Addis Ababa University
School of Graduate Studies

SPACING AND DIAMETER EFFECTS OF RIVETS IN THE FAILURE OF LAMINATED COMPOSITE JOINTS

Tomas Deress

A thesis submitted to the school of
Graduate Studies of Addis Ababa University
in partial fulfillment of the requirements for the Degree of
Master of Science
in
Mechanical Engineering
(Applied Mechanics)

Advisor
Dr. A. Raman
Addis Ababa, Ethiopia 2010

SPACING AND DIAMETER EFFECTS OF RIVETS IN THE FAILURE OF LAMINATED COMPOSITE JOINTS

I have examined the final copy of this thesis for form and content and recommended that it be accepted in the partial fulfillment of the requirements of Master of Science, with major in Mechanical Engineering (Applied Mechanics).

____

Dr. A. Raman
Advisor

We have read this thesis and recommend its acceptance:

____

Dr. Tamirat Tesfaye
Internal Examiner

____

Dr. Alem Bazezew
External Examiner

____

Dr. -Ing Edessa Dribssa
Chairman of Mechanical Engineering Department

____

Acknowledgement

I would like to thank Dr. A. Raman who came up with the idea of the topic in this thesis which I found interesting as well as rewarding. Dr. A. Raman, who was my advisor at the initial stages of this work before he moved back to his country, India, had given me very valuable guidance on how to approach the problem.

I am sincerely grateful to Dr. Edessa Dribssa, chairman of the Department of Mechanical Engineering and Dr. Alem Bazezew for their generous support. I am also extremely grateful to my family and friends for their constant encouragement and support, both morally and financially throughout this study period. I also would like to thank my managers and colleagues at my work place for providing me with the opportunity to study and their continuing support. Last but not least, I extend a special thanks to my friends Dawit Maregn and Bisrat Tamirat for their very special support.

Abstract

Composites have become very important engineering material due to their desirable properties such as high specific strength and light weight. In the use of composite materials for practical purposes, the formations of joints such as mechanical joints are unavoidable; and hence the formation of discontinuities such as holes for rivets or bolts. The aim of this research is to investigate the effects of diameter and spacing (pitch and row spacing) of rivet/hole on composite laminate joints. Mechanical fasteners frequently reduce the load carrying capability of the structure and lead to premature failure. In this thesis, initial failure loads are evaluated with respect to rivet diameter and spacing as a measure of joint strength. The effects of these two parameters are studied with consideration of other directly related parameters such as e/d, w/d and s/d ratios. Finite element analysis and the composite failure criterion Tsai-Wu are used in the study to determine failure loads and from the results obtained conclusions are driven.

.

Contents

List of Figures

List of Tables

List of Abbreviations

3D	Three Dimensional
AISI	American Iron and Steel Institute
ANSYS	Analysis System
CLT	Classical lamination theory
FEM	Finite Element Method
MSC. Marc	MacNeal-Schwendler Corporation's Marc Finite element software
NASA	National Aeronautics and Space Administration
USN	United States Navy

Chapter 1

Introduction

The structural integrity of mechanical structures is usually determined by the integrity and durability of their respective joints. The design of composite joints is more difficult than joints between metallic materials that are isotropic in nature due to their complex mechanical properties. Contrary to many metallic structural members, for which the strength of the joints is mostly governed by the shear and tensile strengths of the pins or bolts, composite joints present specific characteristics owing to their inhomogeneity and anisotropicity. [1]

Although composite structures can be molded in single pieces to simplify manufacturing processes and to reduce assembly cost, they cannot be completely exempted from joining process. There are two general classes of joints for composite materials - mechanical fasteners and adhesive bonding. Adhesive joints would have been the almost always structurally preferred joints due to their capacity to eliminate stress concentrations and to ensure a tight joint. Yet, mechanically fastened joints cannot be avoided when high mechanical stresses have to be transmitted among the jointed structures, or when disassembly is needed to replace damaged structures or to have access to underlying structures.

Mechanical fastening is a critical aspect of designing many engineering structures and is commonly used to form joints between composite laminates. To utilize the full potential of composite materials as structural elements, the strength and failure of the joints between the laminated composites must be understood. Although the exact details of joint design depend on the specific application, all joints have several characteristics in common. One characteristic is heavily loaded joints are designed using mechanical attachments such as rivets and bolts. These fasteners are preferred for easy assembly and disassembly.

The increased use of composites in many engineering applications, due to their superior properties compared to monolithic materials, has proliferated their use in many engineering applications such as structural members in aerospace structures as well as infrastructures. For example, more than 20 % of the structural weight of the biggest commercial passenger aircraft to date, the Airbus A320, is composites. [2] This increased interest in and use of composites has attracted extensive attention of researchers in the past few decades.

There are a number of studies conducted on mechanical joints. For instance, in the design of bolted/riveted joints researchers have identified the important parameters to consider. They include thickness (t), edge-to-hole distance (e), clamping torque, clearance between fastener and hole etc... Some of the researches have also identified the optimum combinations of these parameters which lead to increases in joint strength. Adding to this effort, this thesis is set to investigate the effects of diameter and spacing on the failure of composites in particular the carbon fiber/epoxy composite.

1.1 Objectives of Study

The general objective of this thesis is determining the effects of rivet diameter and spacing on the composite parent material of riveted composite materials joints, in particular, joints between carbon fiber/epoxy panels, on the failure strength of the joints. The work also seeks to make useful inferences from the study and to suggest better design of composite joints.

1.1.1 Specific objectives

The specific objective of this thesis is determining the initial failure loads as measure of joint strength to investigate the effects of rivet diameter and spacing on riveted joints between panels made from CF/E composite material named USN125 connected in double strap butt joints and subjected to in-plane loads.

1.2 Methods

1. Review of existing literature: study of literature on composite laminates and composite structural joint analysis
2. Conducting parametric studies using finite element analysis methods
3. Investigating the results obtained
4. Inferring useful conclusion from the investigation

1.3 Organization and Content

This thesis consists of six chapters. The first is this introductory chapter. Chapter 2 presents the review of literatures and prior studies conducted on composite material joints especially riveted (pinned) joints.

Chapter 3 contains a review of the current accepted theoretical approaches relating to the design and analysis of composite materials and their joints. In doing so, this chapter details the considerations involved and the extent to which existing knowledge is used in this study. This chapter also includes topics relating to the validity of this research by discussing the brief history, application and the analysis complexity of composite material structures.

Chapter 4 presents in detail how the composite material joints in the study are modeled numerically. The finite element program used to create the models is discussed including the selection of the elements, the meshing procedure, the boundary conditions used. Moreover, with the computer model defined, the procedure of parametric study conducted to investigate the effects of spacing and diameter of rivets on the failure strength of the composite laminates is discussed. This chapter is a detailed presentation of the main part of the study conducted.

Following this, Chapter 5 presents all the results obtained and discussion on the obtained results. And then lastly, Chapter 6 draws conclusions from the research. Benefits gained from the work are also noted and possible areas of future work are addressed.

Chapter 2

Literature Review

2.1 Research survey

Because of the importance of and difficulties associated with mechanical composite joints, a number of researches have been conducted throughout the past few decades. The researches conducted are either theoretical, experimental or a combination of both. This chapter presents a brief review of past experimental and numerical studies conducted on riveted or bolted joints.

Liu, D. et. al. [3] conducted both experiments and finite element analysis in their investigation in the interaction between pin diameter and composite laminate thickness. The composite material investigated was made of S-2 woven glass fiber and phenol matrix of quasi-isotropic lay-up $[0/90/\ 45/-45]_s$ and the pins were made of stainless steel. The engineering constants of the composite laminate were determined by mechanical tests and some of the orthotropic material properties that were not obtained from experiments were assumed for computer simulation. Mechanical joints with combination of various composite thicknesses and pin diameters totaling sixteen joint configurations based on four composite thicknesses (namely 8-ply, 24-ply, 40-ply, and 80 ply with average thicknesses of 1.93 mm, 5.89 mm, 9.50 mm and 20.37mm, respectively) and four pin diameters (3.125 mm, 6.25 mm, 12.5 mm, and 25 mm) were examined. Regardless of the composite thickness (t), the width (w) was 100 mm making the w/d ratio always greater than 4. Also the ratio of the diameter of hole (d) to the distance between hole center to specimen end (e), e/d, was greater than 2 for all specimens to avoid premature shear out failure. Along with conducting laboratory experiments for finite element analysis the commercial finite element program ABAQUS was used. From the study, it was found that t^2/d^2could be used to distinguish the two primary damage modes, i.e. pin bending and bearing failure. The results also showed that thick composites with small pins and thin composites with large pins had lower efficiencies for joint stiffness and joint strength than those having similar dimensions between pin diameter and composite thickness.

McCarthy et. al. [4] studied the effects of bolt-hole clearance in composite bolted joints. A three-dimensional finite element analysis was used. Both single-bolt and multi-bolt single-shear joints were modeled and the results were compared with those from a parallel experimental program. The laminates studied were made from graphite/epoxy HTA/6376 (high tensile strength carbon fiber, toughened epoxy) with quasi-isotropic stacking sequence [45/0/-45/90] and 40 plies in each laminate giving a total laminate thickness of 5.2 mm; and most of the material properties were obtained by composite laminate theory. The bolt was made from titanium alloy 6Al-4V. The FEM program MSC.Marc was used to model the joints and for analysis. Four different bolt-hole clearances which varied from a "neat fit" to a slightly larger than is normally found in aerospace structures were tested. It was found that increasing clearance had the effect of reducing the stiffness of single-bolt joints and changing the load distribution in multi-bolt joints. Results were compared with experiments and excellent agreement was generally found.

Sridevi and Satyadevi [5] dealt with the study of failure modes and failure loads of a glass vinylester composite plate with a circular hole subjected to a traction force by a rigid pin. The study is performed using a finite element analysis package ANSYS. In this work, a composite rectangular plate of length 200 mm and thickness 2.8 mm was used. A hole of diameter (d) 5 mm is present at a distance (e) from one edge of the plate. A rigid pin is located at the centre of the hole. A load is applied to the plate along the longitudinal axis. The plate was symmetric with respect to the longitudinal axis and it consists of 12 layers. Different models were obtained by varying e/d and w/d but keeping the diameter and thickness as constant. A 3D model of the specimen in built in ANSYS. To simulate the effect of the pin located at the centre of the hole compressing one half of the hole due to load acting in the other direction, a radial constraint on the hole is applied. The load on the specimen was varied using bisection method till failure occurs. It was determined that failure had occurred when the failure criterion reached a value of 1. From the obtained numerical results of the analysis the researchers determined that the failure load of the composite plate with hole increases as e/d increase, the strength of the plate is found to increase as a result of increase in the width of the plate, the ratio w/d has a greater effect on the mode of failure and that as w/d increases, the specimen fails in the bearing mode. In general, it was observed that the numerical results were in good agreement with the experimental results from an existing literature.

Valenza et. al. [6] conducted research to evaluate composite laminate resistance to failure under tensile bearing tests. Particular attention was focused on the damage mechanisms evidenced near the hole areas. The limit loads corresponding to the damage, and failure modes are evaluated by varying the pin diameter and the hole position. Moreover, the aim of the research was to obtain a failure map by analyzing the effect of joint geometry on the fracture mechanisms. Different joint geometries were analyzed by varying w/d and e/d ratios. The composite material investigated was made from mat and woven glass fiber and the matrix material was a polyester isophtalic resin. The properties of the layers were determined via experimental tests and analytical studies. Both experiments and numerical studies using the ANSYS finite element program were conducted on three different specimens. From the experiments it was found how geometrical parameters influence the resistance to failure and the fracture mode of the joints. The values of the ratios e/d and w/d at the transition between the modes of failure (net tension, shear out and bearing) have been clearly observed. It was observed that for a particular geometry a particular fracture mode starts when its failure or fracture stress is lower than the stresses of the other failure mechanisms in competition with it. The analysis of the effect of joint geometry on the fracture mechanisms at varying w/d and e/d ratios had identified three regions related to the typical failure modes of pinned joints - net tension, shear out and bearing failures. From the finite element studies, different failure modes were observed to occur as a function of geometric parameters. In particular, sometimes net tension and shear out fracture modes occurred, the first at higher loads than the second with a catastrophic loss of the stress carrying capability. The obtained failure map clearly shows the effect of the geometrical parameters on the failure modes. Particularly for high e/d and w/d values, bearing fracture occurs. On decreasing only the w/d ratio, a transition between bearing and net tension is observed, while increasing d with constant width, w, the tensile resistance is strongly reduced. Starting from the net tension failure area and decreasing the e/d ratio, a transition between net tension and shear out occurs (while a transition from net tension and cleavage is observed in experimental tests) in which case cleavage failure can be considered a mixed fracture. Also in this case, on decreasing e with constant d, shear resistance is reduced.

Camanho and Lambert [7] presented a new methodology to predict the onset of damage, final failure and failure mode of mechanically fastened joints in composite laminates. The stress distribution at each ply is obtained using semi-analytical or numerical methods. The elastic limit of the joint is predicted using the ply strengths and stress distribution in failure criteria. Final failure and failure mode are predicted using point or average stress models. Standardized procedures to measure the characteristic distances used in the point or average stress models are proposed. The methodology proposed is applicable in double-shear joints using quasi-isotropic laminates. The predictions are compared with experimental data obtained in pin- and bolt-loaded joints, and the results indicate that the methodology proposed can accurately and effectively predict ultimate failure loads as well as failure modes in composite bolted joints.

Chamis [8] summarized previous studies some of which were very extensive and proposed simplified procedures for designing composite bolted/riveted joints. According to the report of this study released under NASA's Lewis Research Center, mechanical fastened joints are designed to resist certain select failure modes. These select failure modes include 1) tensile failure of net plate cross section, 2) local bearing failure, 3) shear-out failure and 4) tension with shear out (mixed mode) or cleavage failure. These select failure modes and the approximate equations used to quantify them are proposed and recommended for the preliminary design phase, and when complemented with appropriate finite element analysis and selective testing can be used for the final design phase.

Ireman [9] developed a method of three dimensional stress analysis of bolted composite joints to determine non-uniform distribution of stress through the thickness of composite laminate near bolt hole. The aim of this research was to develop a three dimensional finite element model of an isolated region of the joint. The model was validated against experimental strain deformation measurements. Various joint configurations including variations of many significant joint parameters like laminate lay-up, bolt diameter, bolt type, bolt pretension and lateral support conditions were studied. The finite element program ABAQUS was used to analyze the joints. The specimen used were quasi-isotropic $[(\pm 45/0/90)_4]_{S32}$, zero dominated $[(\pm 45/90/0_2/90/0_2)_2]_{S32}$ and quasi-isotropic $[(\pm 45/0/90)_8]_{S64}$, the bolt material was Titanium Ti6A4V. For quasi-isotropic specimen with protruding head bolt, without lateral support and no pretension of the bolt, there was good agreement between measured and calculated strain in the 45 direction, while for all other directions the computed strains are slightly smaller than the measured values.

Ryu, C. et. al. [10] conducted a finite element study on mechanically fastened composite joints of different geometric shapes and dimensions. The main aim of the research was to verify the validity of the use of linear finite element analysis to predict the failure load of the composite joints. It was shown in this study that the prediction accuracies of the failure load by linear analysis and non-linear analysis, which requires a lot of time, were almost the same.

From this finding the researchers have recommended the use of linear finite element analysis for the failure load prediction by the failure area index method. The ANSYS finite element software was used both to model and analyze the joints. The carbon-epoxy unidirectional prepreg USN125 and plane weave prepreg HPW198 composite materials of various stacking sequence were used. The pin of the mechanical joints was assumed to be frictionless rigid body and hence the radial displacements around the hole were made fixed in the finite element modeling of the joint.

Hou, L. et. al. [11] investigated the strengths of double-lap-pin joints made of glass/epoxy composite laminates. The experiments conducted revealed that the joint strength decreased as the joint size increased. Composite laminates made from glass/epoxy prepreg tapes were investigated in the study. The composite specimens were of cross-ply laminates of alternate 0 and 90 degree plies and stacking sequences [0/90/0/90 . . .] n. Their thicknesses were 3.30, 6.48, and 12.95 mm, respectively. For mechanical fastening, steel pins designated as M-2 according to AISI classification system were used. Experimental results revealed that the joint strength decreased as the joint size increased. As the joint size increased, the damage modes of composite joints also shifted from initial bearing damage followed by final net-section failure to directly catastrophic net-section failure. It was also found from experiments that the constraints in the thickness direction played a key role in damage process. Three factors defined the constraints in the thickness direction: composite thickness, bonding strength through laminate thickness and clamping force from bolting. Composite joints with small thicknesses tended to have fiber buckling and delamination that resulted in initial bearing damage before final net-section failure.

2.2 Present Study

Today, despite a large number of researches on the behavior of mechanically fastened joints of composite materials, not enough advancement has been recorded compared to that in homogeneous materials in terms of understanding mechanically fastened joint behavior.

