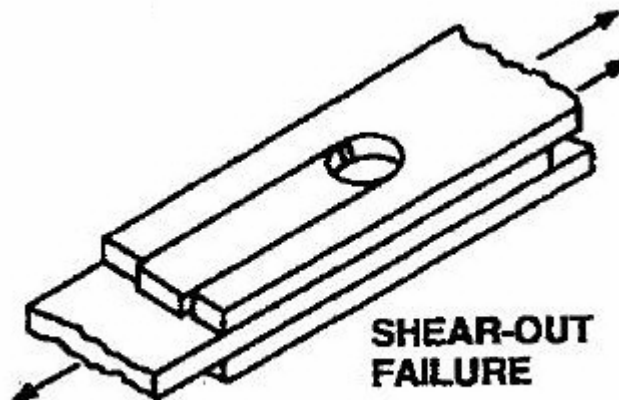


Figure 3.10 Shear-out failure mode of the pinned-joint configuration (Jones, 1999)

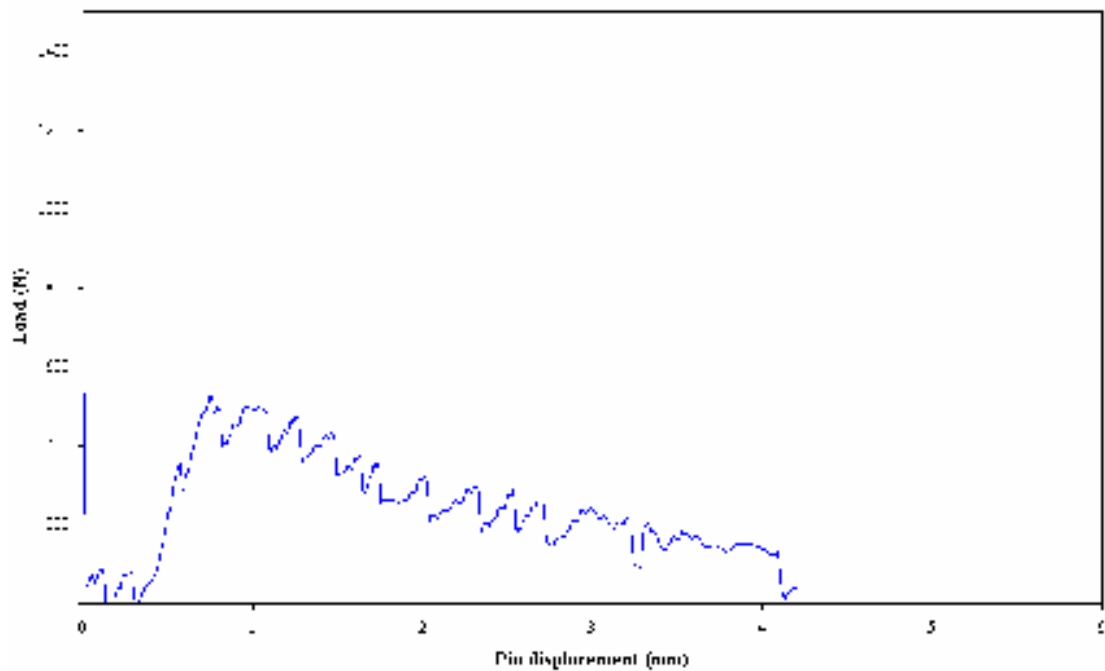


Figure 3.11 Shear-out Failure Mode

The net-tension mode is observed in small (W/D) ratios. Especially, the appearance of the net-tension failure is catastrophic, immediate and without warning. Therefore, the designer should choose optimal pin arrangements to avoid such catastrophic and immediate failure at structural elements in practical applications (Okutan et al. 2001).

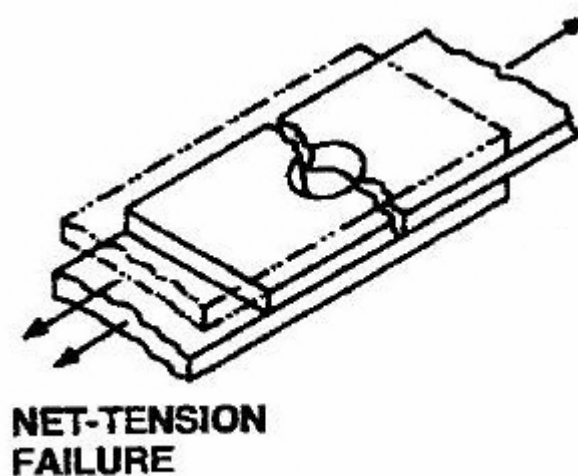


Figure 3.11 Net-tension failure mode of the pinned-joint configuration (Jones, 1999)

