INTERNATIONAL JOURNAL OF ENGINEERING INNOVATIONS IN ADVANCED TECHNOLOGY
ISSN [O]: 2582-1431 VOLUME-III ISSUE-II APR-JUNE-2021

FAILURE ANALYSIS OF MECHANICALLY FASTENED JOINTS

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Abstract:In this paper, a computation method in failure analysis of layered composites containing pin-loaded holes. The investigation is focused on developing a reliable computation procedure to analyze initial failure load for pin-loaded holes at with layered and without layered composite structures. Finite element analysis (FEA) is used to determine stress distribution around the fastener hole. Combining soderberg curve model and Tsai-Wu initial failure criterion are used to determine joint failure. Special attention in this work is paid to pin-load distributions and its effect on the load level of failure and its location. In previous work initial failure analysis was carried out using cosine distribution between pin/lug mechanically fastened joint. Here contact finite element pin/lug model is analyzed. The influence of stacking sequences of layered composites containing pin-loaded holes is also investigated. Special attention is paid to failure load and mode analyses in composites with stacking sequence [0/ ± 90]s.

Keywords: Fastened joint, Finite element analysis, Grey cast iron, Tsai-Wu.

1. INTRODUCTION

Joining by mechanical fasteners is one of the common practices in the assembly of structural components. However, mechanical fasteners introduce complicated stress field near the bolt hole area in the structures. As a consequence, mechanical fastened joints are frequent sources of failure in aircraft and spacecraft structures. It is well known that they can severely reduce the load carrying capability of the components by more than fifty percent. Optimal design of joints improves not only structural integrity and performance, but more importantly, it considerably minimizes the weight of the structures and hence, can increase the load-carrying capability. Fiber reinforced laminated composite materials have been widely used in aircraft and spacecraft structures because of their high strength and stiffness to weight ratios. Due to the complex failure modes of composite materials, the mechanical joining of structures made of composite materials demands much more rigorous design knowledge and techniques than those currently available in the traditional methodology for metallic joints. Damage in bolted composite joints can initiate at an early loading stage and accumulate inside the laminates as the load increases. The accumulation of damage and the mode of failure strongly depend upon the material, ply orientation, laminate thickness, joint geometry, and loading condition, etc. Considerable analyses and experiments on bolted composite joints have been performed to evaluate the effect of material properties and ply orientation as well as layup on the joint response and failure in the literature. There are in general three basic failure modes in bolted composite joints: net-tension, shear-out, and bearing. Net-tension failure is associated with fiber and matrix tension failures, due to stress concentrations, while shear-out and bearing failures result primarily from the shear and compression failures of fiber and matrix. The first two failure types tend to ail catastrophically. The bearing failure is more progressive and may not result in total reduction of the load-carrying capability of the joints.

A combination of any of the three modes may also occur in the joint.

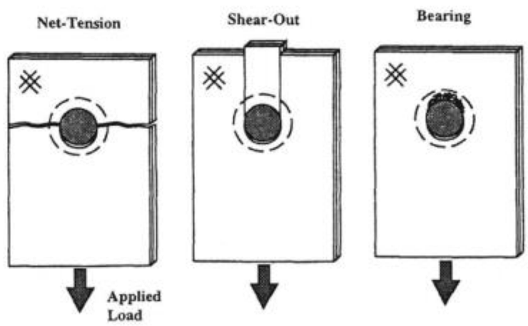


Fig: Illustration of the three failure types in mechanically fastened composite joints

A fastener (US English) or fastening (UK English)[1] is a hardware device that mechanically joins or affixes two or more objects together. In general, fasteners are used to create non-permanent joints; that is, joints that can be removed or dismantled without damaging the joining components.[2] Welding is an example of creating permanent joints. Steel fasteners are usually made of stainless steel, carbon steel, or alloy steel.

Other alternative methods of joining materials include: crimping, welding, soldering, brazing, taping, gluing, cement, or the use of other adhesives. Force may also be used, such as with magnets, vacuum (like suction cups), or even friction (like sticky pads). Some types of woodworking joints make use of separate internal reinforcements, such as dowels or biscuits, which in a sense can be considered fasteners within the scope of the joint system, although on their own they are not general purpose fasteners.

Furniture supplied in flat-pack form often uses cam dowels locked by cam locks, also known as conformat fasteners. Fasteners can also be used to close a container such as a bag, a box, or an envelope; or they may involve keeping together the sides of an opening of flexible material, attaching a lid to a container, etc. There are also special-purpose closing devices, e.g. a bread clip.

Items like a rope, string, wire, cable, chain, or plastic wrap may be used to mechanically join objects; but are not generally categorized as fasteners because they have additional common uses. Likewise, hinges and springs may join objects together, but are ordinarily not considered fasteners because their primary purpose is to allow articulation rather than rigid affixment.