Although composite materials exhibit complex behavior, they are attaining widely increasing areas of application in different engineering structures. This situation encourages researchers in dealing with this subject and puts the failure analysis of composite material joints as currently important issue.

In line with this endeavor, this thesis focuses on and attempts to add to the pool of existing body of knowledge with regard to composite laminate joints behavior by studying the effects of diameter and spacing (pitch and rows spacing) on the failure of composite material joints connected in butt joints. In this research, such directly related parameters such as e/d, w/d and s/d ratios are considered while finite element analysis and the composite failure criterion Tsai-Wu are used as tools.

Chapter 3

Composite Laminates and Composite Riveted Joints

3.1 Composite Materials and Their Applications

It has always been the hope of metallurgists to be able to produce structural materials such as material possessing desirable properties as great strength, ductility and light weight, all at once. With this regard, composite materials have provided an enormous opportunity for balanced pursuit of strength, ductility and lighter weight.

The Composite Material Handbook [12] defines a composite material as a material system composed of a mixture of two or more macro-constituents differing in form and/or material composition and that are essentially insoluble in each other. Simply put, a composite material is one in which two or more materials that are different are combined to form a single structure with an identifiable interface. The properties of that new structure are dependant upon the properties of the constituent materials. A typical composite material consists of a material with high mechanical strength and stiffness known as the reinforcement (for example, unidirectional or woven fibers) embedded in a material with lower mechanical strength and stiffness known as the matrix. To tailor the properties of the composite material, a laminate is formed by stacking on top of each other layers of reinforcement oriented in different directions.

3.2 Mechanical Behavior of Composite Materials

Composite materials have many characteristics that differ from those of more conventional engineering materials. Although some characteristics are merely modifications of conventional behavior, others are totally new and require new analytical and experimental procedures. Most common engineering materials are homogeneous and isotropic where as composite materials are often both inhomogeneous and non-isotropic.

Because of the inherent non-homogenous nature of composite materials, they are conveniently studied from two points of view, micromechanics and macromechanics. In micromechanics, interaction of the constituent materials is examined on a microscopic scale. Therefore, micromechanics is used to determine the elastic constants for the composite material based on the elastic constants of the constituent materials and the proportion and manner they exist in the composite material. In macromechanics, the material is presumed homogeneous and the effects of the constituent materials are detected only as averaged apparent properties of the composite. Therefore, with macromechanics the stress–strain relationships for a lamina as well as the entire laminate is developed. Also, relationships for stiffness, thermal and moisture expansion coefficients, and strengths of angle plies are developed.

What the above means in practice is the global elastic stress-strain relation of a composite lamina can be characterized through various engineering material constants such as E_1, E_2, G_{12}, ν_{12} or ν_{21}. The values of these constants depend on and are determined from the individual properties of the two constituents, i.e., fiber and matrix, and their volume fractions in the lamina. Therefore, through analysis using a micromechanical model, the engineering constants for a lamina can be predicted. Moreover, once these engineering constants are determined.

3.2.1 Analysis of Composite Materials

Composites are manufactured in the form of thin sheets called laminae or layers and these are bonded together to form a laminate with desired thickness and stiffness. In most applications, the thickness of a laminate is small compared to the planar dimensions. Therefore, two dimensional theories are used to analyze composite laminates for stresses.

3.2.1.1 Determination of Laminae Properties

The elastic properties of any given lamina are best determined by conducting experiment. Though, when many candidate laminae are being considered, as in different fiber or matrix volume proportion, analysis methods for estimation of laminae properties become desirable for the experimental procedures are destructive, time consuming and expensive.

The analytical method to determine the properties of a lamina based on the properties of the constituents that make up the lamina is by performing a micromechanical analysis. With micromechanics given the micromechanical geometry and the material properties of each constituent, it is possible to estimate the effective lamina properties and the micromechanical stress/strain state of the material.

In this thesis, however, all the elastic property data of the composite laminae are of experiment results obtained from literature [10]. The properties are the Young's moduli in all the three dimensional directions: E_{11}, E_{22} and $E_{33;}$ the shear moduli: G_{12}, G_{13} and G_{23}; the major Poisson's ratios: ν_{11}, ν_{22} and ν_{33}; the strength data, the fiber volume fraction and thickness of lamina. The data is summarized in Table 2.

3.2.1.2 Analysis of Laminae

Macromechanics deals with the gross properties of a composite as a structural element without considering the individual properties or identity of the constituents. It is used to develop the stress–strain relationships, stiffness relationships, and failure theories.

At this level of analysis, the strain or stress of an individual fiber or an element of matrix is not considered. The effect of the fiber reinforcement is smeared over the volume of the material. We assume that the two-material fiber-matrix system is replaced by a single homogeneous material. Obviously, this single material does not have the same properties in all directions. Such material with different properties in three mutually perpendicular directions is called an orthotropic material. Therefore, the layer (lamina) is considered to be orthotropic.

For an orthotropic material, the stress-strain relationship with the compliance matrix components in terms of the engineering constants is

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{xz} \end{Bmatrix} = \begin{bmatrix} 1/E_{xx} & -\nu_{xy}/E_{xx} & -\nu_{xz}/E_{xx} & 0 & 0 & 0 \\ -\nu_{yx}/E_{yy} & 1/E_{yy} & -\nu_{yz}/E_{yy} & 0 & 0 & 0 \\ -\nu_{zx}/E_{zz} & -\nu_{zy}/E_{zz} & 1/E_{zz} & 0 & 0 & 0 \\ 0 & 0 & 0 & 1/G_{xy} & 0 & 0 \\ 0 & 0 & 0 & 0 & 1/G_{yz} & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/G_{xz} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{Bmatrix} \quad (1)$$

As the thickness of the laminae is very small compared with its length and width and all the applied loads are assumed in-plane, plane stress conditions are considered; i.e., $\sigma_{xz}, \sigma_{yz}, \sigma_{zz} = 0$

In this case, the above equation reduces to

$$\begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{Bmatrix} = \begin{bmatrix} S_{11} & S_{12} & 0 \\ S_{12} & S_{22} & 0 \\ 0 & 0 & S_{66} \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} \quad (2)$$

Which may be written as:

$$\{\varepsilon\} = [S]\{\sigma\} \quad (3)$$

Where [S] is the compliance matrix and is reduced as follows in the plane stress case

$$S = \begin{bmatrix} 1/E_{xx} & -\nu_{xy}/E_{xx} & 0 \\ -\nu_{yx}/E_{yy} & 1/E_{yy} & 0 \\ 0 & 0 & 1/G_{xy} \end{bmatrix} \quad (3)$$

Equation 3 can be inverted to :

$$\{\sigma\} = [S]^{-1}\{\varepsilon\}$$

or

$$\{\sigma\} = [Q]\{\varepsilon\} \quad (5)$$

Where the [Q] is defined as the inverse of the compliance matrix and is known as the reduced lamina stiffness matrix.

3.2.1.3 Analysis of Laminates

The procedures developed to evaluate stresses and deformations of laminates are crucially dependent on the fact that the thickness of laminates is much smaller than the in-plane dimensions. As typical thickness values for individual plies range between 0.125 and 0.25 mm, consequently, laminates using from 8 to 50 plies are still generally thin plates and, therefore, can be analyzed on the basis of the usual simplifications of thin plate theory.

Classical lamination theory is used to combine the individual lamina properties to predict the linear elastic behavior of arbitrary laminates. Lamination theory requires the determination of lamina elastic properties, their orientation within the laminate, and their stacking position. The following assumptions are made in the classical lamination theory to develop the relationships: 1) each lamina is orthotropic 2) each lamina is homogeneous 3) plane sections remain-plane, i.e., a line straight and perpendicular to the middle surface remains straight and perpendicular to the middle surface during deformation. Lamination theory will solve for the loads/stresses/strains for each lamina within the laminate at a given location for a given set of applied loads. This combined with appropriate failure theory will predict the strength of the laminate.

The constitutive law in CLT couples extensional, shear, bending and torsional loads with strains and curvatures. The stresses in the k^{th} layer can be expressed in terms of the laminate middle surface strains and curvatures as

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = \begin{bmatrix} \overline{Q_{11}} & \overline{Q_{12}} & \overline{Q_{16}} \\ \overline{Q_{12}} & \overline{Q_{22}} & \overline{Q_{26}} \\ \overline{Q_{16}} & \overline{Q_{26}} & \overline{Q_{66}} \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{xy} \end{Bmatrix} + z \begin{Bmatrix} \kappa_{xx} \\ \kappa_{yy} \\ \kappa_{xy} \end{Bmatrix} \quad (6)$$

Where $[\bar{Q}]$ is the reduced stiffness matrix in the laminate coordinate system.

The strains in the above equation are of the general form as shown in [13]

$$\epsilon_{ij} = \epsilon_{ij}^{(0)} + z\kappa_{ij} \tag{7}$$

Here, $\epsilon_{i}^{(0)}$denote the strains associated with the stretching and in-plane shearing of the mid-plane and are called the membrane strains. The quantities κ_{ij} are the curvatures. Both are functions of *x* and *y* only and in CLT have the following explicit form

$$\epsilon_{xx}^{(0)} = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial \omega}{\partial x}\right)^2$$

$$\epsilon_{yy}^{(0)} = \frac{\partial u}{\partial y} + \frac{1}{2}\left(\frac{\partial \omega}{\partial y}\right)^2$$

$$\epsilon_{xy}^{(0)} = \frac{\partial u}{\partial y} + \frac{\partial v}{\partial z} + \frac{\partial \omega}{\partial y}\frac{\partial \omega}{\partial x}$$

$$\kappa_{xx} = -\frac{\partial^2 \omega}{\partial x^2}$$

$$\kappa_{yy} = -\frac{\partial^2 \omega}{\partial y^2}$$

$$\kappa_{xy} = -2\frac{\partial^2 \omega}{\partial x \partial y}$$

(8)

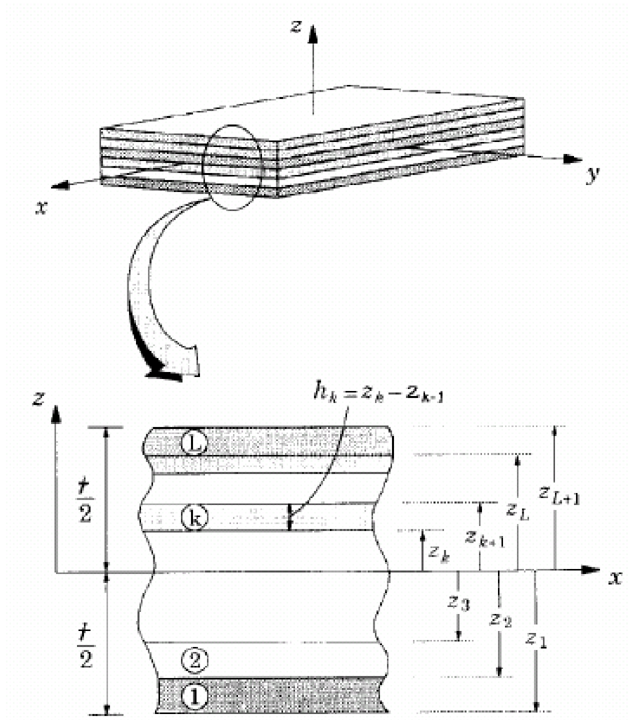

Figure 1- Geometry of an N-layered laminate

The resultant forces and moments acting on a laminate are obtained by integration of the stresses in each layer or lamina through the laminate thickness and the complete set of the equations can be expressed in matrix form as

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{11} & D_{11} \\ B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \\ \kappa_x \\ \kappa_y \\ \kappa_{xy} \end{bmatrix} \tag{9}$$

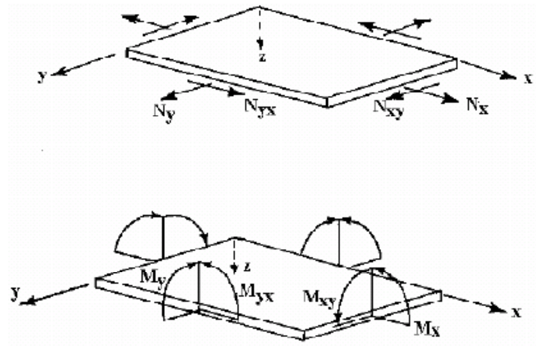

Figure 2- In-plane forces and moments on flat laminate

Where N are loads, M are moments, ε are strains, κ are curvatures and the [A], [B], and [D] sub-matrices are the extensional (including shear), coupling, and bending stiffness matrices, respectively.

For example,

$$N_x = \int_{-t/2}^{t/2} \sigma_x dz$$

$$M_x = \int_{-t/2}^{t/2} \sigma_x z dz \tag{10}$$

The extensional stiffness matrix [A] relates the resultant in-plane forces to the in-plane strains, and the bending stiffness matrix [D] relates the resultant bending moments to the plate curvatures. The bending-extensional coupling stiffness matrix [B] couples the force and moment terms to the mid-plane strains and mid-plane curvatures.

$$A_{ij} = \sum_{k=1}^{N} Q_{ij}^{(k)} (z_{k+1} - z_k) dz$$

$$B_{ij} = \frac{1}{2} \sum_{k=1}^{N} Q_{ij}^{(k)} ({z_{k+1}}^2 - {z_k}^2) dz$$

$$D_{ij} = \frac{1}{3} \sum_{k=1}^{N} Q_{ij}^{(k)} ({z_{k+1}}^3 - {z_k}^3) dz$$

(11)

Where $Q_{ij}^{(k)}$ are the material stiffnesses of the kth lamina, as referred to the laminate coordinates and where N is the number of layers in the laminate, and (z_k, z_{k+1}) are the thickness coordinates of the bottom and top of the kth layer as shown in Figure 1.

3.3 Failure Theory in Composite Laminates

Failure criteria are used to learn if a layer has failed due to the applied loads. With composite materials, the strength of a laminate is related to the strength of each individual lamina. Unlike with isotropic materials, the failure theories of a lamina are not based on principal normal stresses and maximum shear stresses, but on the stresses in the material or local axes. This is because a lamina is orthotropic and its properties are different at different angles, unlike the former.

There are four common failure theories developed for composite laminae – 1) Maximum stress failure theory 2) Maximum strain failure theory 3) Tsai-Hill failure theory 4) Tsai-Wu failure theory

In ANSYS, there are three predefined failure criteria from which on can choose from. The three predefined criteria are:

1) Maximum Strain Failure Criterion

This theory is based on the maximum normal strain theory by St. Venant and the maximum shear stress theory by Tresca as applied to isotropic materials [13]. The strains applied to a lamina are resolved to strains in the local axes. Failure is predicted in a lamina, if any of the normal or shearing strains in the local axes of a lamina equal or exceed the corresponding ultimate strains of the unidirectional lamina. Given the strains/stresses in an angle lamina, one can find the strains in the local axes. A lamina is considered to be failed if

$$-({\varepsilon_{11}}^C)_u < (\varepsilon_{11}) < ({\varepsilon_{11}}^T)_u, \text{ or}$$

$$-({\varepsilon_{22}}^C)_u < (\varepsilon_{22}) < ({\varepsilon_{22}}^T)_u, \text{ or}$$

$$|\varepsilon_{12}| < (\varepsilon_{12})_u \quad (12)$$

This failure criterion has an option in ANSYS that allows up to nine failure strains. A lamina is considered to be failed if any of the normal or shear strains in the local axes of a lamina equal or exceed the corresponding ultimate strains of the unidirectional lamina.

2) Maximum Stress Failure Criterion

Related to the maximum normal stress theory by Rankine and the maximum shearing stress theory by Tresca, this theory is similar to those applied to isotropic materials. The stresses acting on a lamina are resolved into the normal and shear stresses in the local axes. Failure is predicted in a lamina, if any of the normal or shear stresses in the local axes of a lamina is equal to or exceeds the corresponding ultimate strengths of the unidirectional lamina.

The lamina is considered to be failed if

$$-\left(({\sigma_{11}}^{C})_u{}^{C}\right)_u < (\sigma_{11}) < ({\sigma_{11}}^{T})_u, \text{ or}$$

$$-({\sigma_{22}}^{C})_u < (\sigma_{22}) < ({\sigma_{22}}^{T})_u, \text{ or}$$

$$|\sigma_{12}| < (\sigma_{12})_u \tag{13}$$

The available option in ANSYS for this criterion also allows nine failure stresses. Failure is predicted in a lamina, if any of the normal or shear stresses in the local axes of a lamina is equal to or exceeds the corresponding ultimate strengths of the unidirectional lamina.