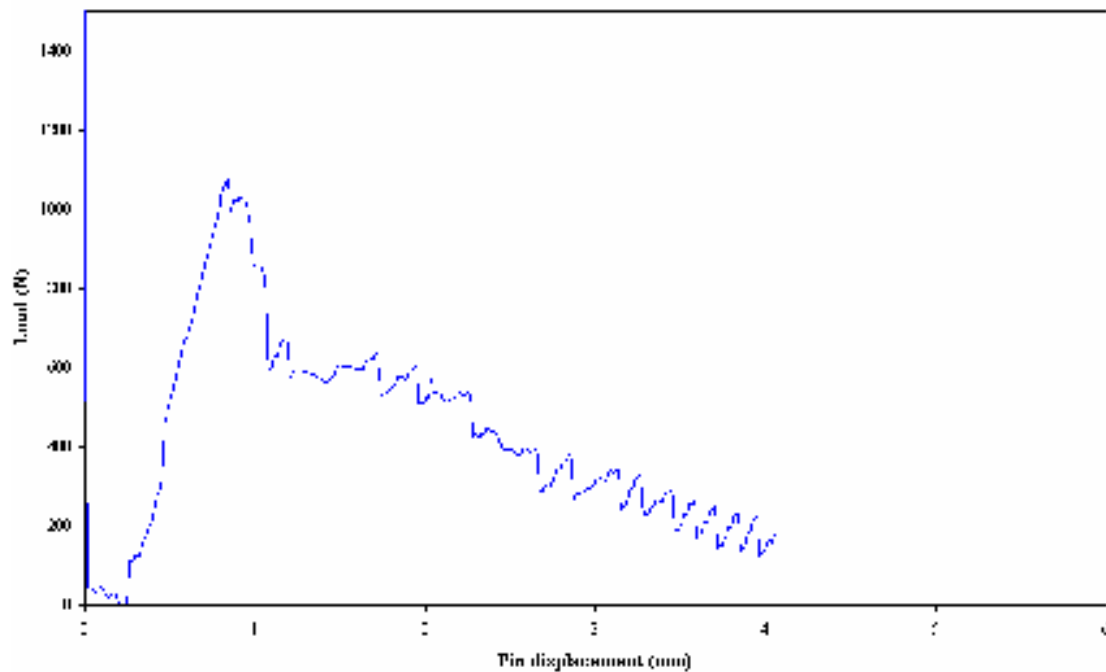


Figure 3.12 Net Tension Failure Mode

The bearing mode generally occurs in the composite plates of high E/D and W/D ratios. However, combinations of these failure modes may be observed in practical applications. Generally, the very wide joints will fail in bearing modes. As the width is reduced, the failure mode will eventually change to tension. However, the width at which the mode will change depends on the lay-up, the hole size effect as well as the basic material properties. Changing the end distance can have the same effect on shear out failure as width has on tensile failure. Obviously a joint must have adequate end distance if it is to achieve its full bearing strength. The overall tensile strength is reduced as the hole diameter increases. However, for bolted joints in all types of fibre reinforced composite laminate, there is a minimal effect of hole size on net tensile and shear strength. The bearing strength of fibre reinforced composite laminate is similarly unaffected. For low modulus materials such as Kevlar, there is a huge reduction in bearing strength for a diameter to thickness ratio of greater than 3. (Akovali, 2001)



Figure 3.12 Bearing failure mode of the pinned-joint configuration (Jones, 1999)

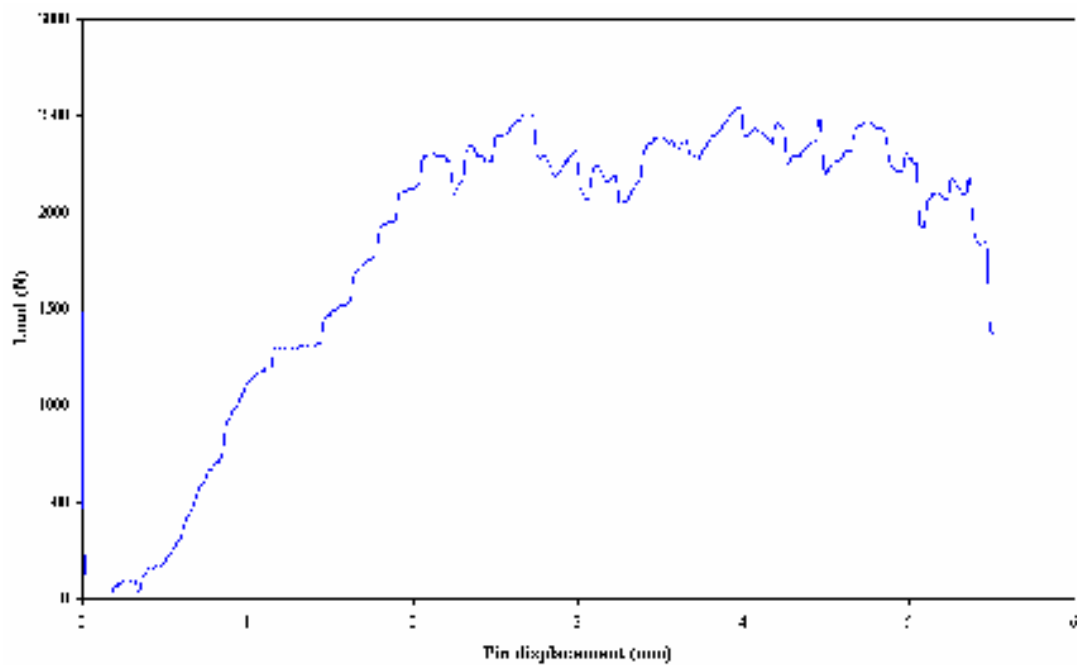


Figure 3.10 Bearing Failure Mode

The bearing stress in a composite laminated specimen can be calculated as,

$$\sigma_b = P/Dt \quad (3.5)$$

where P , D and t are the applied force, the diameter of the pin or bolt and the thickness of the plate, respectively.

Some experiments were carried out without preload moments. The preload moment was applied to test specimens as 3 and 6 Nm. The test fixture is shown in Figure 13. The pinned joint apparatus was manufactured without a preload moment as 0 Nm. The bolted joint was constructed for carrying the preload moment.