1.1 Failures of Fasteners

Failure because of Overload : Many accidents can be characterized as an impact with a non-compliant object such as a truck impacting a concrete bridge support. The fine, grey appearance of the fracture surface is consistent with a sudden overload failure. **Failure from lack of Locking Mechanism:** To prevent bolts from loosening over time, various locking mechanisms are employed. They include lock Washers, locking nuts, jam nuts, mechanical deformations, wire wrap, cotter pins, metal locks, and expansion Anchors, helical coils and polymer locking compounds. Machinery that is subject to vibratory environments usually is equipped with some sort of locking mechanism. If the locking mechanism is not applied to the Machinery during manufacture, a catastrophic event may result.

Metal Fatigue: Metal fatigue is the phenomenon characterized by progressive crack growth during cyclic loading. A crack is often initiated at a flaw or stress riser (sharp notch) in a part. Cyclic forces such as vibrations or repeated impact cause the crack to increase in size until the part can no longer sustain the load, and a final fracture occurs.

Failure from Improper Torque: When threaded fasteners are utilized, the amount of tightening or bolt torque is often important. Motor vehicle wheel studs require torques ranging from about 100 ft-lbs for smaller vehicles to over 400 ft-lbs for large trucks.

The appropriate torque is required in order to prevent relative flexing of the two parts being fastened and to assure an acceptable mechanical connection. Bolt failures as a result of improper torque have occurred in automobile applications.

Corrosion Failure: Corrosion of metals can be disastrous to threaded fasteners. Surface and pitting corrosion attacks threaded Fasteners as a result of contact with moisture or other corroding media. Since bolts often carry high loads, stress corrosion cracking is another corrosion related failure mode. Corrosion, coupled with forces in a bolt, tends to accelerate cracking.

Hydrogen Embrittlement (HE): A permanent loss of ductility in a metal or alloy caused by hydrogen in combination with stress, either externally applied or internal residual stress.

Galling: If you've ever had the pleasure of installing or removing stainless steel fasteners, you've more than likely experienced galling. Galling is a cold-welding processes those results when the threads are in contact under heavy pressure and friction. Or in other words, when fasteners are assembled or disassembled.

Fig 1.1: Fasteners

1.2 Application of Fasteners

Some of applications of fasteners are as follows:

Military – Fasteners specially designed to withstand the stress of high temperature, high wear and corrosive environments such as engines, motors, heat exchangers and process equipment. We offer a wide range of diameters, lengths and thread configurations using stainless steel, copper alloys, alloy steels, nickel alloys and exotic alloys.

Oilfield – Fasteners manufactured using stainless steel, tool alloys, nickel alloys and exotic metals that will perform well in the high stress, corrosive environment found in oilfield and mining applications. Our fasteners are used in drilling rigs, tanks and pumping equipment.

Turbine & Power Generation – Fasteners used in electrical equipment, turbines, motors, exhaust systems, pumping systems and storage vessels. Nickel alloys, aluminum, steel alloys and stainless steel are used for their strength, high wear and anti-corrosive properties. Copper alloys are used for their conductive properties.

Chemical Refining – Fasteners manufactured using stainless steel, tool alloys, nickel alloys and exotic metals that will perform well in the high stress, corrosive environment found in chemical processing applications. Our fasteners are used in heat exchangers; exhaust systems, tanks and vessels, and processing equipment.

American screws, bolts, and nuts were historically not fully interchangeable with their British counterparts, and therefore would not fit British equipment properly. This, in part, helped lead to the development of numerous United States Military Standards and specifications for the manufacturing of essentially any piece of equipment that is used for military or defense purposes, including fasteners. World War II was a significant factor in this change.

A key component of most military standards is traceability. Put simply, hardware manufacturers must be able to trace their materials to their source, and provide traceability for their parts going into the supply chain, usually via bar codes or similar methods. This traceability is intended to help ensure that the right parts are used and that quality standards are met in each step of the manufacturing process; additionally, substandard parts can traced back to their source

2. METHODOLOGY

2.1 MATERIALS AND METHODS

Carbon Fiber: In fiber reinforced composites, fiberglass is the "workhorse" of the industry. It is used in many applications and is very competitive with traditional materials such as wood, metal, and concrete. Fiberglass products are strong, lightweight, non-conductive, and the raw material costs of fiberglass are very low.In applications where there is a premium for increased strength, lower weight, or for cosmetics, then other more expensive reinforcing fibers are used in the FRP composite,

Table: mechanical properties of carbon fiber

Young’s modulus(Mpa)	70000
Tensile strength(Mpa)	3900
Poisson’s ratio	0.30
Density(kg/mm3)	0.00000020

2.2. Finite element analysis

Finite element analysis is a method of solving, usually approximately, certain problems in engineering and science. It is used mainly for problems for which no exact solution, expressible in some mathematical form, is available. As such, it is a numerical rather than an analytical method. Methods of this type are needed because analytical methods cannot cope with the real, complicated problems that are met with in engineering. For example, engineering strength of materials or the mathematical theory of elasticity can be used to calculate analytically the stresses and strains in a bent beam, but neither will be very successful in finding out what is happening in part of a car suspension system during cornering.