3) Tsai-Wu Failure Criterion

The Tsai-Wu failure criterion is a phenomenological failure theory which is widely used for composite materials which have different strengths in tension and compression. The Tsai-Wu failure criterion has its derivation being based on linking experimental constants rather than on a physical interpretation of material behavior. [14]

With this theory, failure is assumed to occur in the lamina if the following condition is met

$$F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\sigma_{12}^2 + F_1\sigma_{11} + F_2\sigma_{22} + F_{12}\sigma_{11}\sigma_{22} \leq 1 \tag{14}$$

The coefficients F_{11}, F_{22}, F_{66}, F_{1}, and F_{2} are determined according to the material strengths as follows

$$F_{11} = \frac{1}{\sigma_{11}^{T}\sigma_{11}^{C}},\ F_{11} = \frac{1}{\sigma_{22}^{T}\sigma_{22}^{C}},\ F_{1} = \frac{1}{\sigma_{11}^{T}} - \frac{1}{\sigma_{11}^{C}},\ F_{2} = \frac{1}{\sigma_{22}^{T}} - \frac{1}{\sigma_{22}^{C}} \text{ and } F_{11} = \frac{1}{(\sigma_{12}^{F})^{2}} \qquad (15)$$

And F_{12} is a coefficient that is determined experimentally. However, Tsai-Hahn [13] has determined the following approximate expression to obtain it analytically:

$$F_{12} \approx -\frac{1}{2}\sqrt{F_{11}F_{22}} \qquad (16)$$

Using this theory, ANSYS allows nine failure stresses and three additional coupling coefficients, and failure is assumed to occur in the lamina if the following condition in equation 14 is met.

3.4 Material and Fiber Pattern Selection

The composite material used in this study is a unidirectional high-modulus carbon fiber/epoxy with ply thickness 0.125 mm. The considerations behind this selection are the facts that carbon-epoxy composites represent one group of composite materials with a constant increase in their applications and production. These materials have excellent properties, such as high tensile strength and modulus, small relative density, and good corrosion and abrasion resistance. Due to their desirable properties these composites have found greater application in aircraft and space industries despite their limiting relatively high cost [14]. The basic properties of the carbon fiber/epoxy USN 125 selected for the study are shown in Table 1.

Property	Symbol	Value
Elastic Modulus in the Fiber Direction	E_{11}	172GPa
Elastic Modulus in the Transverse Directions	E_{22}, E_{33}	12GPa
Shear Moduli in 1-2 and 1-3 Planes	G_{12}, G_{13}	4.5GPa
Shear Modulus in 2-3 Plane	G_{23}	3.5
Poisson's Ratio	ν_{12}, ν_{13}	0.3
	ν_{23}	0.47
Tensile Strength in Fiber Direction	$S_{11(t)}$	760MPa
Compressive Strength in Fiber Direction	$S_{11(c)}$	760MPa
Tensile Strength in Transverse	$S_{22\,(t)}$	28MPa

Direction		
Compressive Strength in Transverse Direction	$S_{22(c)}$	138MPa
Shear Strength in 1-2 and 1-3 Planes	$S_{11(s)}$	62MPa
Shear Strength in 2-3 Plane	$S_{11(s)}$	35MPa
Fiber Volume Fraction	V_f	0.6
Thickness of Lamina	t	0.13mm

Table 1 - Material properties of the unidirectional carbon fiber\Epoxy composite lamina USN125

The USN125 unidirectional composite lamina are used in this study as in [10] with stacking sequence of the pseudo-isotropic $[0/+45/-45/90]_s$ lay- up; 25% 0-degree, 50% ± 45-degree, and 25% 90-degree plies. Quasi-Isotropic Laminates are balanced and symmetric laminates for which constitutive properties of interest at a given point display isotropic behavior in the plane of the laminate. The quasi-isotropic lay-up is selected due to the results obtained from researches conducted by researchers such as Arnold [15] and Hamada [16] which led to the current belief that efficient joint design is achieved by when quasi-isotropic stacking sequences are used.

Material	Stacking Sequence	Average Thickness of Lamina (mm)	Total Number of Lamina	Average Thickness of Laminates (mm)
USN125	**$[0/+45/-45/90]_s$**	**0.125**	**16**	**2**

Table 2- Ply orientations of the laminated composite plates

Hart-Smith [17] also has suggested the stacking sequence design guideline illustrated in Figure 9. The diagram has resulted from the author's extensive experimental research on joints in carbon fiber-epoxy laminates.

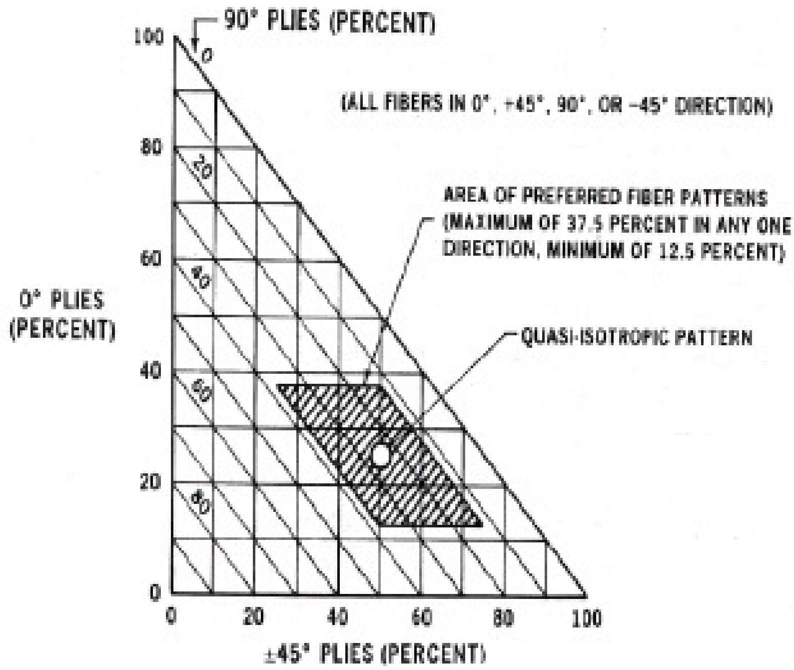

Figure 3- Selection of ply stacking sequence for fibrous composites **[17]**

3.5 Composite Joints

In this paper, what is meant by a composite joint is a joint between two or more composite materials. As there are no engineering structures that did not involve some type of joint, they often occur in composite structures. In composites, joints connect laminate sections together and provide mechanisms for the inclusion of secondary structures, such as fittings, ribs and bosses.

Assembly of parts in composite structures involves either adhesive bonding or mechanically fastened joints or both. In principle, adhesive joints are structurally more efficient than mechanically fastened joints because they provide better opportunities for eliminating stress concentrations. In many cases, however, mechanically fastened joints cannot be avoided because of requirements for disassembly of the joint. In addition, adhesive joints are highly sensitive to manufacturing deficiencies, including poor bonding technique, poor fit of mating parts and sensitivity to temperature and environmental effects. Thus mechanical fastening tends to be preferred over bonded construction in highly critical and safety priority applications such as primary aircraft structural components

Joints represent one of the greatest challenges in the design of structures in general and in composite structures in particular. The reason for this is that joints entail interruptions of the geometry of the structure and often, material discontinuities, which almost always produce local highly stressed areas, except for certain types of adhesive joint.

3.5.1 Rivets

For permanent joints, rivets have been widely used to secure both structural joints for which strength is an important design consideration and lower-performance industrial joints for which strength requirements are modest but production costs and assembly time are key factors. Structural rivets, traditionally, have been used in many mechanical engineering applications such as pressure vessels, automotive applications, ships and aircraft structures. Rivets are also the preferred choices for lower-performance industrial joints such as used in the assembly of household appliances and electronic devices, and other similar applications due to their potential lower costs and higher assembly speeds. [18]

Rivets are made from bar stock by either hot - or - cold forming the manufactured head. The head is usually of the high button type although flattened and countersunk rivets are made for applications with limited clearance. The riveting process consists of inserting the rivet in matching holes of the pieces to be joined and subsequently forming a head on the protruding end of the shank.

Figure 4 - Different Rivet Types

Most rivets are manufactured from structural steel. Structural rivet steels are of three types - ASTM A502 grade 1, carbon rivet steel, ASTM A502 grade 2, high-strength structural steel rivets, and ASTM A502 grade 3, similar to grade 2 but with enhanced atmospheric corrosion resistance. [18]

Rivets and other mechanical fasteners for use with carbon fiber composites are made of either titanium, A286 CRES (corrosion resistant steel) or Monel, a series of nickel cooper alloys with high strength and excellent corrosion resistance. [14] One of the main reason for this choices of rivet materials is to reduce the potential for galvanic corrosion, except in the case of such applications as space applications where galvanic corrosion is not a problem.

Titanium fasteners are the most common means of mechanical attachment in carbon fiber composites. This is because titanium is non-corrosive in the galvanic atmosphere created by the dissimilar materials due to the fact that Titanium is closer to carbon on the cathodic scale. [14]

3.5.2 Types of Riveted Joints

Mechanically fastened joints are conveniently classified according to the type of forces to which the fasteners are subjected. These classes are 1) shear, 2) tension, and 3) combined tension and shear. Rivets use, however, is virtually always restricted to lap and butt joints because rivets are efficient in shear but inefficient in tension. If the line of action of the applied load passes through the perpendicular to the axis of fastener, then the fasteners are loaded in shear. Therefore, in this study the riveted composite material joints studied are of butt joints.

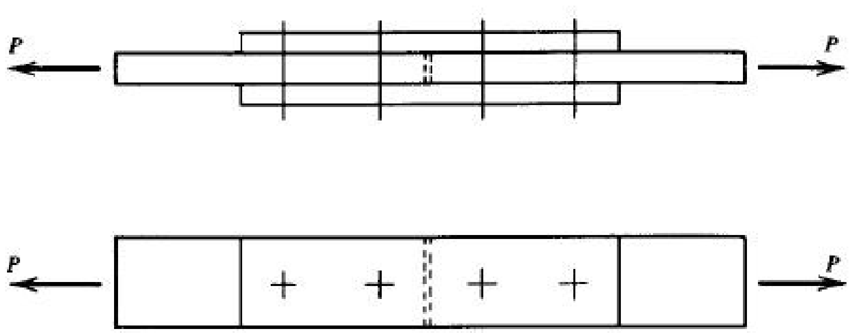

Figure 5 - Schematic of a double cover plate (double strap) butt joint showing the line of action of the applied load

3.6 Failure in composites

A composite laminate fails when it is subjected to increasing load. However, the laminate failure may not be catastrophic initially. It is possible that some layer fails first and that the composite continues to take more loads until all the plies fail. Failed plies may still contribute to the stiffness and strength of the laminate. However, the overall strength and stiffness of the laminate is degraded continually until complete failure of laminate occurs. [13]

3.6.1 Failure in Mechanical Composite Joints

Usage of composite materials in structures such as aircraft requires detailed knowledge about their behavior. In particular, it is important to know the strength of the joints and the mode in which they fail.

According to [14], the principal failure modes of the laminates in mechanically fastened composite joints are 1) Tension failure, 2) tensile failure, 3) shear-out failure of the material, and 4) any combination of the three failure modes.

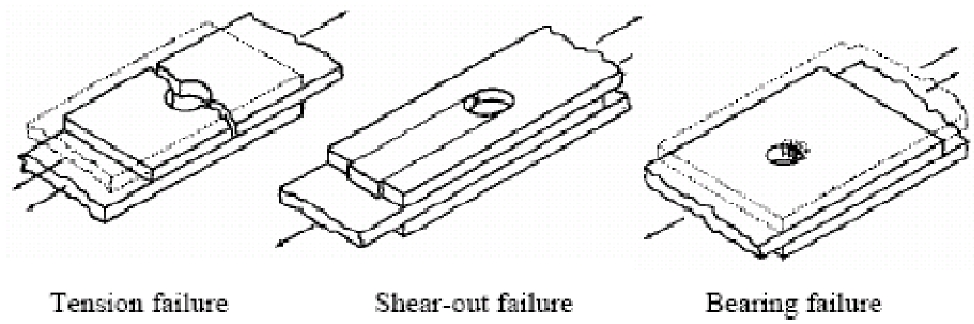

Figure 6- Typical failure modes for mechanically fastened joints in composites

At NASA's Lewis research center Chamis [8] reported the development of a simplified procedure of calculating the stresses and strains that have been verified by numerical methods and experiment to be valid in the preliminary analysis of riveted or bolted joints and connections. It is usually assumed that bending and tension in the rivets may be neglected, that friction between the parts does not contribute to transfer load across joint, and that residual stresses are negligible. Further, shear in rivet is assumed to be uniform and equally shared among rivets.

According to [8], the various stresses can be obtained by the following procedures.

Tensile Failure

Tensile failure modes are characterized by "net-section" laminate fracture. For tensile failure of the plate between rivets, the plate tensile stress, σ_t, from [6] and [19] is

$$\sigma_t = \frac{F_t}{(w - N_r d)t} \quad (17)$$

Where, F_t = total tensile load

w = gross plate width

t = plate thickness

d = hole diameter

N_r = number of load-carrying rivets

Bearing failure

Local bearing failure modes are characterized by a local compressive failure caused by the bolt diameter which tends to crush the composite. For compressive bearing failure, the compressive bearing stress, σ_c, from [6] and [19] is

$$\sigma_{\mathrm{b}} = \frac{f_b}{td} = \frac{F_{\mathrm{b}}}{tdN_r} \tag{18}$$

Shear-out failure

The shear out failure modes in composite bolted joints are characterized by shear-out part of the laminate ahead of the rivet. For edge shear-out of the plate edge, the shear-out stress, τ_e, from [6] and [19] is

$$\sigma_s = \frac{f_s}{2et} = \frac{F_s}{2etN_r} \tag{19}$$

Where   e = distance from rivet hole center to edge of plate

Generally, a joint fails in one of these modes or a combination of these. The strength of the joint is the least of the normal (tensile), shearing and bearing strengths. The mode of failure depends on the type of strength, which is the least. Actually, failure of a joint means either the failure of the plate or the failure of the fastener. The normal mode of failure occurs for plate while shearing and bearing modes of failure occur either for plate or fastener depending on which one is weaker. In the present work, the fastener is considered to be rigid and therefore joint failure is considered only due to plate.

Chapter 4

Finite Element Model Development and Analysis

4.1 Introduction

The following chapter discusses in detail the 3D finite element model development and the solution procedure implemented in the study of the effects of spacing and diameter of rivets on the failure of fiber reinforced laminated composites connected in double strap butt joints with rivets. The geometric model development, finite elements chosen, the boundary and loading conditions implemented as well as the procedural parametric study undertaken are described.

4.2 Finite Element Modeling

The finite element method (FEM) used in structural analysis is an approximate numerical method used to solve boundary value problems of continuous systems. The approach is to divide the continuous medium into a finite number of regions using basic geometric shapes. Key points on these individual elements are selected as nodes where equilibrium conditions and continuity of displacement are maintained. Mathematical functions for each element degree-of-freedom (usually its nodal displacements) are assumed which relate the displacement at any point on the element to nodal displacements. Stress-strain and strain-displacement relationships in each element are employed to develop element stiffness equations, the relationships among nodal internal forces and nodal displacements.

ANSYS, which is a general purpose finite element modeling package for numerically solving a wide variety of mechanical problems, is used to create and analyze the finite element model. ANSYS has extensive library of element types which can be readily used to model any geometry. In addition to element library, extensive list of material models are found to simulate any engineering material. In most simulations the only parameters the user has to provide are geometry of the structure, material properties, the boundary conditions and the loads applied. [20]

4.2.1 Development of the model

The models developed for this study are only the composite laminate panels as shown in figures below. Table 1 illustrates the main dimensions of the components of riveted joints. The joints are assumed to be assembled from prismatic connected plates made of carbon fiber/epoxy composite fastened with rivets. Three models are considered; the purpose being to study the effects of parameters such as spacing and diameter of hole/rivet on the failure of the composite joints.