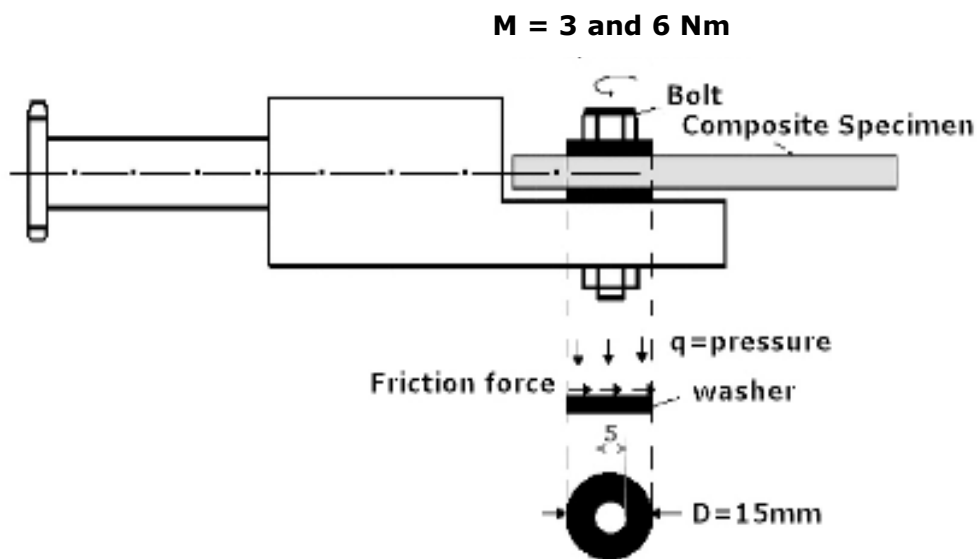


Figure 3.13 Experimental setup for bolted-joint test

Some specimens were observed in dry and unimmersed conditions; meanwhile, some specimens were kept in sea water for 200 days (Haque, A., Mahmood, S., Walker, L. and Jeelani, S., 1991). The sea water was taken from İzmir Gulf.

CHAPTER FOUR

RESULTS AND DISCUSSIONS

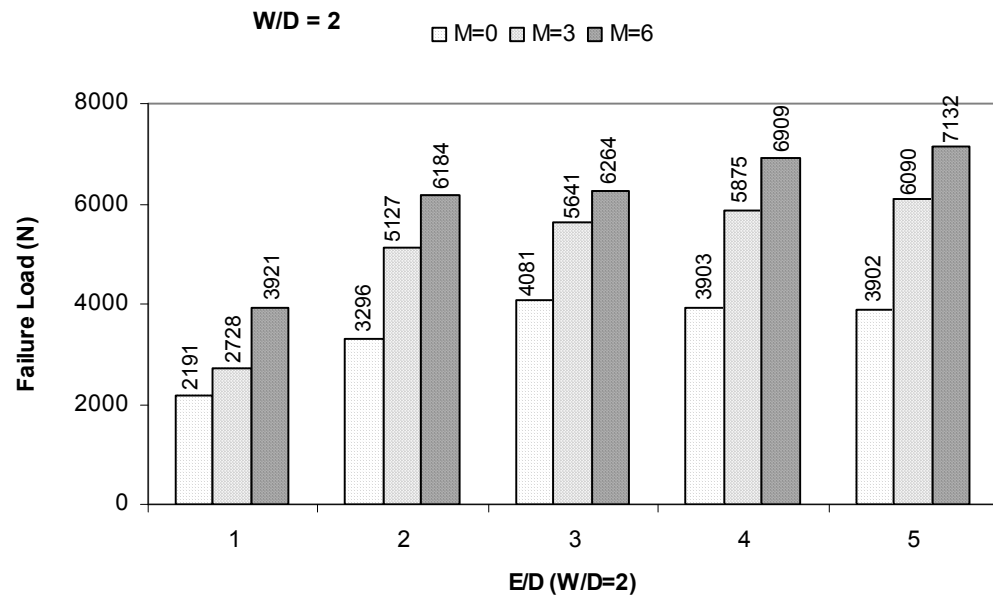
In all the experiments, the cross head of the Instron test machine was chosen 1 mm/min. Different failure modes and combination of failure modes occurred in the tests. Test modes are presented in Table 4.1.

Table 4.1. Failure modes: (a); unimmersed specimens, (b); immersed specimens

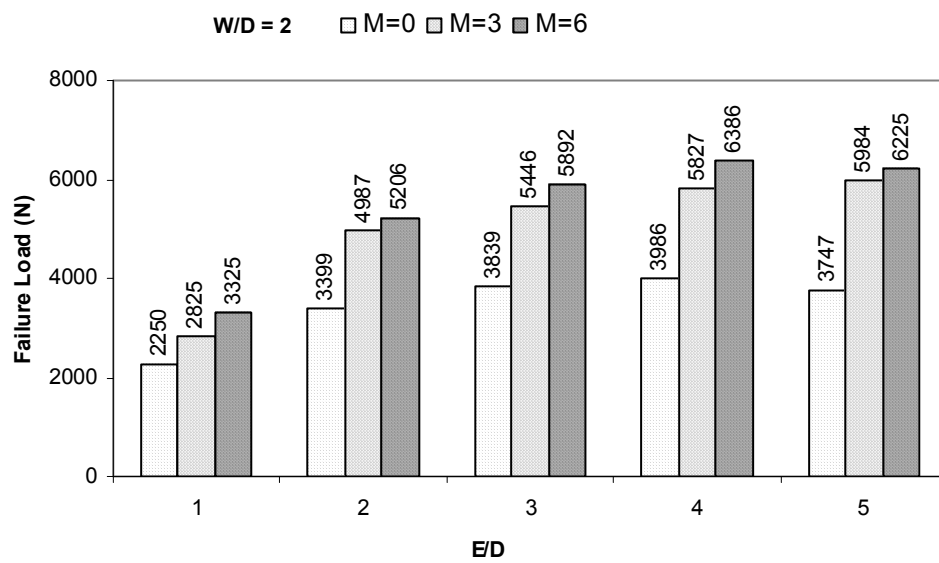
<i>W/D</i>	<i>E/D</i>	Preload Moments (a)			Preload Moments (b)		
		0	3 Nm	6 Nm	0 Nm	3 Nm	6 Nm
2	1	S	S	S	S	S	S
	2	B+N	S+N	N	N	N	S
	3	B+N	S+N	N	B+N	N	N
	4	N	N	N	B	N	N
	5	N	N	N	B	N	N
3	1	S	S	S	S	S	S
	2	B+N	B+N	S+N	B	B+N	N
	3	B+N	B+N	N	B	B+N	B+N
	4	B	N	N	B	B+N	B+N
	5	B	B+N	B+N	B	B+N	B+N
4	1	S	S	S	S	S	S
	2	B	B+N	S	B	B+N	S+N
	3	B	B+N	N+B	B	B	B
	4	B	B+N	B	B	B	B
	5	B	B	B	B	B	B
5	1	S	S	S	S	S	S
	2	B+S	S	S	B	B+S	B+S
	3	B	B	S+B	B	B	B+S
	4	B	B	B	B	B	B
	5	B	B	B	B	B	B