2.3 CATIA PARAMETRIC SOFTWARE

Computer-aided design (CAD), also known as computer-aided design and drafting (CADD), is the use of computer technology for the process of design and design-documentation. Computer Aided Drafting describes the process of drafting with a computer. CADD software, or environments, provide the user with input-tools for the purpose of streamlining design processes; drafting, documentation, and manufacturing processes. CADD output is often in the form of electronic files for print or machining operations. The development of CADD-based software is in direct correlation with the processes it seeks to economize; industry-based software (construction, manufacturing, etc.) typically uses vector-based (linear) environments whereas graphic-based software utilizes raster-based (pixelated) environments.

CADD environments often involve more than just shapes. As in the manual drafting of technical and engineering drawings, the output of CAD must convey information, such as materials, processes, dimensions, and tolerances, according to application-specific conventions.

CAD may be used to design curves and figures in two-dimensional (2D) space; or curves, surfaces, and solids in three-dimensional (3D) objects.

CAD is an important industrial art extensively used in many applications, including automotive, shipbuilding, and aerospace industries, industrial and architectural design, prosthetics, and many more. CAD is also widely used to produce computer animation for special effects in movies, advertising and technical manuals. The modern ubiquity and power of computers means that even perfume bottles and shampoo dispensers are designed using techniques unheard of by engineers of the 1960s. Because of its enormous economic importance, CAD has been a major driving force for research in computational geometry, computer graphics (both hardware and software), and discrete differential geometry.

The design of geometric models for object shapes, in particular, is often called computer-aided geometric design (CAGD).

Current computer-aided design software packages range from 2D vector-based drafting systems to 3D solid and surfacemodellers. Modern CAD packages can also frequently allow rotations in three dimensions, allowing viewing of a designed object from any desired angle, even from the inside looking out. Some CAD software is capable of dynamic mathematic modeling, in which case it may be marketed as CADD — computer-aided design and drafting.

CAD is used in the design of tools and machinery and in the drafting and design of all types of buildings, from small residential types (houses) to the largest commercial and industrial structures (hospitals and factories).

CAD is mainly used for detailed engineering of 3D models and/or 2D drawings of physical components, but it is also used throughout the engineering process from conceptual design and layout of products, through strength and dynamic analysis of assemblies to definition of manufacturing methods of components. It can also be used to design objects.

3. ANALYSIS

3.1 INTRODUCTION TO FINITE ELEMENT ANALYSIS

The basic concept in fem is that the body or structure may be divided into smaller elements of finite dimensions called “Finite Elements”. The original body or the structure is then considered as an assemblage of these elements connected at a finite number of joints called “nodes” or “nodal points”. Simple functions are chosen to approximate the displacements over each finite element. Such assumed functions are called “shape functions”. This will represent the displacement with in the element in terms of the displacement at the nodes of the elements.

The Finite Element method is a mathematical tool for solving ordinary and partial differential equation because it is a numerical tool, it has the ability to solve the complex problem that can be represented in differential equation from. The application of FEM are limitless as regards the solution of practical design problems.

Due to high cost of computing power of years gone by, FEM has a history of being used to solve complex and cost critical problems.

Now a days, even the most simple of products rely on the finite element method for design evaluation. This is because contemporary design problems usually cannot be solved as accurately & cheaply using any other method that is currently available. Physical testing was the norm in the years gone by, but now it is simply too expensive and time consuming also.

3.2 BASIC CONCEPTS:

The finite element method is based on the idea of building a complicated object with simple blocks or driving a complicated object into small and manageable pieces. Application of this simple idea can be found everywhere in everyday life as well as engineering. The philosophy of FEA can be explained with a small example such as measuring the area of a circle.

Area of one triangle: Si=1/2*R2*sin θI.

Area of the circle: SN=1/2*R2*N*Sin (2∏/N) →∏R2 as N→∞.

Where N= total number of triangles (elements)

If one needs to evaluate the area of the circle without using the conventional formula, one of the approaches could be to divide the above area into a number of equal segments. The area of each triangle multiplied by the number of such segments gives the total area of the circle

3.3 FEA:

Finite Element Analysis was first developed for use in the aerospace and nuclear industries where the safety of the structures is critical. Today, the growth in usage of the method is directly attributable to the rapid advances in computer technology in recent years. As a result, commercial finite element packages exist that are capable of solving the most sophisticated problems, not just in structural analysis. But for a wide range of applications such as steady state and transient temperature distributions, fluid flow simulations and also simulation of manufacturing processes such as injection moulding and metal forming.