Model No.	Length (l)	Width (w)	Thickness (t)
01	100	15	**2**
02	100	30	**2**
03	**100**	**30**	**2**

Table 3- Basic dimensions of the plates

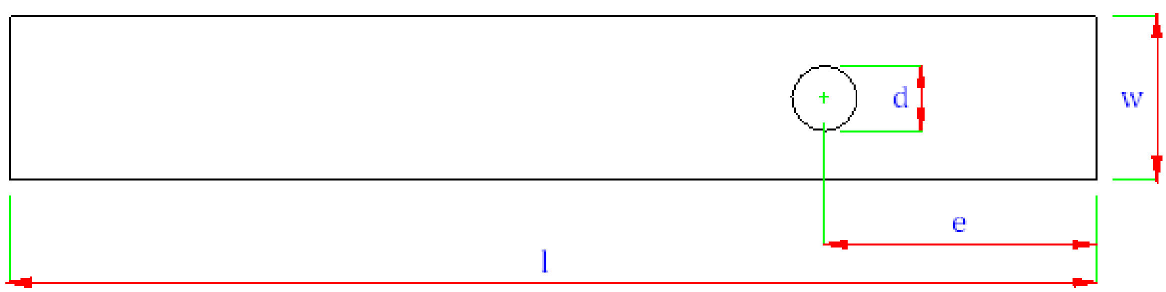

Figure 7- Dimensions of Model 01

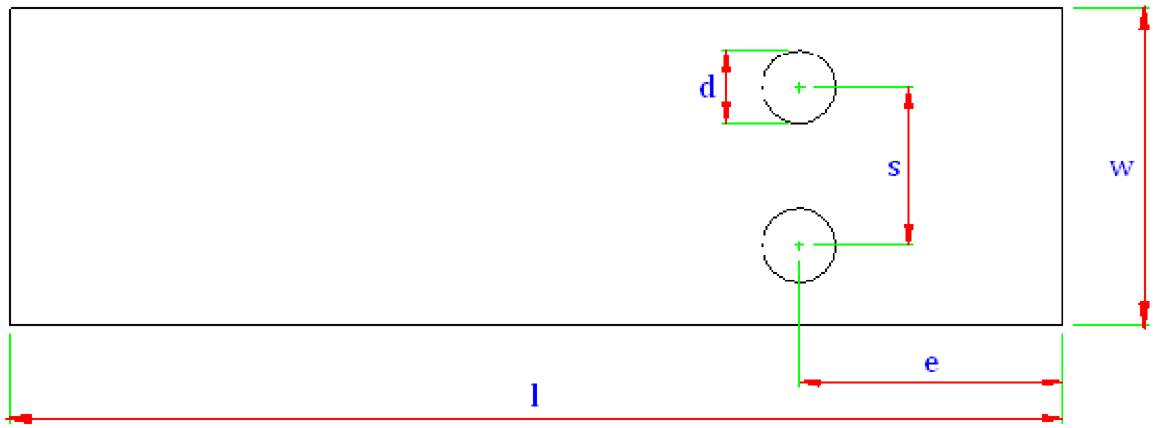

Figure 8- Dimensions of Model 02

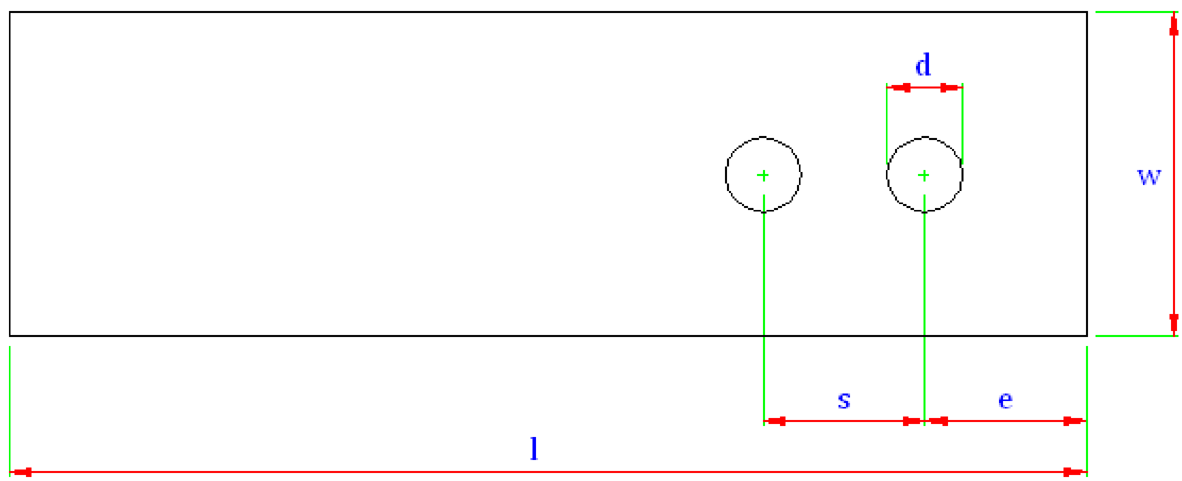

Figure 9- Dimensions Model 03

Model 01 is prepared to investigate the effect of diameter on the composite joint where as models 02 and 03 are prepared for the investigation in to the effect of spacing between rivet holes - the first one when in the case of holes are parallel to the loaded plate end and the latter otherwise, named series holes.

4.2.2 Element Types

Elements are the fundamental entities in the finite element method. They specify the topological (geometrical) and constitutive properties of a finite element model. The geometry of elements and hence that of the finite element model is defined by nodes. Nodes are selected space locations that also provide as resident locations for degrees of freedoms which specify the state of the finite element model. In ANSYS, there are a number of data that are associated with elements and they include type and material properties.

In this study, the element named SOLID46 is found to be appropriate for the problem at hand and used in the development of the finite element model. SOLID46 is a 3-D 8-node layered structural solid element designed to model layered thick shells or solids. The element allows up to 250 different material layers. The element is defined by its eight nodes, layer thicknesses, layer material direction or angles, and orthotropic material properties. The element has three degrees of freedom at each node: translations in the nodal x, y, and z directions; and has two alternative shapes – prismatic and tetrahedral. One more advantage with using this element type is t that it allows failure criteria to be specified. [20]

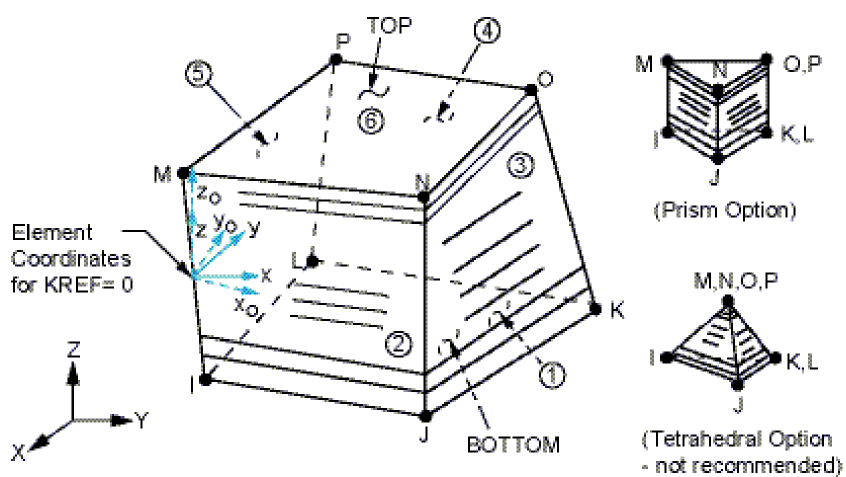

Figure 10- The geometry, node locations, and the coordinate system of element SOLID46

4.2.3 Material Model

The material model of the panel is simulated by assuming linear elastic plastic model. This model in ANSYS assumes an equivalent isotropic homogeneous material, which can be used in conjunction with shell, solid or beam elements alike. The study conducted by this model assumes that the joined plates or panels are made of unidirectional fiber reinforced composite named carbon fiber/epoxy of mechanical properties described in Table 2. The fiber orientation and stacking sequence are as discussed in section 3.3 and as shown in Figure 11. The rivets are assumed to be rigid and frictionless for reasons justified in coming section and are not physically modeled. Perfect bonding between each layer is also assumed.

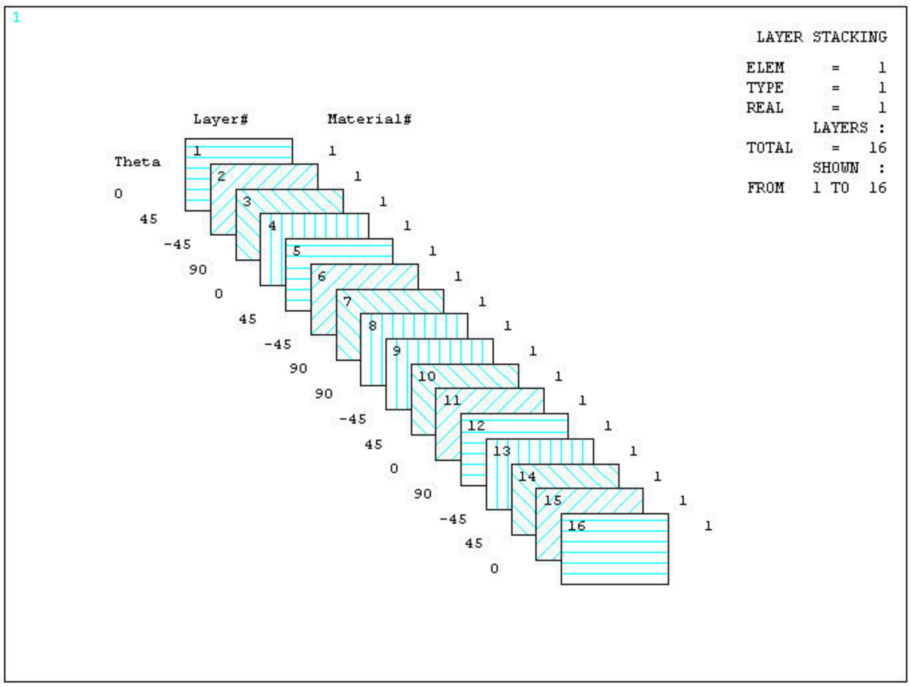

Figure 11- Stacking sequence of laminae of plates

4.2.4 Meshing

The process of representing a physical domain with finite elements is referred to as meshing, and the resulting set of elements is known as the finite element mesh. Meshing is the most important issue that arises during finite element analysis. Care must be given to the determination of the finite element mesh size or density in order to obtain reasonably good results. If the mesh is too coarse, the results can contain serious errors. If the mesh is too fine, it may be a waste of computer resources such as computation time and memory space.

In order to determine the mesh size and density of the finite element models in this study, a preliminary analysis was conducted. An initial analysis was performed using what was thought to be a reasonable mesh and again the model was reanalyzed with twice as many elements around the hole(s) region, which is the critical region, and when the two meshes gave nearly the same results then the former mesh was accepted as adequate.

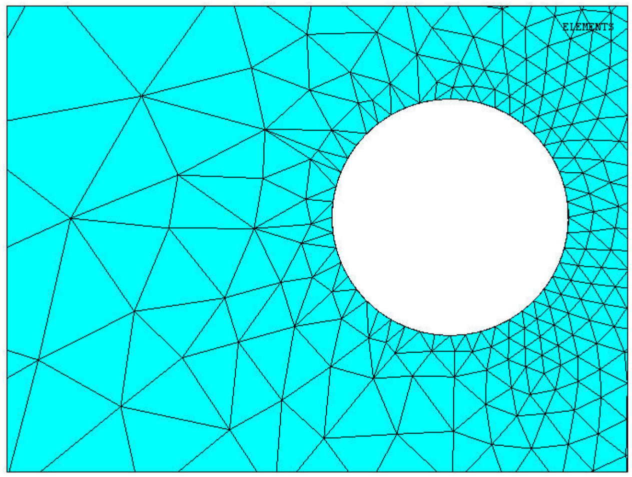

Figure 12- The finite element mesh around a hole

4.2.5 Boundary and Loading condition

Another important step in the finite element model development is the specification of the boundary and loading condition that realistically represents the problem to be simulated. The accuracy of a finite element simulation results depends extensively on proper application of boundary conditions on the model. Figure 13 shows two of the most typical boundary conditions used in a linear finite element analysis of riveted/bolted joints. Figure 13(a) shows the boundary condition in which half of the hole is in contact with the fastener and is subjected to the cosine load. For isotropic materials, cosine load distribution around the hole of the joint is suitable. According to Chang [21] when the cosine load distribution is used, the load is taken to vary according to the relationship

$$\sigma_i = \frac{4P}{\pi d} n_i cos\theta \qquad (20)$$

Where:

P = the applied load

σ_i = the load distribution

n_i = the unit vector normal to the hole

d = diameter of hole

and the angle is in x-y plane and is measured from the x-axis.

However, the cosine load around hole is not recommended as the boundary condition of the composite joint since the load distribution can differ from the cosine load in the joint analysis of the orthotropic material [21]. Figure 13(a) shows the boundary condition of the linear finite element analysis in which the fastener of the composite joint is assumed to be a frictionless rigid body. In this type of boundary condition, the radial displacements around the hole are fixed and the load distribution around the hole can be simulated regardless of joint material [10].

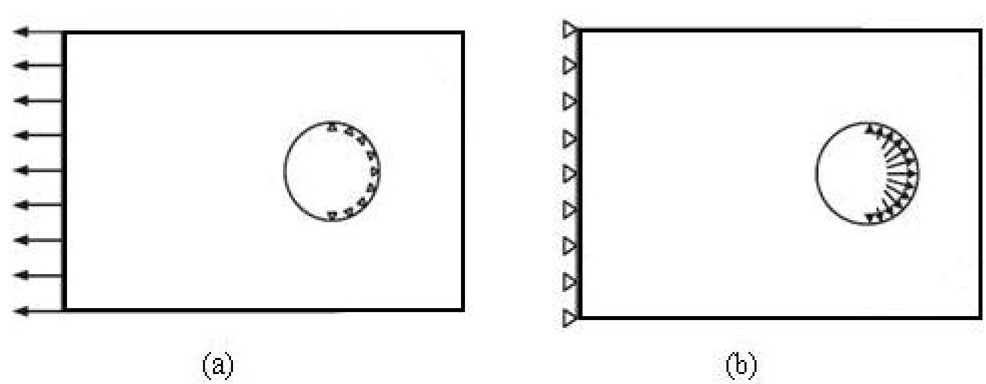

Figure 13- Boundary conditions for the linear analysis of mechanically fastened joints: (a) fixed radial displacement along hole boundary and (b) cosine pressure along hole boundary

Because of the above reasons, the boundary condition of Figure 13(a) is used for the finite element analysis of the composite joints in this study by assuming a rivet of the composite joint as frictionless rigid pin in which half of the hole is in contact with this pin. Moreover, as shown in Figure 14, a uniform axial load in the form of pressure is applied. This load applied to the left free end of the finite element model of the joined panels is increased up until initial failure is observed.

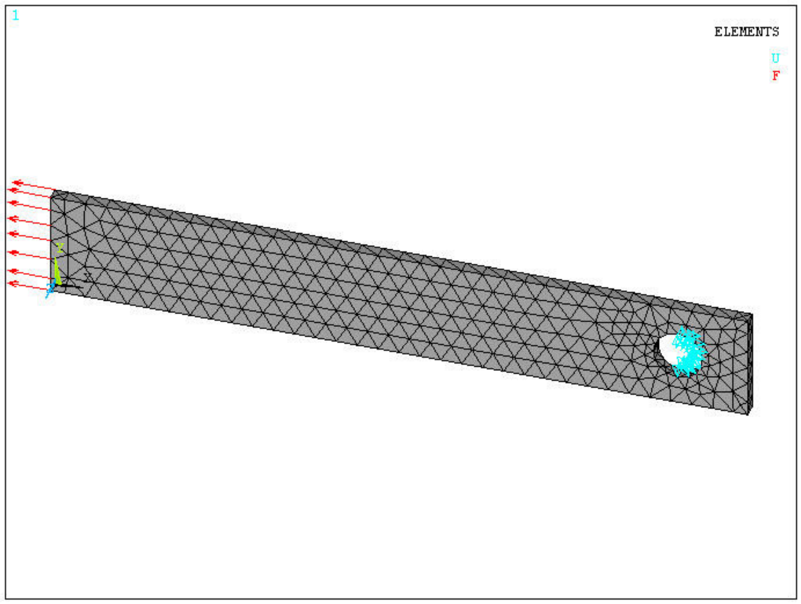

Figure 14- Boundary conditions: fixed radial displacement at half of the hole boundary and constant pressure load on the free edge

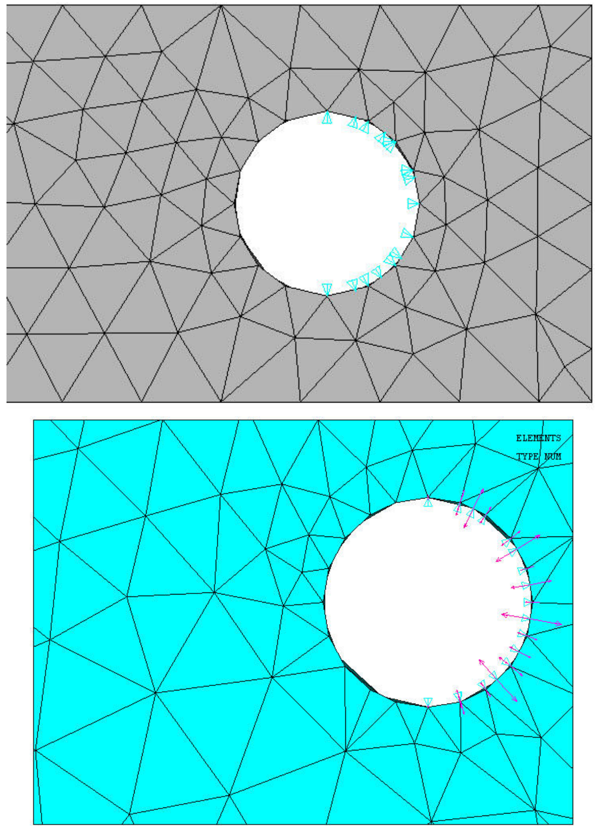

Figure 15- Radial Constraints around hole

4.3 Solution Procedure

In the study of the effects of spacing and diameter of rivets on the laminated composite materials joined in double strap butt joints, the effects of these two geometric parameters on the failure of the joint is investigated by conducting parametric study described in the next sub section.