As seen in the Table, $E/D=1$ produces the shear-out mode. When both W/D and E/D ratios increase, the bearing failure mode occurs under without preload moment. The net-tension failure mode is observed for $W/D=2$ under preload moments. Also under preload moments, the bearing and net-tension both occur for $W/D=3$ and $E/D=2, 3, 4, 5$. The bearing failure mode is observed for high values of W/D and E/D .

The failure load in the values of $E/D=1-5$ and $W/D=2$ for unimmersed and immersed specimens is presented in Figures 4.1 (a), (b). It is observed that when E/D ratio increases, the failure load reaches high values for both cases. The mean failure load of the pinned specimens kept in sea water for 200 days decreases 1% in comparison with the unimmersed specimens case due to the corrosivity and changing of the mechanical properties and residual stresses. The failure load of the specimens increases under preload moments for both immersed and unimmersed cases. The mean failure load for the immersed specimens decreases 1 and 12 % under 3 and 6 Nm preload moments, with respect to unimmersed specimens, respectively. The mean failure load of immersed specimens for pinned joints decreases 3% in comparison with the unimmersed specimens. The decrease of the mean failure load of immersed specimen is 3 and 10% for 3 and 6 Nm bolted cases, respectively. The effect of the sea water under 6 Nm preload moment affects the failure load more than under 3 Nm preload moment and without preload moment.



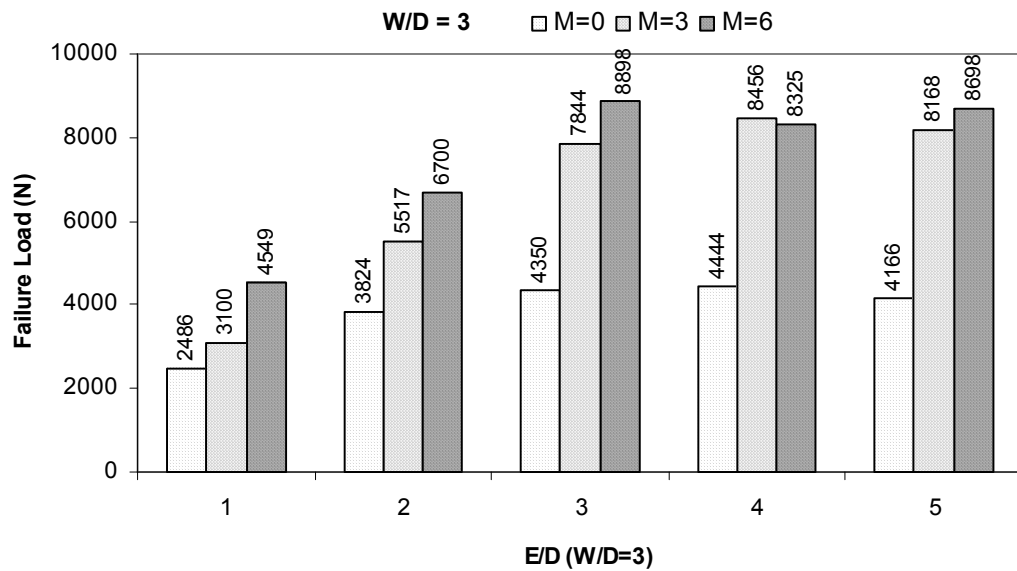
(a)



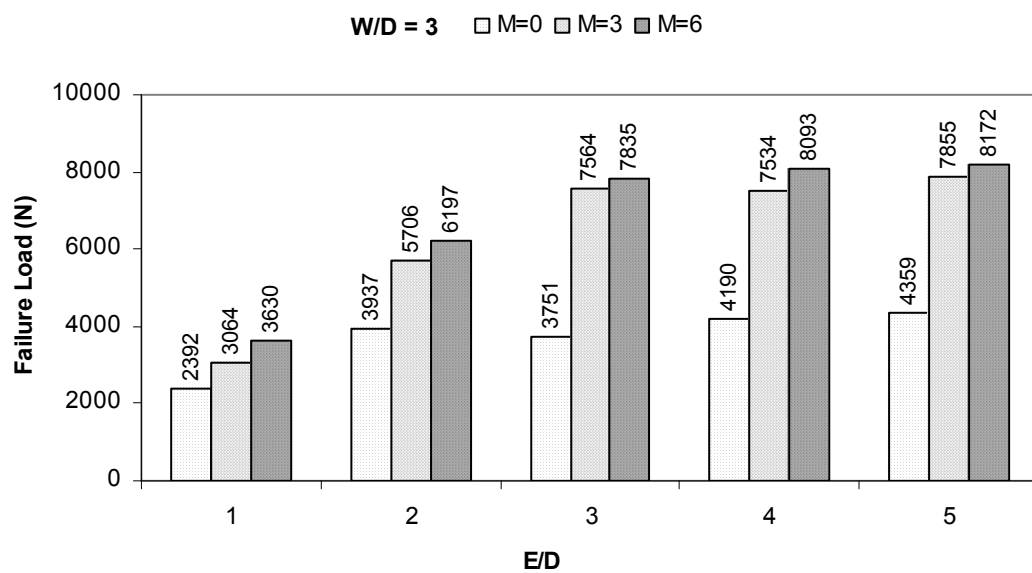
(b)

Figure 4.1 The failure load for: (a); unimmersed specimens under preload moments, (b); immersed specimens under preload moments.

The failure load in $E/D=1-5$ and $W/D=3$ for the immersed and unimmersed cases is shown Figures 4.2 (a), (b). As seen in the figures when E/D ratio increases, the failure load generally attains high values for the both cases.



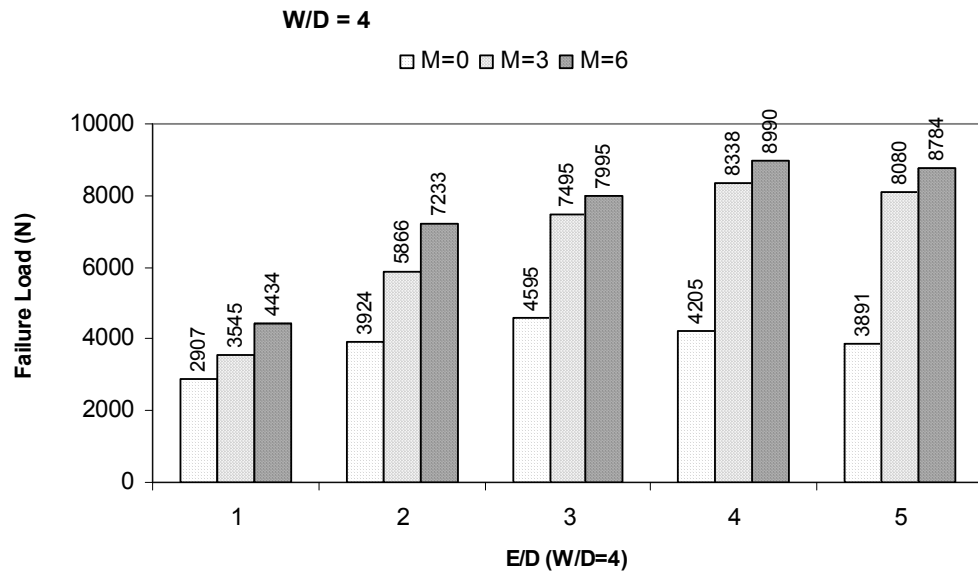
(a)



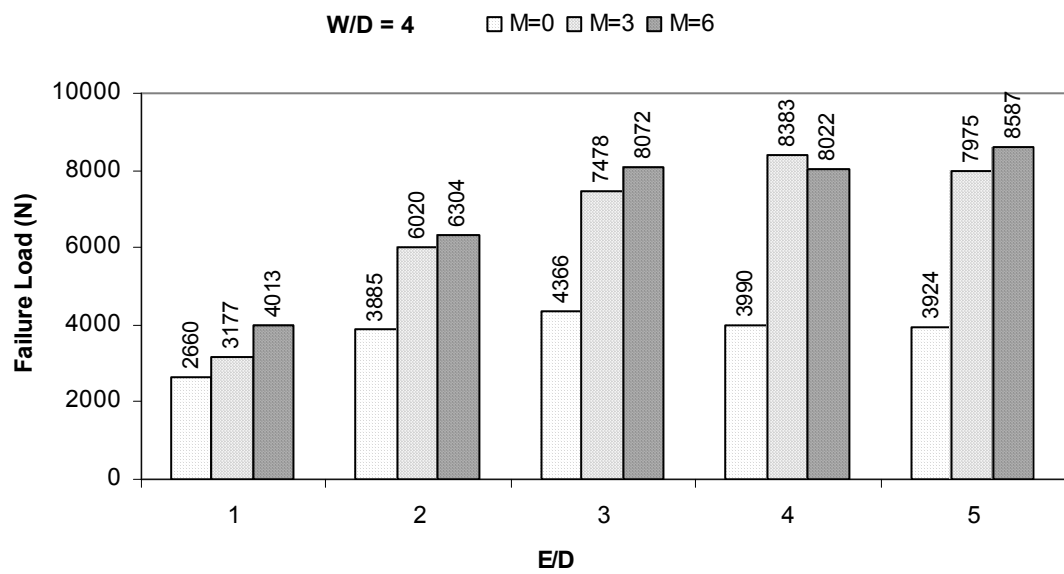
(b)

Figure 4.2 The failure load for: (a); unimmersed specimens under preload moments, (b); immersed specimens under preload moments.

The failure load at $E/D=1-5$ and $W/D=4$ and 5 for the both unimmersed and immersed specimens is represented in Figure 4.3 (a), (b) and 4.4 (a), (b), respectively. It is observed again that the failure load increases for high values of E/D . Besides, the failure load for unimmersed specimens without preload moment is 4% higher than immersed specimens with sea water. The mean failure load for the immersed specimens is 98% and 90% of the unimmersed specimens under 3 Nm preload moment and 93%, 93% of the unimmersed specimens under 6 Nm preload moment. As seen, in all the experiments, the failure load for specimens immersed in the sea water decreases under 6 Nm more than 3 Nm and without moment.