In the analysis or design of any structure, the strength of the material that the structure uses is an important property and all solution procedures involve a comparison of the actual stress field with allowable stress field. Hence, the theory of failure criterion has been used to predict the strength of the composite laminates using strength data obtained from literature and presented in Table 2.

4.3.1 Parametric Study

In evaluating the effects of these two geometric parameters, i.e., rivet/hole diameter and spacing that this thesis set to assess, other key geometric variables which have already been identified by previous studies as to affect the failure mode of joints are also incorporated.

From a theoretical point of view, a given failure mode occurs when the apparent strength of a particular mode is lower than that of other failure modes, for particular geometrical condition. The geometry governing the failure mode and the transition from one failure mode to another can be shown by equating the failure loads of the three failure modes in equations 17, 18 and 19 (namely: $F_b = F_t$, $F_t = F_s$, *and* $F_b = F_s$). In this way, three equations are obtained:

$$\frac{w}{d} = \frac{\sigma_b}{\sigma_t} + 1$$

$$\frac{w}{d} = 2\frac{\sigma_s}{\sigma_t}\frac{e}{d} + 1$$

$$\frac{e}{d} = \frac{\sigma_b}{2\sigma_s} + 1 \qquad (21)$$

The above equations suggest the values e/d and w/d determine the failure characteristics as well as when transition occurs from one mode of failure to another failure mode. The first equation shows that as w/d increases the failure characteristics can exhibit transition of failure mode from bearing failure to net-tension. Similarly, the second equation shows transition from shear out failure to net-tension as e/d value increases as w/d value is kept constant. The last equation shows transition can occur from the bearing failure mode to shear-out.

In general, when composite specimens joined in double strap butt joints are loaded to final failure, the following are theoretically predicted simplified approach and experimentally observed -

1. Shear out failure mode occurs where the distance between the hole edge and edge of free laminate is small.

2. Net tension failure occurs when and where cross-section of laminate is small.
3. Bearing failure is strongly affected by lateral constraint of material surrounding the loaded hole.

In riveted joints, rivets are maintained at certain distance to each other, which is called pitch (distance between rivets). Pitch is measured as the distance between the centers of two adjacent rivets, and it is expressed in terms of the nominal diameter of the rivets. According to previous research on isotropic materials, the pitch should be no less than three times that of the nominal diameter of the rivet.

As can be intuitively understood, the effect of spacing and diameters cannot be considered excluded from other geometric parameters such as edge-to-hole distances and width of plate. For example, it easily can be anticipated that for rivet holes arranged in serious, increasing the diameter keeping the pitch constant will surely weaken the joint and is only possible geometrically to certain extent. Hence in the investigation of effects of diameter and the spacing or pitch of rivet/hole should be studied by considering w/d, e/d ratios as well as the ratio of pitch distance to diameter.

4.3.1.1 Investigation of the Effect of Diameter

The effect of the rivet diameter on the strength (or failure) on laminated composite joints is studied by running the finite element analysis of the model for various values of hole/rivet diameter. Diameters of 3mm, 4mm, 5mm, 6mm and 7.5mm are used and since the value of width w is kept a constant 15 mm in each case, as the diameter is varied w/d ratios of 5, 3.75, 3, 2.5 and 2 are obtained and each diameter is studied for various e/d values of 1 to 4. This is summarized in Table 4.

d (mm)	w/d	e/d					
		1	2	3	4	5	6
3	5	x	x	x	x	x	x
4	3.75	x	x	x	x	x	x
5	3	x	x	x	x	x	x

6	2.5	x	x	x	x	x	x
7.5	2	x	x	x	x	x	x

Table 4- The investigated geometric parameters for the effect of diameter

The values of the diameter are chosen so that the w/d ratios as well the e/d ratios represent all the possible failure situations as predicted by the simplified equations without creating imposed weaknesses in the joints. In other words, it was with the intent of maximizing the range of all possible failure situations in order to explore all the possible joint behavior.

4.3.1.2 Investigation of the Effect of Spacing

By changing the distance between the holes in the jointed plates its effect on the strength of the joints is studied. In this study, e/d values of 1, 2, 3 and 4 are selected with the intent of maximizing the chance that the model fails in different modes. Three spacing s values 9mm, 12mm and 15mm and hole diameter of 3mm resulting in three s/d values of 3, 4 and 5 are used as in [7]. A total of 24 parametric studies are conducted in the investigation of the effects of spacing (pitch) on the joint strength – i.e., 12 for the series holes and 12 for the parallel hole joints.

s	s/d	e/d = 1	e/d = 2	e/d = 3	e/d =4
12	4	x	x	x	x
15	5	x	x	x	x
18	6	x	x	x	x

Table 5- Investigated geometric parameters for the case of spacing

4.3.2 Determination of Failure Strength

Failure criterion encloses all the stress states that the material can sustain without failure and hence used to identify the failure load and mechanism. This allows the consideration of orthotropic materials, which might be much weaker in one direction than the other. In composites, the stress along the principal material axes in each lamina is checked for the appropriate failure theories. Failure criteria in ANSYS are available during solution and in the postprocessor only for composite elements such as SOLID46.

The present work uses the failure theory proposed by Tsai and Wu describe in chapter 3, for the static analysis of the joints. The models are analyzed by Tsai-Wu failure criterion using ANSYS. During solution, if there are no failures in a load step, then the applied load is incremented and the next load step is pursued for the occurrence of failure; this goes on until failure occurs. Failure is assumed to occur in the models when the Tsai-Wu failure criterion reaches a value of 1.

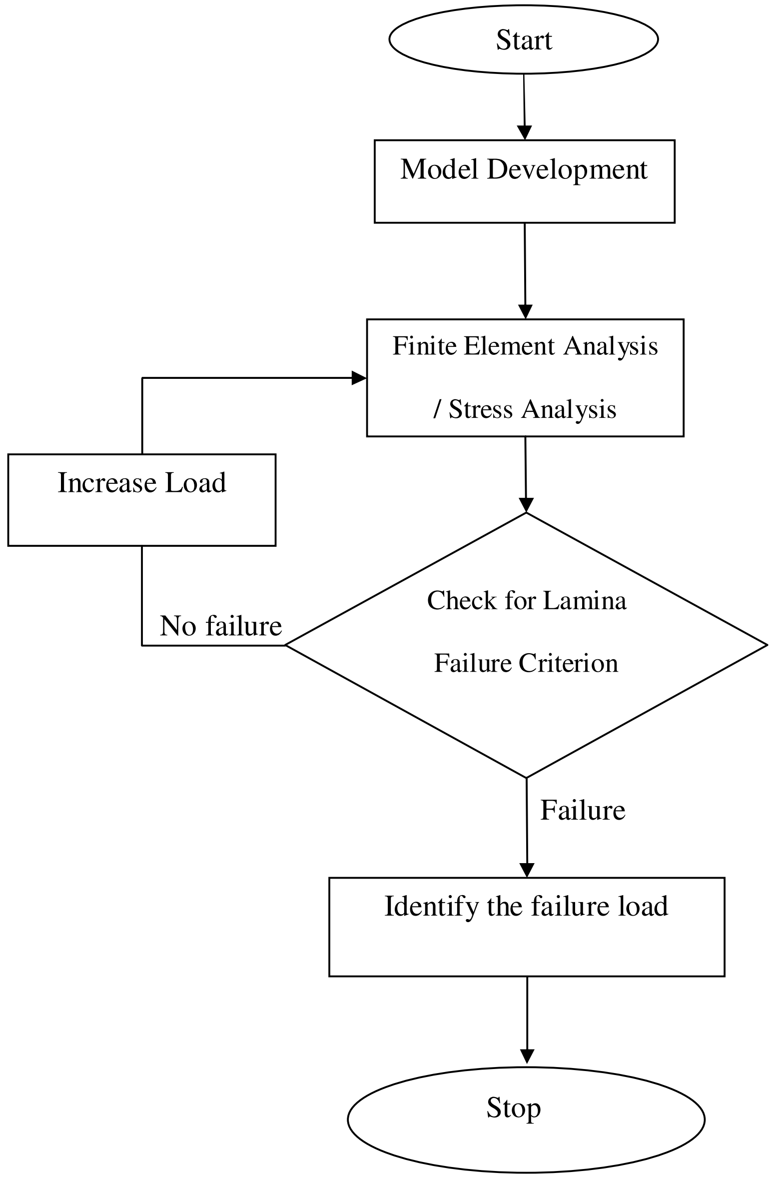

Figure 16 - Flowchart showing solution procedure

Failure in composites is progressive as discussed in the previous chapter and in this study with the help of finite element program ANSYS, only the onset of damage or first-ply failure is detected.

Chapter 5

Results and Discussions

The finite element analysis results of the riveted composite laminates are presented in this chapter. Because the appropriate value of joint strength depends upon the failure load, failure loads as a measure of joint strength were obtained from FEM simulations and are presented below.

5.1 Effect of Diameter on Failure Strength

The effect of diameter on the failure of composite joints was studied as described in section 4.3.1.1. The results obtained are tabulated in Table 6 and articulated in following figures and discussion.

w/d	d (mm)	e/d	e (mm)	Failure Load in KN/mm²	Failure Criterion
2	7.5	1	7.5	21	Tsai -Wu
		2	15	28	
		3	22.5	38	
		4	30	47	
		5	37.5	53	
2.5	6	1	7.5	23	Tsai-Wu
		2	12	34	
		3	18	44	
		4	24	56	
		5	30	60	
3	5	1	5	29	Tsai-Wu
		2	10	39	
		3	15	39.5	
		4	20	54	
		5	25	54.5	
3.75	4	1	4	19	Tsai-Wu
		2	8	24	
		3	12	32	
		4	14	44	
		5	16	42	

5	3	1	3	19	Tsai-Wu
		2	6	19.5	
		3	9	20	
		4	12	26	
		5	15	27	

Table 6- Results obtained from finite element analysis with ANSYS – diameter effects

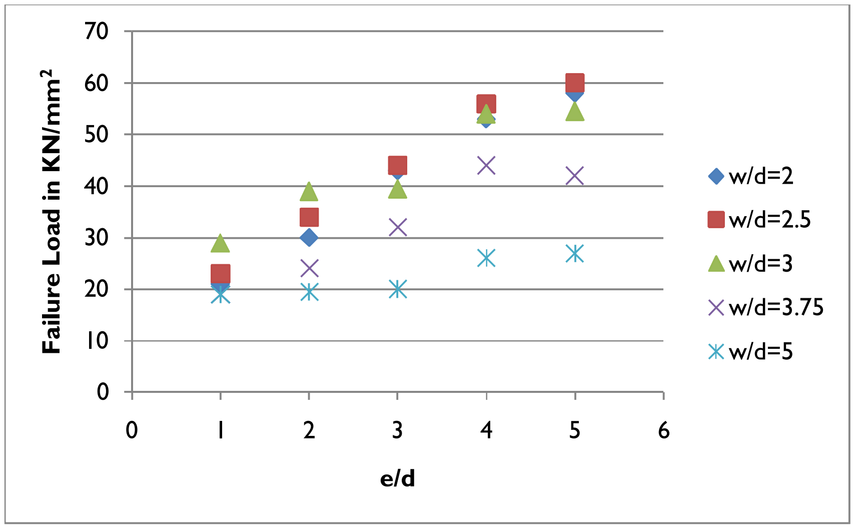

Figure 17 - Failure load for all configurations as e/d increases

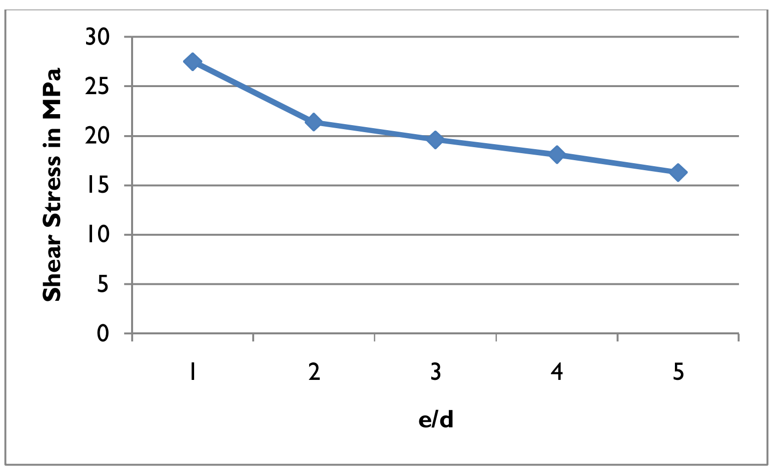

Figure 18 – Maximum shear Stress value: w/d = 2.5 (d = 6 mm), Load = 23 N/mm^2

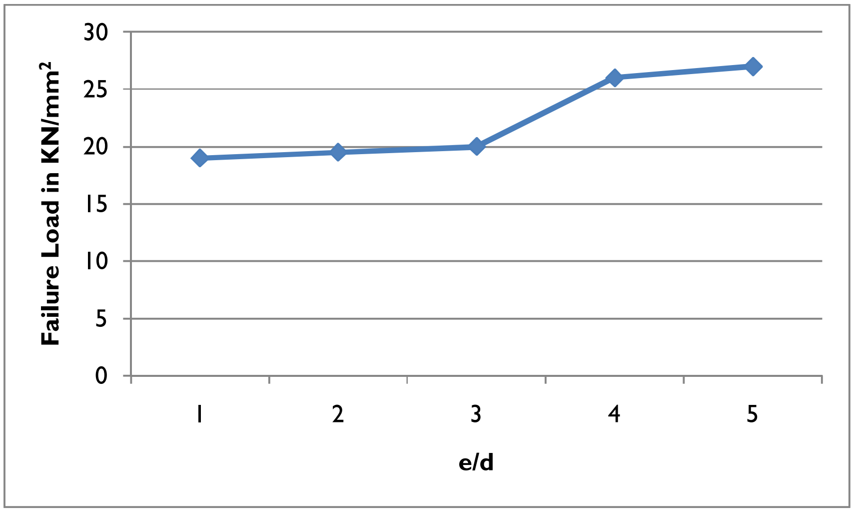

Figure 19- Failure load vs. e/d for w/d =2

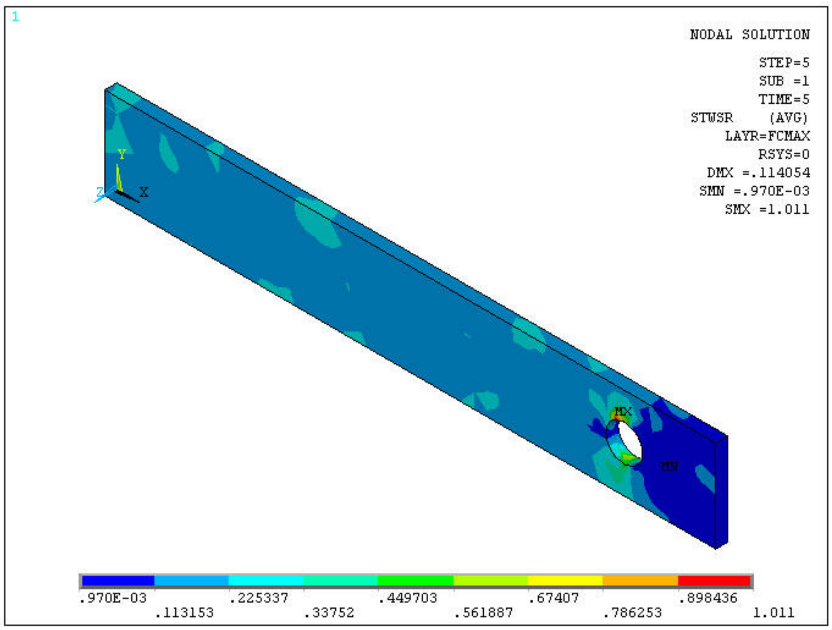

Figure 20- The Tsai-Wu strength ratio for d = 7.5mm and e = 15 mm (w/d=2 and e/d=2)