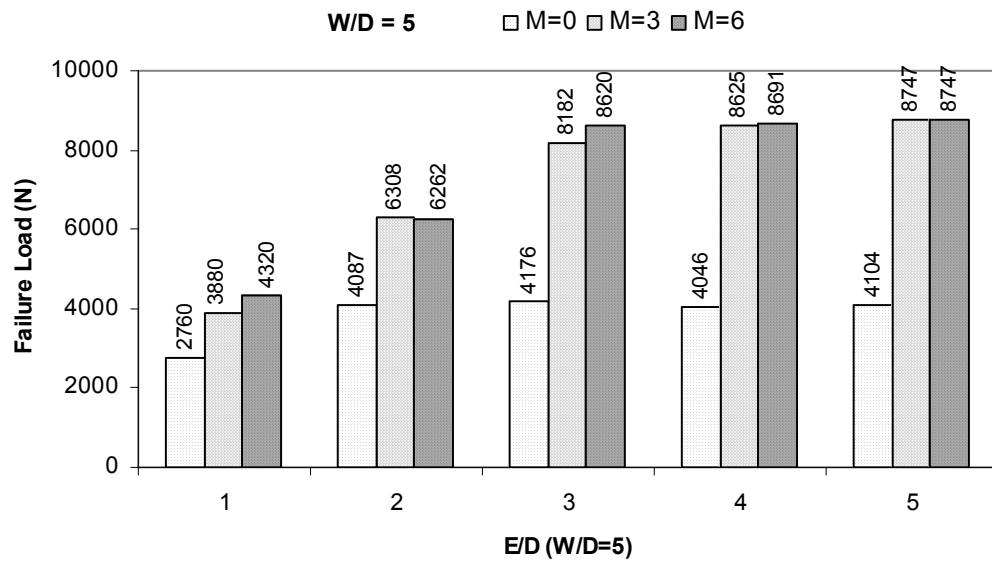


(a)

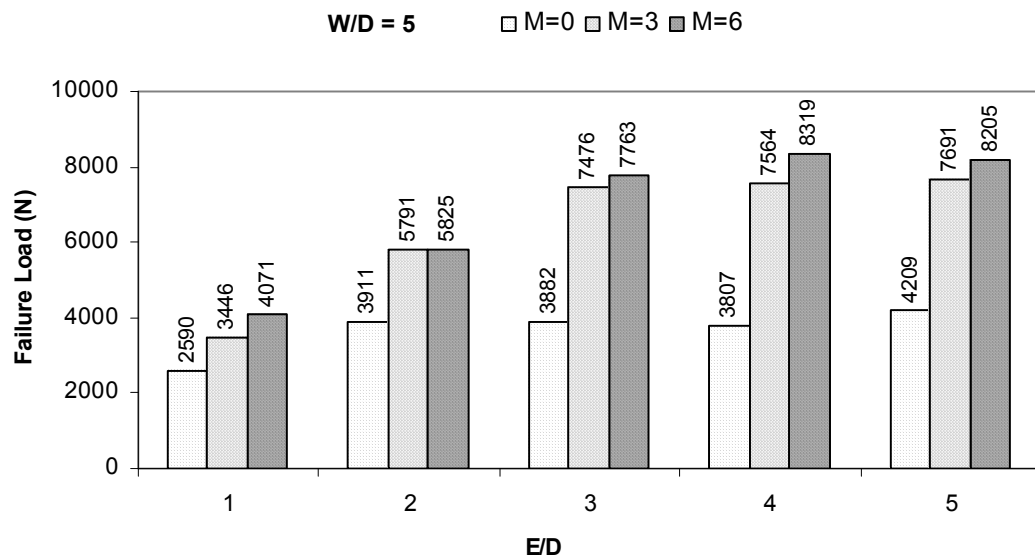


(b)

Figure 4.3. The failure load for: (a); unimmersed specimens under preload moments, (b); immersed specimens under preload moments.



(a)



(b)

Figure 4.4 The failure load for: (a); unimmersed specimens under preload moments, (b); immersed specimens under preload moments.

The failure load, such as, for $E/D = 5$ and $W/D=2-5$ in unimmersed and immersed specimens is shown in Figure 4.5. It is observed that when W/D ratio increases, the failure load reaches high values. Similar results can be said for the specimens under the preload moments of 3 and 6 Nm.

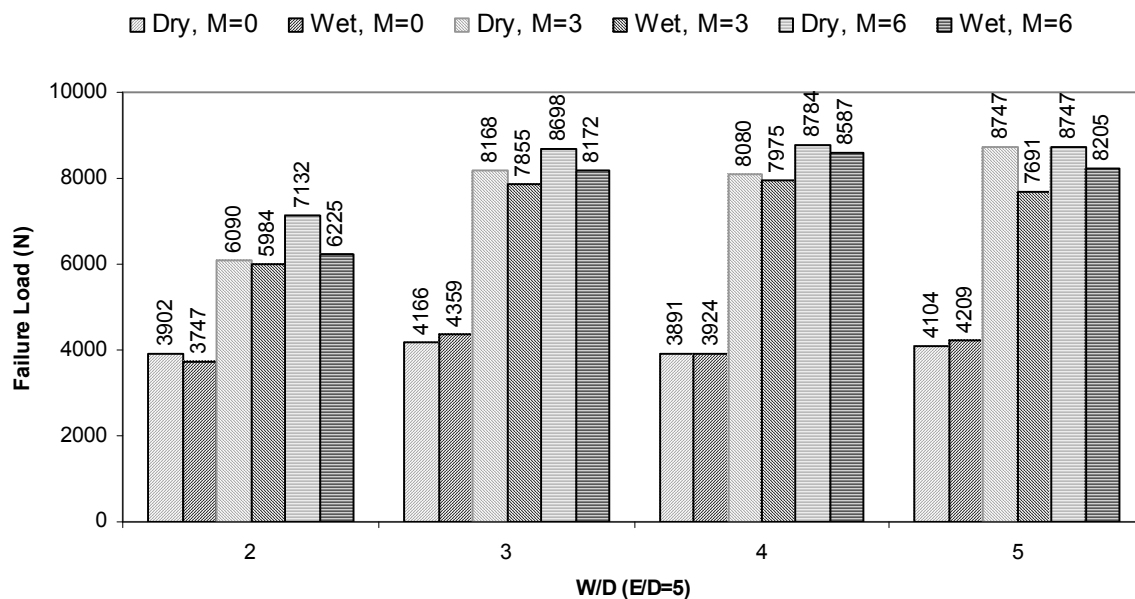


Figure 4.5 The failure load for unimmersed and immersed specimens under preload moments.

The preload force applied to the specimens under $M=3\text{Nm}$ was measured by strain gauges as shown in Figure 4.6. It is seen that the load versus displacement curve increases at high values gradually since especially the bearing failures cause an increase in the lateral clamping force at high values of the axially applied force.

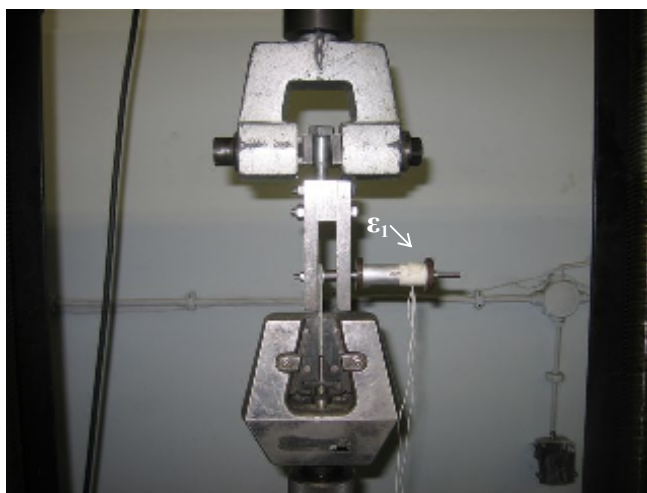


Figure 4.6a Text fixture for measuring lateral force.

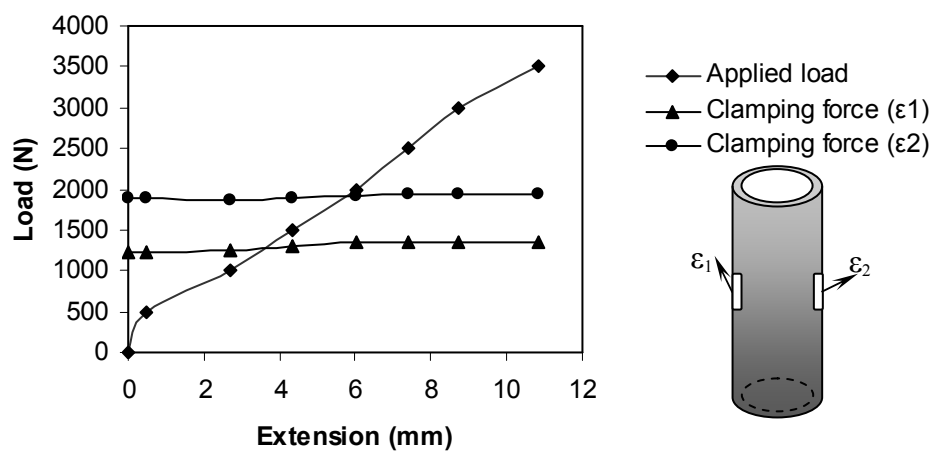


Figure 4.6b Applied load and clamping force versus the axial extension for specimen with an applied moment of 3 Nm.

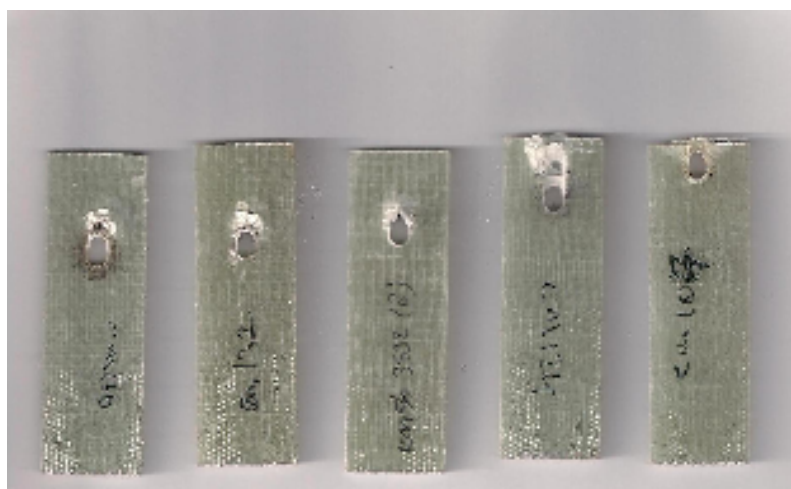


Figure 4.7 Specimens used in experiments – W= 25 mm (unimmersed condition)