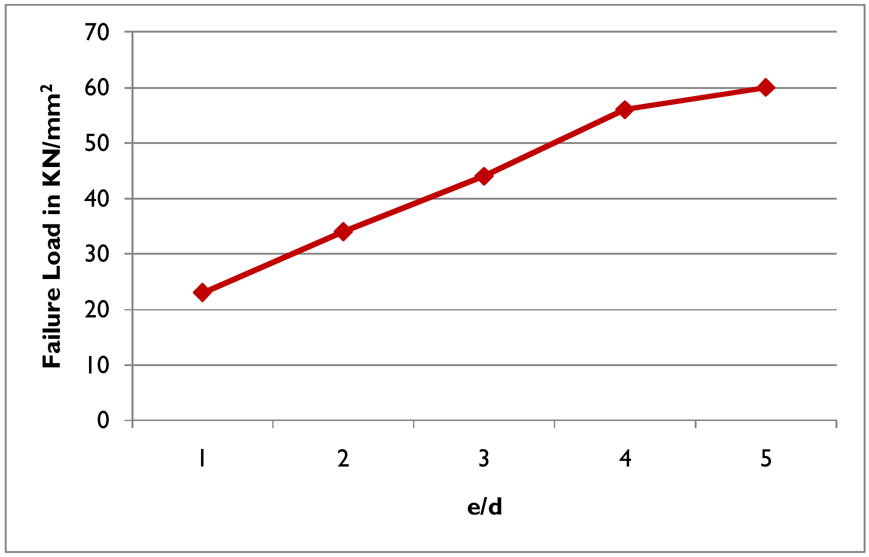

Figure 21- Failure load vs. e/d for w/d =2.5

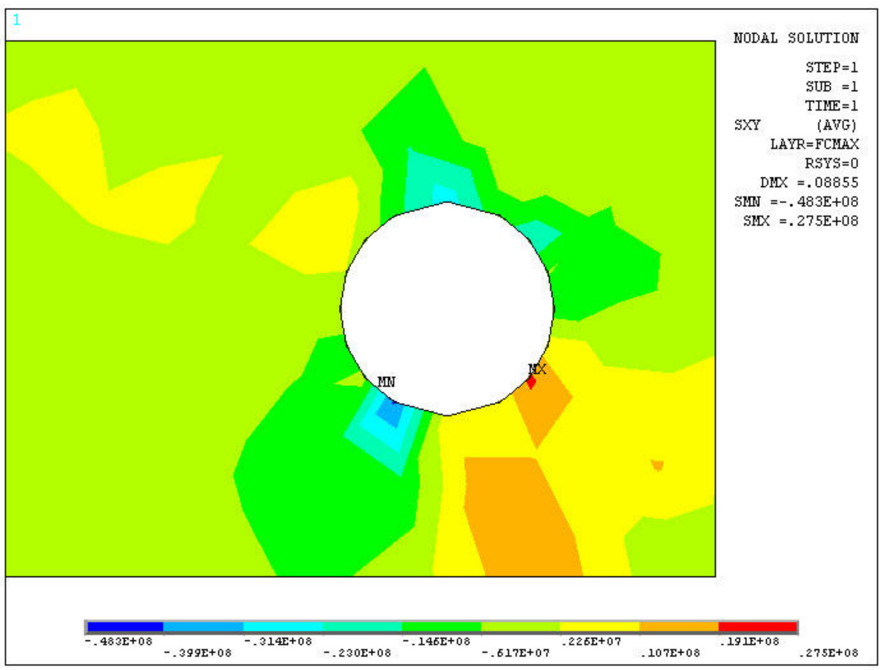

Figure 22- Figure showing stress distribution around hole w/d=2.5 and e/d=1, Load = 23N/mm^2

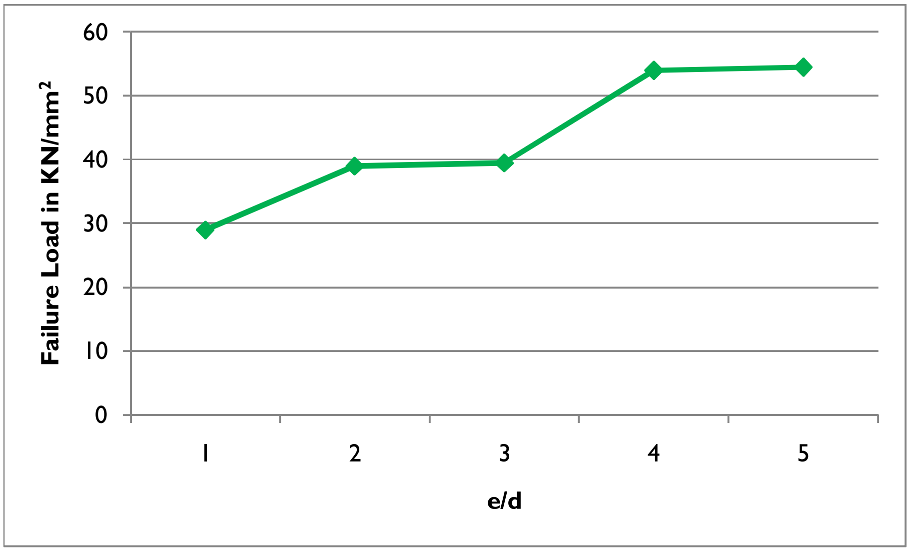

Figure 23- Failure load vs. e/d for w/d =3

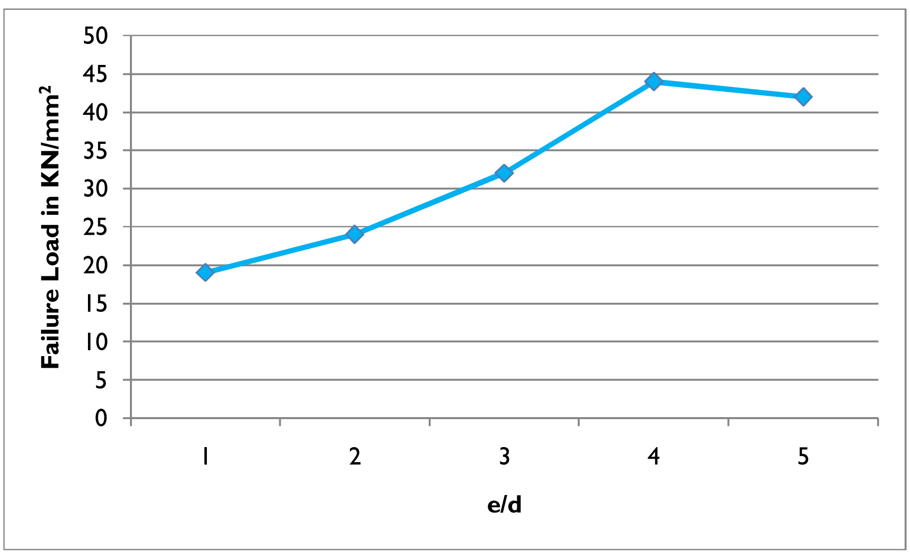

Figure 24- Failure load vs. e/d for w/d =3.75

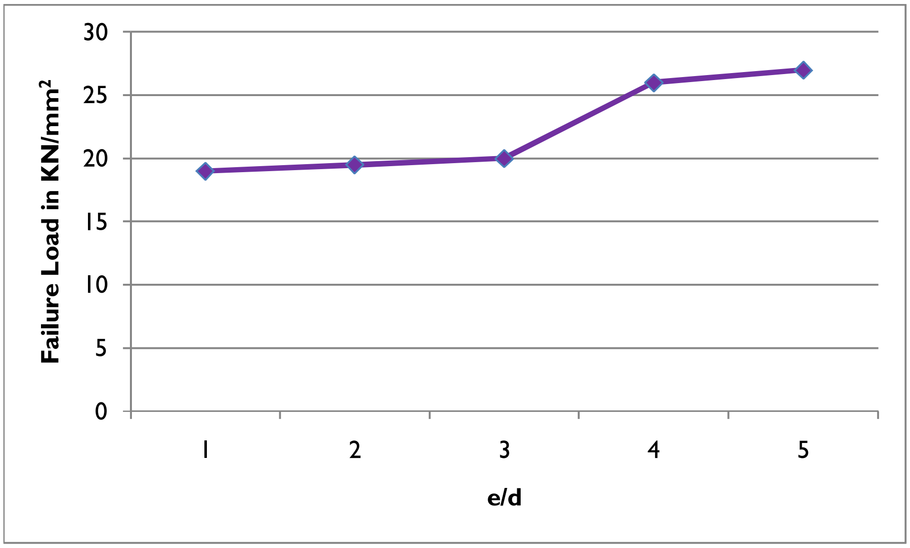

Figure 25- Failure load vs. e/d for w/d =5

It is observed from the graphs in Figure 18 and data presented in Table 6 that for a constant w/d, the failure strength of the FEM model increases with increase in e/d. This is because keeping the diameter of hole constant, when e/d increases, the distance of the hole from one edge of the plate increases. This increases the shear strength of the joint; maximum load sustained was used as a measure joint strength. The effect of e/d ratio on the failure load of the joint for each case of w/d is presented in the figures 20 to 25. Initial failure load is taken when the Tsai-Wu value reaches 1.

The effect of e/d ratio on the shearing stress of the composite joint is shown in Figure 19. The figure shows the shear stress results obtained when the model is subjected to a pressure load of 23 N/mm^2 while the ratio e/d increases and the diameter of hole is kept at a constant 6 mm.

Next, the effect of w/d ratio on the failure load of the composite is presented in Figures 26.

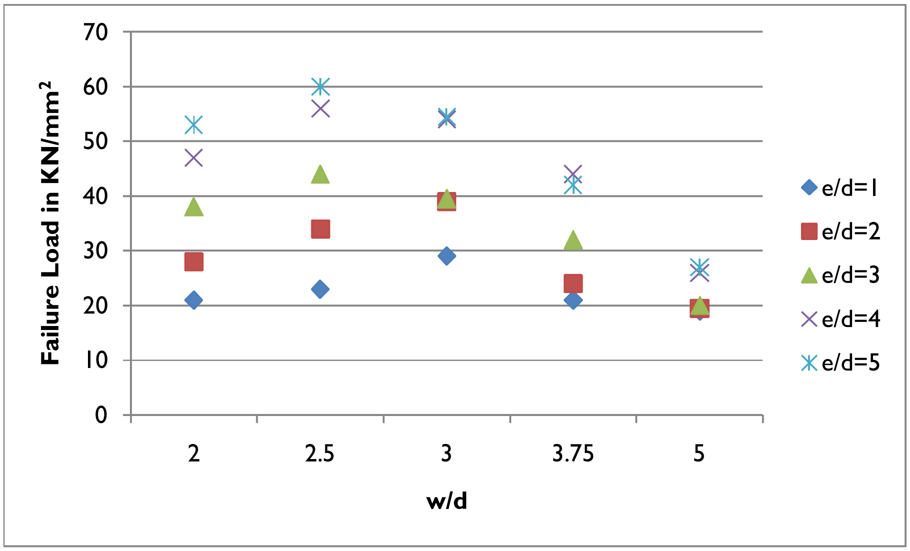

Figure 26 - Failure load vs. w/d increases for all configurations

As w/d increases the simplified equations discussed in Chapter 3 predict mode of failure changes from normal to bearing. As is shown in the figures above as w/d increases overall failure load briefly increases and then decrease. This is because, even though as w/d increases the diameter of the specimen decreases and hence the load carrying cross sectional area leading the specimen become stronger in tensile mode, the observed decrease in failure strength can be attributed to the fact that predominant modes of failure as w/d decreases and d increases are either in bearing or shearing depending on the edge-to-hole distance, e; hence, the overall trend seen in the figure above.

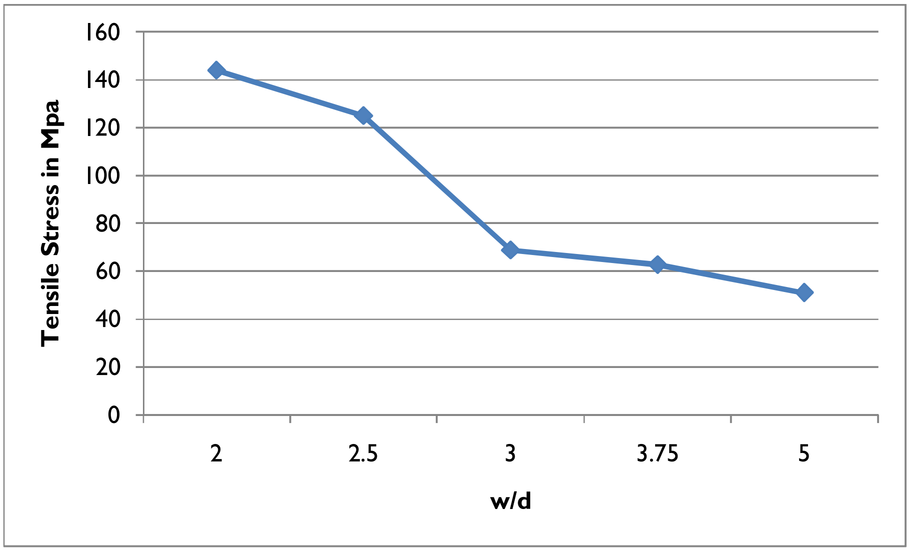

Figure 27 – Maximum tensile stress values: e/d = 3, Load = 20 N/mm^2

In general, the results obtained show the strength of riveted joints to be dependent on diameter and other geometric parameters that are directly related with the diameter of hole such as e/d and w/d. Though discussion of the effect of e/d or w/d ratio on joint strength has to be combined with a consideration of the related failure, this study does not determine the mode of failure directly as the failure load obtained is only the initial or first ply failure. However, from the available results this can be inferred indirectly - that failure mode change as w/d and e/d ratios change.

5.2 Effect of Spacing on Failure Strength

The effect of spacing on the failure of composite joints was studied as described in 4.3.1.2. The results obtained are tabulated in Table 7 and articulated in figures below and the discussion that follows in the next subsections.

			Series holes		Parallel Holes		
e/d	d (mm)	s/d	s (mm)	Failure Load in N/mm^2	s (mm)	Failure Load in N/mm^2	Failure Criterion
1	3	3	9	15	9	19	Tsai -Wu
		4	12	18	12	18	
		5	15	13	15	16	
2	3	3	9	16	9	22	Tsai-Wu

		4	12	20	12	21	
		5	15	21	15	21	
3	3	3	9	21	9	28	Tsai-Wu
		4	12	19	12	27	
		5	15	23	15	24	
4	3	3	9	23	9	35	Tsai-Wu
		4	12	21	12	30	
		5	15	25	15	28	

Table 7 - Results obtained from finite element analysis with ANSYS – spacing effects

The results obtained from the investigations of rivets/holes in different rows (series) are presented in section 5.2.1 and those that from rivets/holes in the same row (parallel) are presented in section 5.2.2.