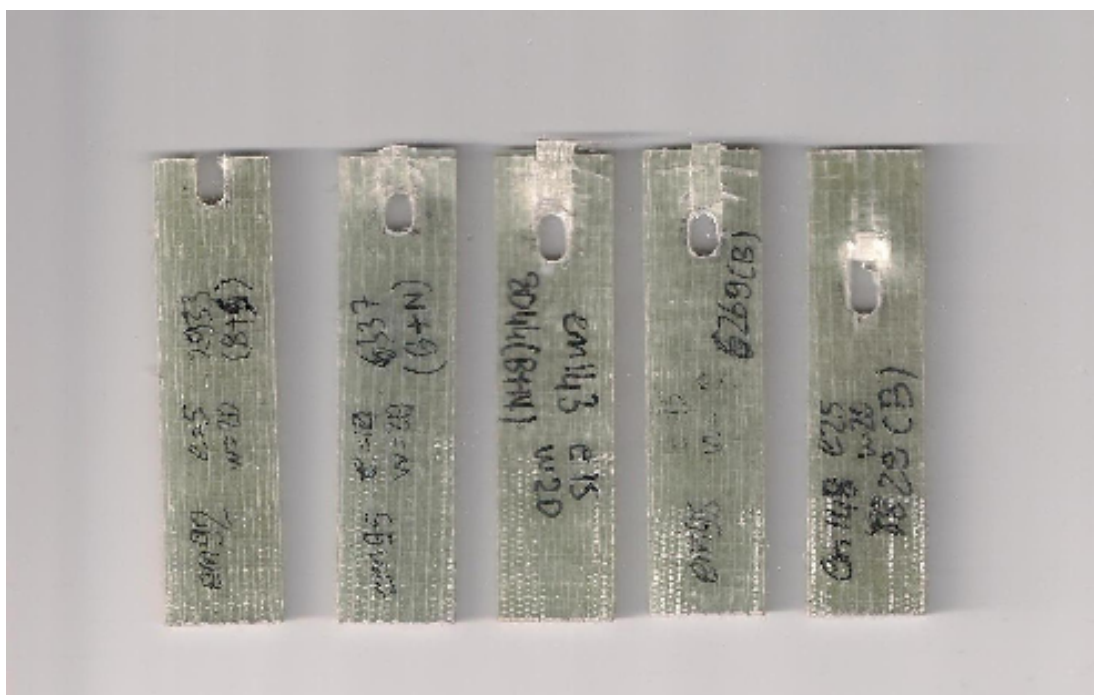


Figure 4.8 Specimens used in experiments – W= 20 mm (unimmersed condition)



Figure 4.9 Specimens used in experiments – W= 15 mm (unimmersed condition)



Figure 4.10 Specimens used in experiments – W= 10 mm (unimmersed condition)



Figure 4.11 Specimens used in experiments – W= 25 mm (immersed condition)



Figure 4.12 Specimens used in experiments – W= 20 mm (immersed condition)

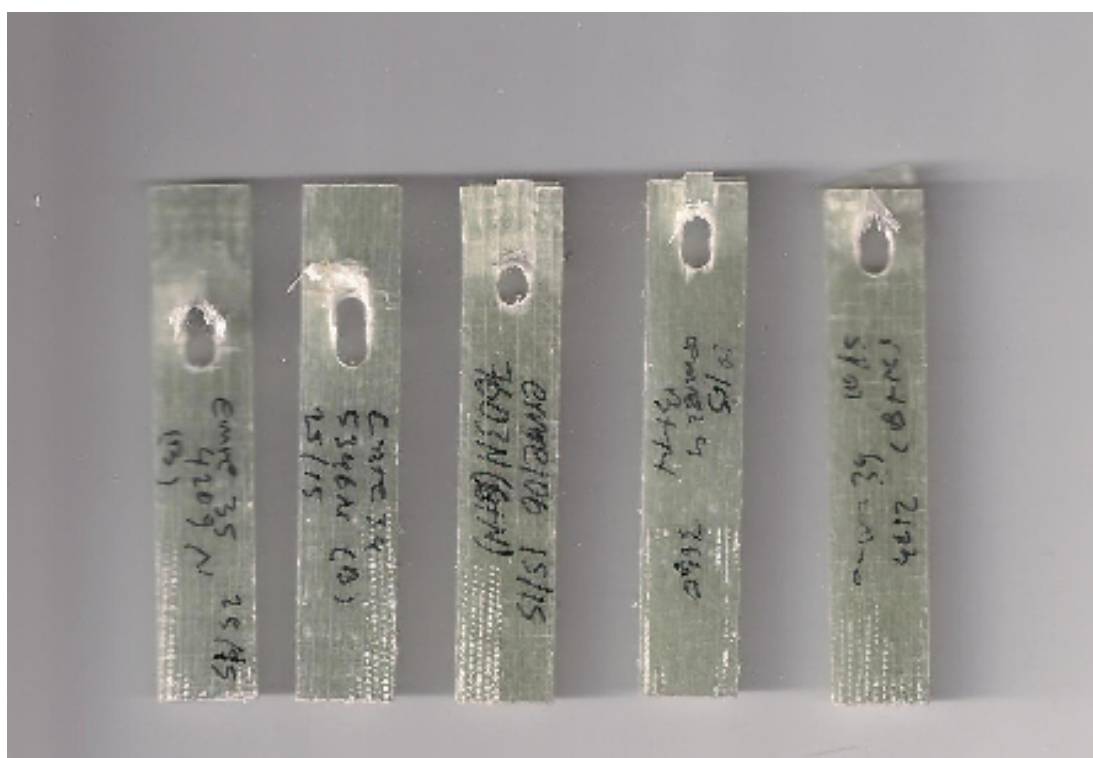


Figure 4.13 Specimens used in experiments – W= 15 mm (immersed condition)



Figure 4.14 Specimens used in experiments – W= 10 mm (immersed condition)

CHAPTER FIVE

CONCLUSIONS

The effect of sea water absorption on the failure response of the pinned and bolted joints has been investigated experimentally. The specimens were manufactured from the glass-epoxy laminated plate oriented as $[0/0/90/45]_s$. In this study, it is concluded that:

- a) The failure load of the bolted joints is higher than that of the pinned joints.
- b) The increase of the E/D and W/D ratios produces high failure loads or bearing strengths.
- c) The immersion into sea water causes a decrease in the failure load, notably.
- d) Preload moments increase the failure load capacity of the specimens up to some value of preload moments. Namely, the relation between the failure load and preload moments is not linear.
- e) The failure load of the unimmersed specimens is higher than that of the immersed specimens in sea water. The mean failure load of immersed specimens is weaker than the unimmersed specimens for $M=0$ and 3Nm and 6Nm, as 3, 4 and 11 %, respectively.

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