5.2.1 Rivet holes in Series

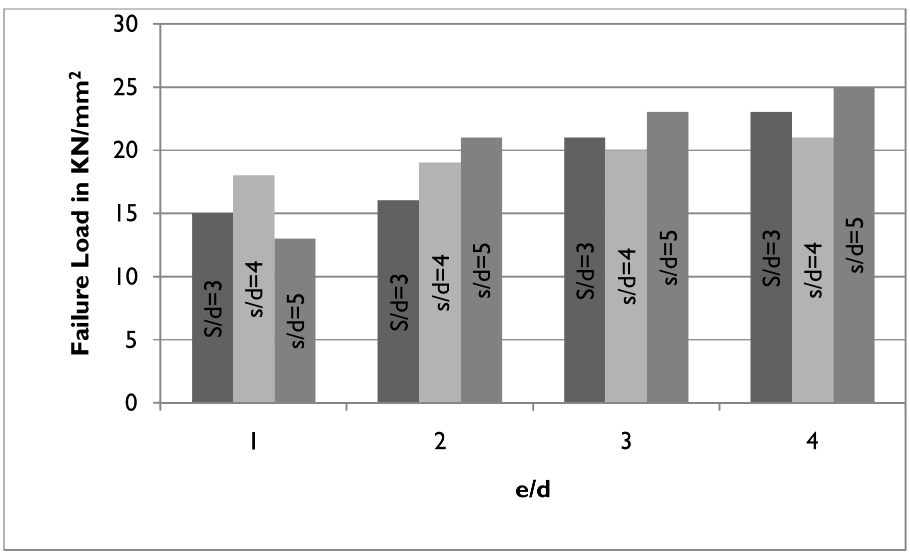

Figure 28 - Failure load vs. e/d values of rivets in series

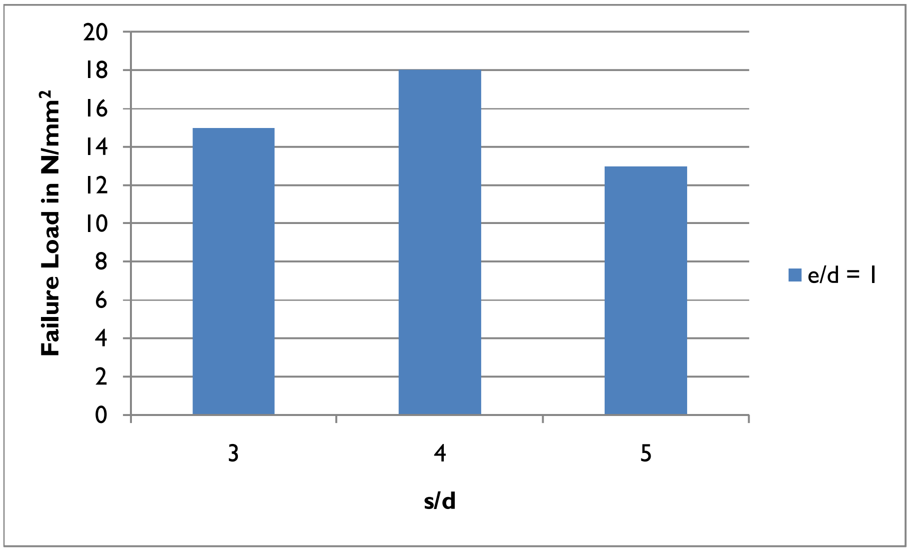

Figure 29 - Failure load vs. s/d for e/d =1

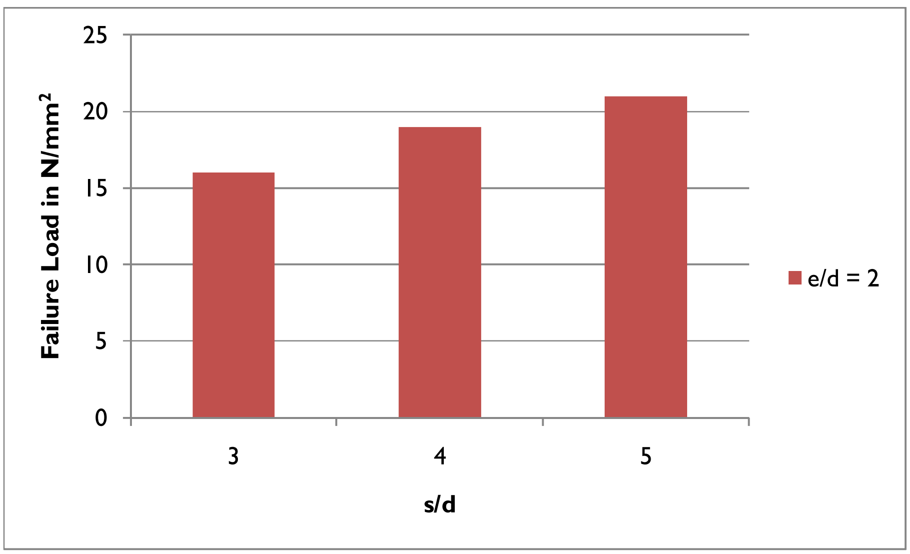

Figure 30- Failure load vs. s/d for e/d = 2

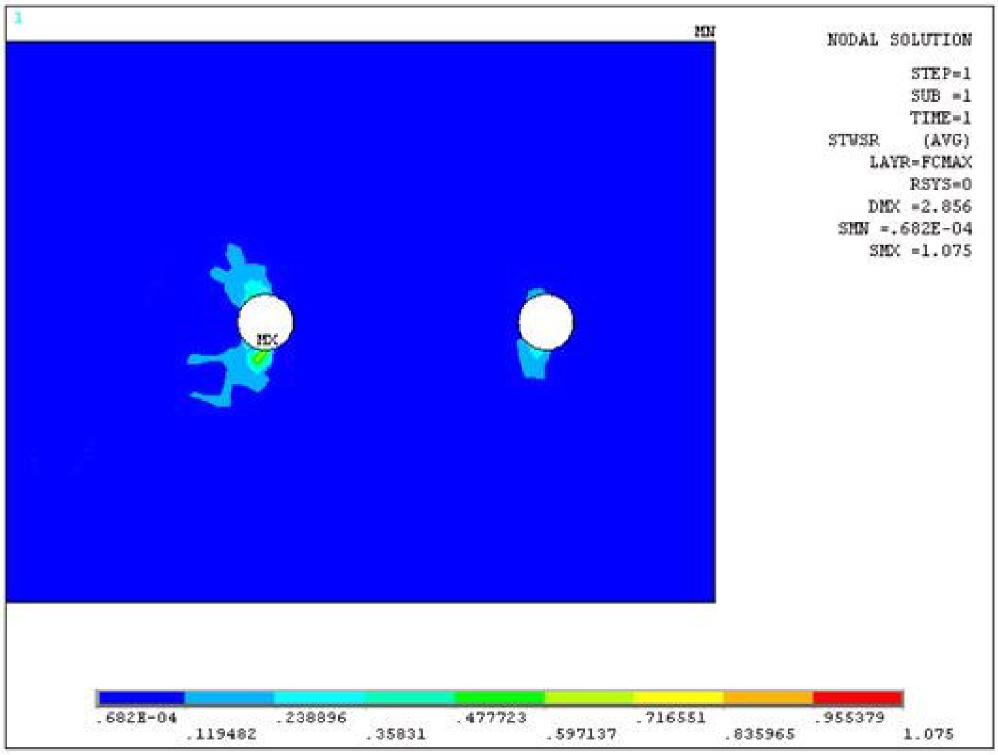

Figure 31 – Tsai-Wu value at failure for s/d = 4 and e/d = 3

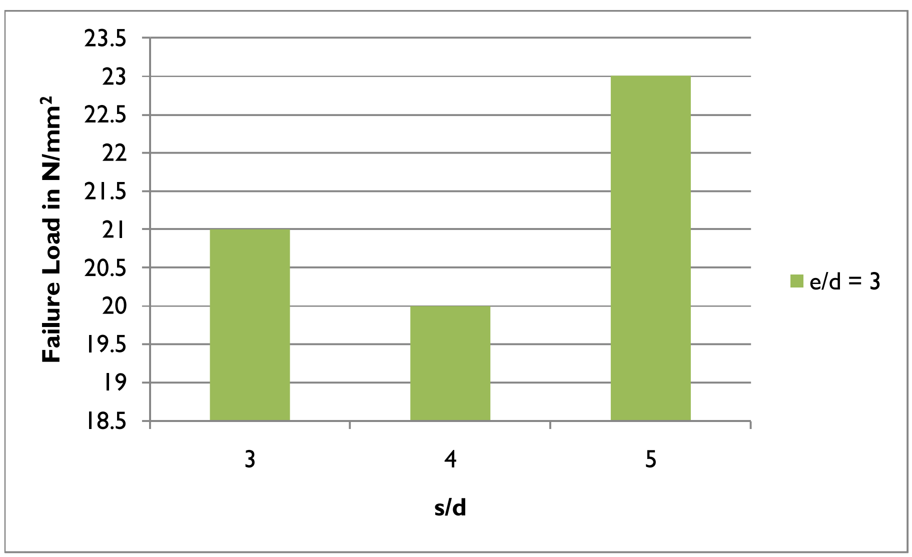

Figure 32 - Failure load vs. s/d for e/d = 3

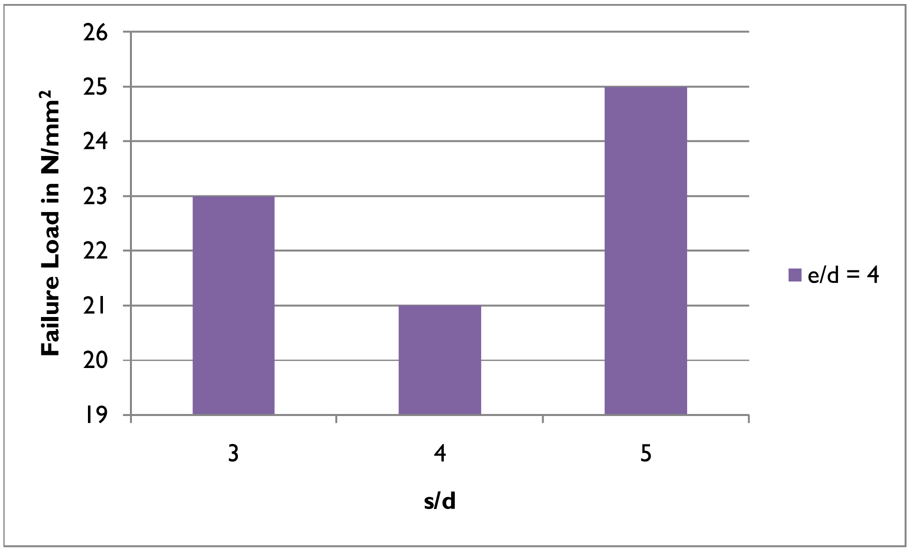

Figure 33 - Failure load vs. s/d for e/d = 4

The failure loads of the composite joint models in the study of the effects of spacing were also predicted by the use of failure criterion. Figure 31 and 36 show the Tsai-Wu value at the initial failure loads obtained from the results of ANSYS analysis. As shown in these figures and discussed in previous chapters, failure occurs when the maximum value of the Tsai-Wu reaches 1.

In this study, in all cases diameter of rivet and hence w/d value is kept constant where as the spacing between value and hence s/d ratio is varied. Also, the e/d ratio is made to vary from a value of 1 to 4 with the intention of encompassing a number of possible configurations and parameters that have interrelated effect.

As is shown in the figures above as e/d increases overall load carrying capacity of the joint varies suggesting a dependence on the edge distance. At e/d=1 Figure 29 shows the joint is strongest at s/d=4, whereas at e/d =2, 3 and 4 the strongest configuration is the ratio between the spacing and diameter is 5. This shows as the edge distance is increase the load carrying capacity changes with a less predictability. In general, the results above show the joint is more strong when s/d value is 5.

5.2.2 Rivet holes in parallel

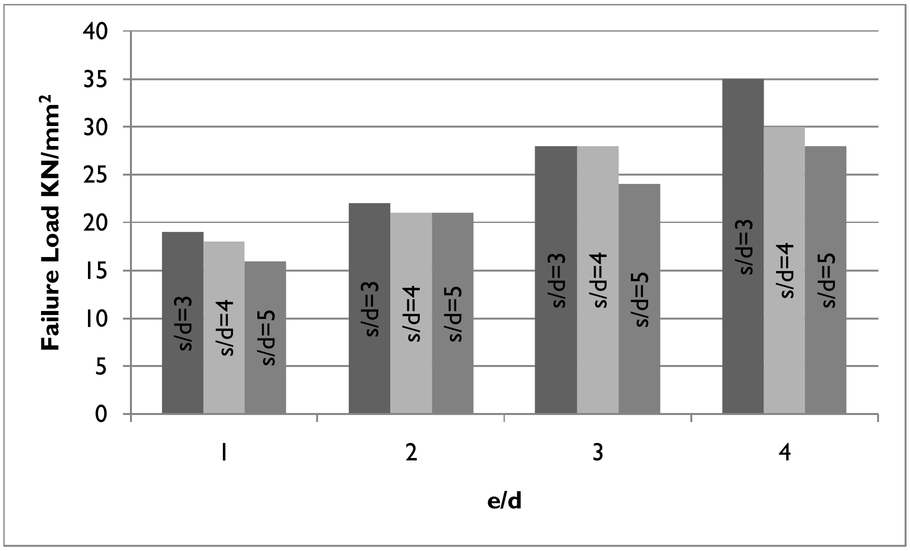

Figure 34 - Failure load vs. e/d of rivets in parallel

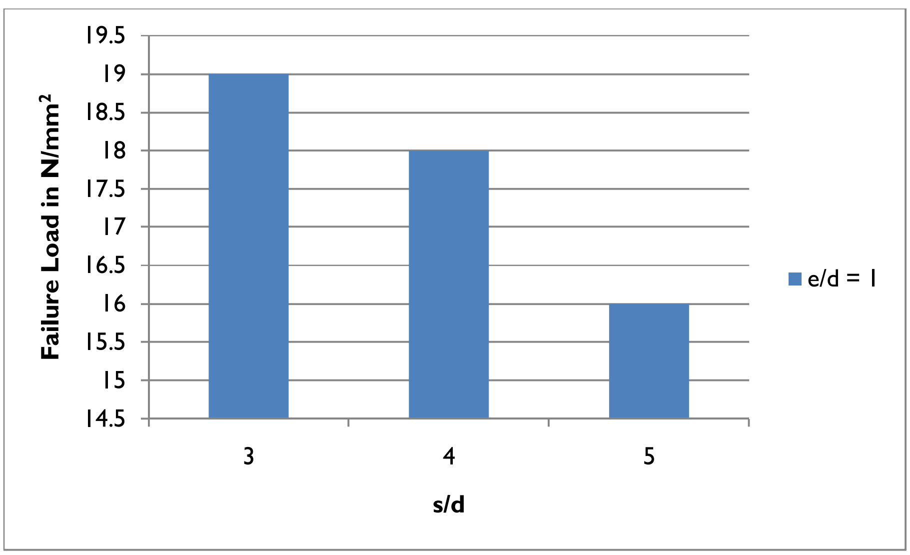

Figure 35 - Failure load vs. s/d for e/d =1

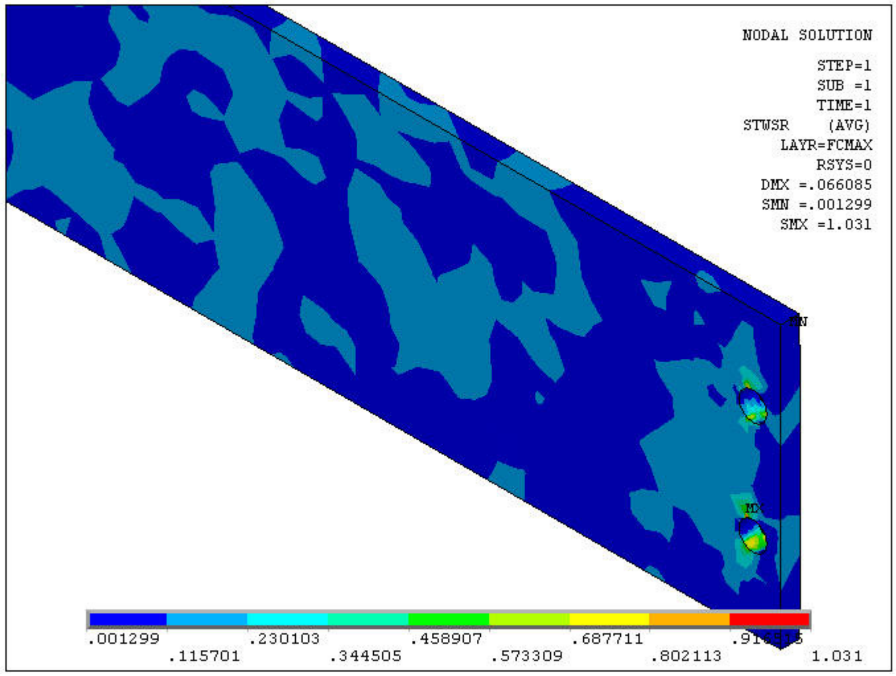

Figure 36 – Tsai-Wu values at failure, parallel holes (s/d = 4, e/d =1)

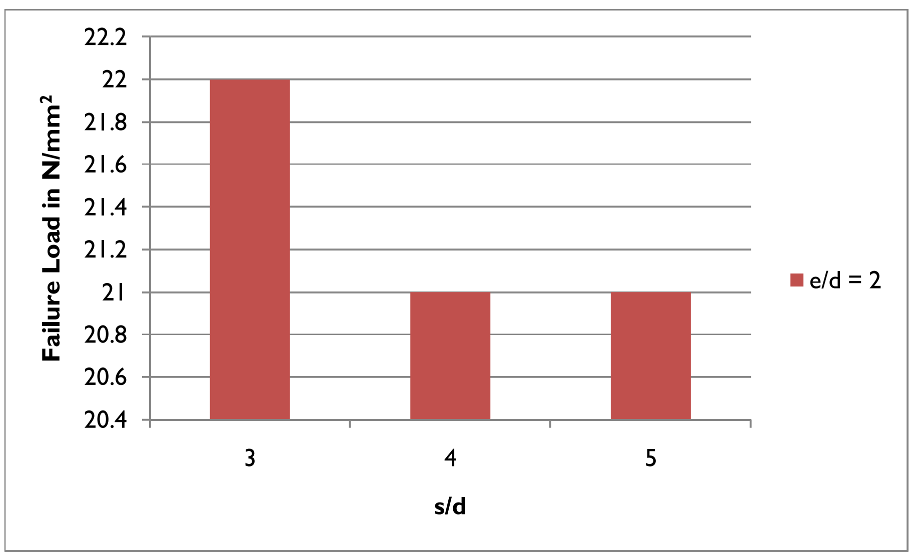

Figure 37 - Failure load vs. s/d for e/d =2

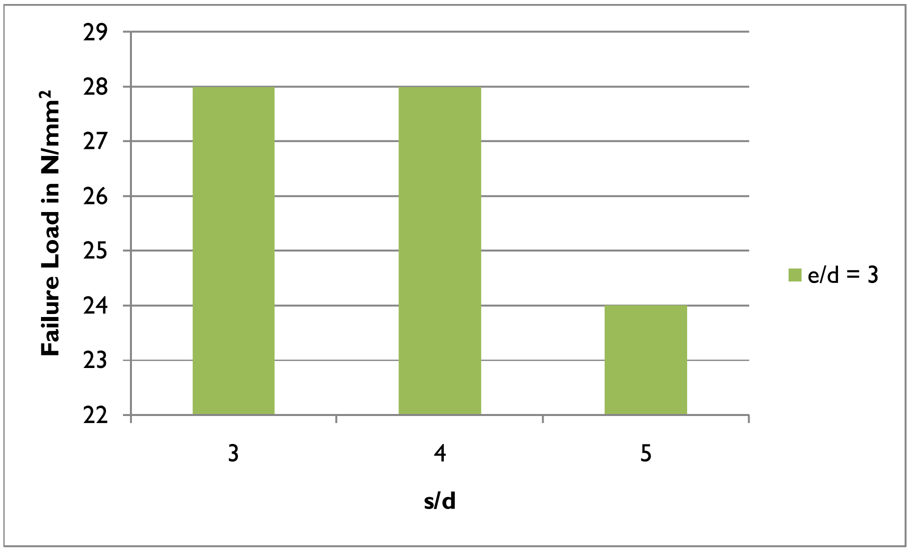

Figure 38 - Failure load vs. s/d for e/d =2

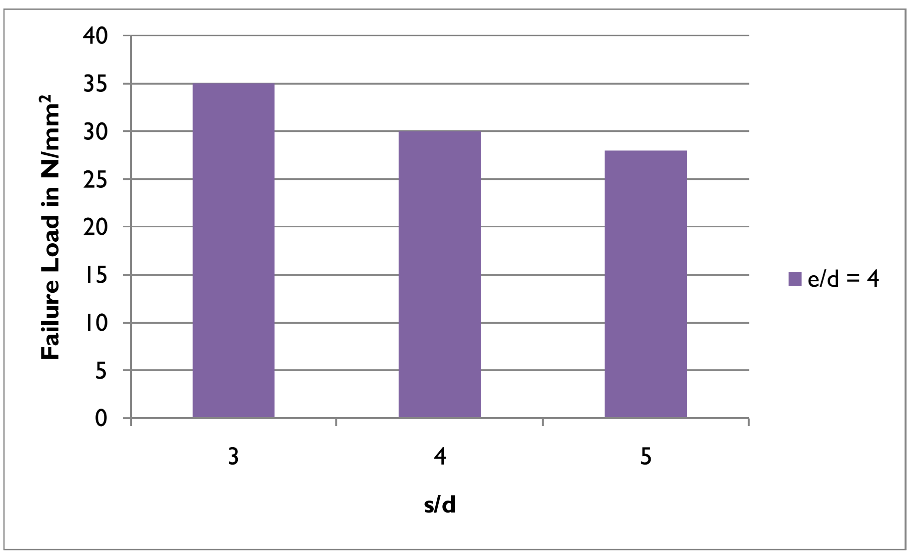

Figure 39 - Failure load vs. s/d for e/d =1

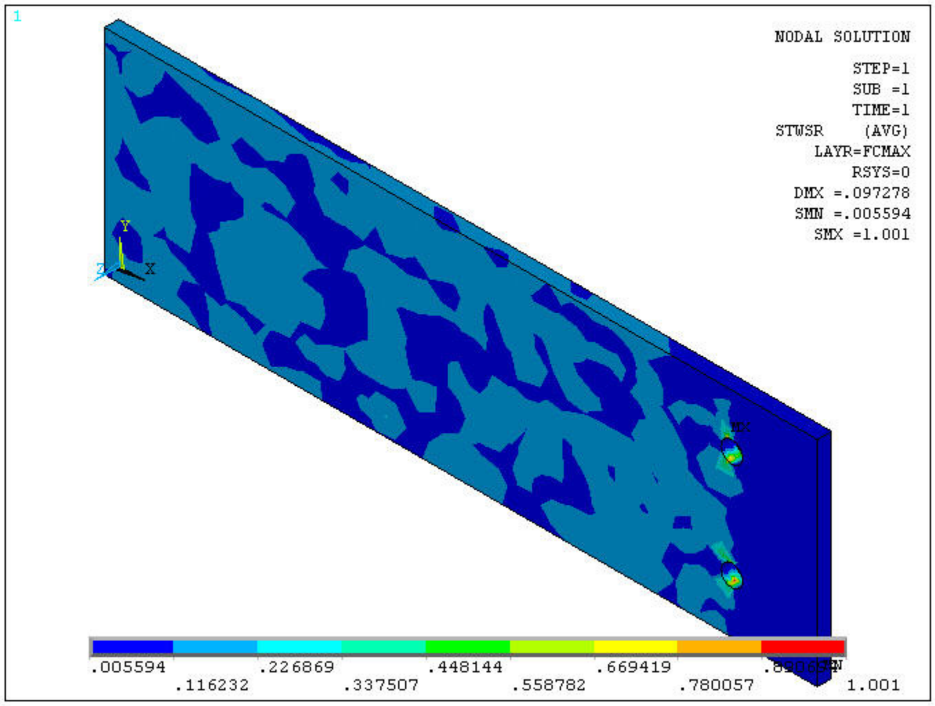

Figure 40 – Tsai-Wu values at failure, parallel holes (s/d = 4. e/d = 3)

As in the study of the rivets in series, in the rivets in parallel case diameter of rivet and hence w/d value is kept constant where as the spacing between value and hence s/d ratio is varied. Also, the e/d ratio is made to vary from a value of 1 to 4 with same intention.

The effects of changing spacing clearly demonstrate that though the width of the cross-section through the rivet holes remains equal in all cases, it significantly affects the strength of the joint. In all cases, s/d value of 3 is the most strongest of all and the overall failure load keeps increasing as e/d value increases. The latter is also in agreement with what has been observed in the study of the effects of diameter which showed that the overall joint strength increases as e/d value increases, i.e. as the distance of the holes increases from the free edge.

Chapter 6

Conclusions, Limitations and Recommendations

6.1 Conclusions

This study is an attempt to further understand the effects of diameter and spacing (row spacing and pitch) of rivets on the failure characteristics of riveted joints. The prediction of both initial failure loads as a measure of joint strength was a major goal. Such a capability would allow synthesis rather than analysis to be used in the future design of fastener joints. In this study, the failure loads and failure characteristics of the high strength carbon fiber/epoxy composite laminate USN125 were investigated when the layers of the material are stacked in a quasi-isotropic symmetric lay-up. To investigate the two parameters on the failure of riveted composite joints, a series of finite element analysis was performed.

From the results obtained from the study and the overall undertaking on the effects of diameter and spacing on the failure of composite joints, the following points of discussion are summarized and concluded:

- To simulate the rivet joint for FEM analysis, the technique of radial boundary condition was used as it is suitable for the problem at hand compared to other techniques such as the cosine load distribution and the full contact method. By comparing the advantages and disadvantages of these methods, radial displacement boundary conditions used in constructing the model were seen to be the most suitable conditions to apply to the nodes around hole where the rivet (pin) contacts the composite.

- In the FEM analysis, the composite failure criteria Tsai-Wu are used in the study to determine start of failure and the amount of the load
- From the finite element simulation results some relevant observations were made about how geometrical parameters, especially, diameter and spacing influence failure of riveted composite joints. Following such consideration simple models representing butt joints were modeled. A single rivet joint is designed for the study of diameter effects whereas a two rivet multi fastener joint is considered in the investigation of spacing effects.
- From this study joint strength, for riveted (pinned joints, in general), is developed when failure due to shear is suppressed by providing proportionately and sufficiently large end distance. For a constant width, when the diameter of hole increases the width carrying load is reduced and the joint eventually fails. A previous study [21] has shown that the width at which the mode change occurs will depend on the lay-up.
- The shear stress of single-hole joints has been shown to be strongly dependent on the edge distance to diameter ratio. Whereas the tensile stress has been shown to be dependent on the width to diameter ratio.
- In general, it is concluded from the study of the effects of diameter that
    - The failure load of the composite joint with a constant diameter hole increases as e/d increases.
    - The strength of the joint is found to increase as a result of decrease in the diameter of the hole.
    - w/d has a greater effect on the mode of failure. The material is found to be weak and fails in tension or shear mode when w/d = 2.

    - As w/d increases, the specimen is found to fail in the bearing mode, which is preferred.
- It follows from the above that comparison of finite element analysis results with the qualitative predictions from the simplified analytical procedure shows good correlation. This in effect validating the acceptability of the procedures suggested by previous work to be good enough to be used in preliminary design stage of mechanical composite joints.
- From the study of the effects of spacing the following are concluded
    - In the case of rivets in series the failure load of the composite joint the strongest joint configuration is when the ratio between the spacing and diameter is 5 in most of the cases; however, a predictable pattern could not be observed from the results as the e/d value significantly and unpredictably affects the strength of the joint.
    - In the case of rivets in parallel the strength of the joint is found to increase as e/d value increases.
    - In all cases, for rivets in parallel, s/d value of 3 is the most strongest of all and the overall failure load keeps increasing as e/d value increases which also is in agreement with what has been observed in the study of effects of diameter

The strength of riveted joints has been shown to be dependent on diameter and other geometric parameters that are directly related with the diameter of rivet/hole such as e/d and w/d, as well as on the spacing between holes and the related parameter s/d. In general, discussion of the effect of diameter and spacing on joint strength has to be combined with a consideration of the related parameters for a complete picture cannot be captured if only each parameter is considered. In such a case, the result obtained most likely will mislead to an incorrect.

From the analysis on the behavior of mechanically fastened joints, it can be concluded that there are some unresolved issues. In this study, the effect of friction, clearance or interference between the pin and edge of the hole are ignored. The static behavior of mechanical fastened composites can be studied by inducing those effects. However, the results achieved from this study and the conclusions inferred from it are encouraging and can be used as a stepping stone for further work.

6.2 Limitations

There are a number of limitations to this work that the author admits. Among these, the following are outlined.

One of the limitations of this work is the assumption that the rivets fastening the joints taken as rigid frictionless bodies. Though this assumption has been reported to deliver fairly reasonable results by many authors it is essential to correctly model the plates and fastener to accurately describe the joint behavior. In this study, the effect of the friction, clearance or interference between the pin and edge of the hole are ignored. The static behavior of pin-loaded composites can also be studied by inducing those effects.

The second limitation is in the study, of diameter effects only a single rivet configuration is considered where as in the study of the effects of spacing only two rivet configurations are investigated. For extensive research on the behavior of riveted composite joints, it is the author's belief that a wide range of configurations should be investigated to arrive to an all encompassing conclusion.

The third limitation is the fact that it only studies a quasi-isotropic carbon fiber/epoxy of lay-up (45, 0, -45, 90). However, there are a number of possible lay-up that provide quasi-isotropic laminates. This study does not explore what the nature of the joint would be if different lay ups are employed.

The fourth limitation of the work is that the method employed does not show how the joint fails eventually, i.e. at last ply failure. What it does is predict at what load joint starts to fail, i.e. first ply failure. However, knowing that a first ply has does not tell what the eventual mode of failure will be.

6.3 Recommendations

It is recommended that future works be focused on composite material joints that incorporate points stated here as the limitation of this work.

Further work would need to be done in order to assess the efficiency of joints from the points of view of fatigue, corrosion, temperature and other environmental effects. Nonetheless, the results presented here are encouraging and serve as a useful guide to the potential application of mechanical joints to laminated composite structural components.

Bibliography

1. Pierron, F. Cerisier, F. and Grediac. "A Numerical and Experimental Study of Woven Composit Pin-Joints." *Journal of Composite Materials*, Sage Publishers Vol. 34 (2000): 1028-1054.
2. Ekh, J., "Multi-Fastener Single-lap Joints in Composite Structures." Doctoral Thesis, Department of Aeronautical and Vehicle Engineering, Royal Institute of Technology, Stockholm, 2006.
3. Liu, Dahsin, Basavaraju B. Raju, and Junling You, "Thickness Effects on Pinned Joints for Composites." *Journal of Composite Materials*, SAGE Publications, Vol. 33, no. 01 (1999): 2-21.
4. McCarthy, M.A., and C. T. McCarthy, "Finite Element Analysis of the Effects of Clearance on Single-Shear, Composite Bolted Joints." *Journal of Plastics, Rubber and Composites.*
5. Sridevi, K., and A. Satyadevi. "Failure Analysis of a Pin Loaded Glass Vinylester Composite Plates Using FEM." *http://webmail.iitg.ac.in.* [Online]
6. Valenza, A., V. Fiore, C. Borsellino, and L. Calabrese, "Failure Map of Composite Laminate Mechanical Joint." *Journal of Composite Materials*, SAGE Publications, Vol. 41, no. 8 (2007).
7. Camanho, P.P., and M. Lambert, "A design methodology for mechanically fastened joints in laminated composite materials." *Composites Science and Technology,* Elsevier Ltd., no. 66 (2006): 3004–3020.
8. Chamis, Christos C., *Simplified Procedures for Designing Composite Bolted Joints.* Cleveland: National Aeronautics and Space Adminstration, 1988.

9. Ireman, T., "Design of Composite Structures Containing Bolt Holes and Open Holes." Doctoral Thesis, Department of Aeronautics, Royal Institute of Technology, Stockholm, 1999.

10. Ryu, Choong-O, Jin-Ho Choi, and Jin-Hwe Kweon, "Failure Load Prediction of Composite Joints using Linear Analysis." *Journal of Composite Materials*, Sage Publications, Vol 41, no. 7 (2007): 865-878.

11. Hou, Li, and Dahsin Liu, "Size Effects and Thickness Constraints in Composite Joints." *Journal of Composite Materials*, Sage Publications, Vol. 37, no. 21 (2003).

12. Schwartz, M. M, *Composite Materials Handbook,* New York: McGraw-Hill, Inc., 1984.

13. Kaw, Autar K., *Mechanics of Composite Materials,* Boca Raton, Florida: CRC Press LLC, 1997.

14. *Composite Materials Handbook: Polymer Matrix Composites Materials Usage, Design, and Analysi,* MIL-HDBK-17-3F. Vol. 3, 5 vols., 2002: U.S. Department of Defense.

15. Arnold, W.S., I. H. Marshall, and J. Wood, "Optimum Design Donsiderations for Mechanically Fastened Composite Joints." *Composite Structures,* Vol. 16 (1990): 85-101.

16. Hamada, H., K. Haruna, and Z. Maekawa, "Effects of Stacking Sequences on Mechanically Fastened Joint Strength in Quasi-isotropic Carbon-Epoxy Laminates." *Journal of Composites Technology and Research,* Vol. 17, no. 3 (1995): 249–259.

17. Hart-Smith, L.J., "Design and Analysis of Bolted and Riveted Joints Fibrous Composite Structures 7739." Douglas Aircraft Company, 1986.

18. Fisher, John W., John H.A. Struik, and Geoffrey L. Kulak, *Guide to Design Criteria for Bolted and Riveted Joints,* 2nd Edition, Chicago: American Institute of Steel Construction, Inc., 2001.

19. Collins, Jack A., *Mechanical Design of Machine Elements and Machines: A Failure Prevention Perspective,* New Jersey: John Wiley & Sons, 2003.

20. *ANSYS Documentation Release 10.0.* Online Document. ANSYS, Inc. Canonsburg, PA, 2006.

21. Chang, F.K., and R. A. Scott, "Failure of Composite Laminates Containing Pin Loaded Holes-Method of Solution." *Journal of Composite Materials,* Sage Publications, Vol. 18 (1984): 255–278.

22. To, Q.D, "Failure analysis of tempered glass structures with pin-loaded joints." Marne-la-Vall´ee Cedex 2, 2006.

23. Vasiliev, Valery V., and Evgeny V. Morozov, *Mechanics and Analysis of Composite Materials,* Amsterdam: Elsevier Science Ltd., 2001.

24. Djordjevic, Isidor, Momcilo Stevanovic, and Danijela Pesikan Sekulic, "Carbon Fiber Composites, Main Engineering Elastic Constants and Macromechanical Characterization." *Journal of Reinforced Plastics and Composites*, Sage Publications, Vol. 26, no. 12 (2007): 1193-1199.

25. Ochoa, O. O., and J. N. Reddy, *Finite Element Analysis of Composite Laminates,*. Dordrecht: Kluwer Academic Publishers, 1992.

26. Voyiadjis, George Z., and Peter I. Kattan, *Mechanics of Composite Materials with MATLAB,* Heidelberg: Springer-Verlag, 2005.

27. Hirano, N., Y. Takao, and W. X. Wang, "Effects of Temperature on the Bearing Strength of CF/Epoxy Pinned Joints." *Journal of Composite Materials*, Sage Publishers, Vol. 32, no. 2: 335-351.

28. Kelly, G., "Load Introduction in Carbon Fibre Compositesfor Automotive Applications." Doctoral Thesis, Department of Aeronautics, Royal Institute of Technology, Stockholm, 2002.

29. Ireman, T., "Three-dimensional Stress Analysis of Bolted Single-lap Joints." *Composite Structures,* Vol. 43 (1998): 195-216.

Candidate's Declaration

I hereby declare that the work which is being presented in this thesis entitled "**SPACING AND DIAMETER EFFECTS OF RIVETS ON THE FAILURE OF LAMINATED COMPOSITE JOINTS**" is original work of my own, has not been presented for a degree in any other university and that all sources of material used for the thesis have been duly acknowledged.

____________________ ________________

Tomas Deress Date
(Candidate)

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

____________________ ________________

Dr. A. Raman Date
(Thesis Advisor)