FEA consists of a computer model of a material or design that is loaded and analysed for specific results. It is used in new product design, and existing product refinement. A design engineer shall be able to verify the proposed design, which is intended to meet the customer requirements prior to the manufacturing. Things such as, modifying the design of an existing product or structure in order to qualify the product or structure for a new service condition. Can also be accomplished in case of structural failure, FEA may be used to help determine the design modifications to meet the new condition.

Mathematically, the structure to be analysed is subdivided into a mesh of finite sized elements of simple shape. Within each element, the variation of displacement is assumed to be determined by simple polynomial shape functions and nodal displacements. Equations for the strains and stresses are developed in terms of the unknown nodal displacements. From this, the equations of the equilibrium are assembled in a matrix from which can be easily be programmed and solved on a computer. After applying the appropriate boundary conditions, the nodal displacements are found by solving the matrix stiffness equation. Once the nodal displacements are known, element stresses and strains can be calculated.

3.4 DISCRITIZATION OF THE DOMAIN:

The task is to divide the continuum under study into a number of subdivisions called element. Based on the continuum it can be divided into line or area or volume elements.

3.5 APPLICATION OF BOUNDARY CONDITIONS:

From the physics of the problem we have to apply the field conditions i.e. loads and constraints, which will help us in solving for the unknowns.

3.6 VIEWING THE RESULTS:

After the completion of the solution we have to review the required results.

The first two steps of the above said process is known as pre-processing stage, third and fourth are the processing stage and the final step is known as post-processing stage.

3.7 ANSYS INTRODUCTION:

The ANSYS program is self-contained general purpose finite element program developed and maintained by Swason analysis systems Inc .the program contain many routines, all inter related and all for main purpose of achieving a solution to an engineering problem by finite element method.

The ANSYS program has a compressive graphical user interface (GUI) that gives users easy, interactive access to program functions, commands, documentation and reference material. An intuitive menu system helps users navigate through the ANSYS program. Users can input data using a mouse, a keyboard, or a combination of both. A graphical user interface throughout the program, to guide new users through the learning process and provide more experienced users with multiple windows, pull-down menus, dialog boxes, tool bar and online documentation.

3.8 ORGANIZATION OF THE ANSYS PROGRAM

Begin level acts as a gateway into and out of the ANSYS program. It is also used for certain

Global program controls such as changing the job name, clearing (zeroing out) the database, and copying binary files. When we first enter the program, we at the begin level.

At the processor level, several processors are available; each processor is a set of functions that perform a specific analysis task. For example, the general preprocessor (PREP7) is where we build the model, the solution processor (SOLUTION) is where we apply loads and obtain the solution, and the general postprocessor(POST1) is where we evaluate the results and obtain the solution. An additional postprocessor (POST26), enables we to evaluate solutions results at specific points in the model as a function of time.

3.9 PERFORMING A TYPICAL ANSYS ANALYSIS

The ANSYS program has many finite element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis. The analysis guide manuals in the ANSYS documentation set describe specific procedures for performing analysis for different engineering disciplines.

3.10 PRE-PROCESSOR

The input data for an ANSYS analysis are prepared using a preprocessor. The general preprocessor (PREP 7) contains powerful solid modelling and mesh generation capabilities, and is also used to define all other analysis data with the benefit of data base definition and manipulation of analysis data. Parametric input, user files, macros and extensive online documentation are also available, providing more tolls and flexibility for the analyst to define the problem. Extensive graphics capability is available throughout the ANSYS program, including isometric, perceptive, section, edge and hidden-line displays of three-dimensional structures-y graphs of input quantities and results, and contour displays of solution results.

3.11 POST PROCESSOR:

Post processing means the results of an analysis. It is probably the most important step in the analysis, because we are trying to understand how the applied loads affects the design, how food your finite element mesh is, and so on.

The analysis results are reviewed using post processors, which have the ability to display distorted geometries, stress and strain contours, flow fields, safety factor contours, contours of potential field results, vector field displays mode shapes and time history graphs. The post processor can also be used for algebraic operations, database manipulators, differentiation and integration of calculated results. Response spectra may be generated from dynamic analysis. Results from various loading may be harmonically loaded axis metric structures.

3.12 MESHING:

Before meshing the model and even before building the model, it is important to think about whether a free mesh or a mapped mesh is appropriate for the analysis. A free mesh has no restrictions in terms of element shapes and has no specified pattern applied to it.

Compare to a free mesh, a mapped mesh is restricted in terms of the element shape it contains and the pattern of the mesh. A mapped area mesh contains either quadrilateral or only triangular elements, while a mapped volume mesh contains only hexahedron elements. If we want this type of mesh, we must build the geometry as series of fairly regular volumes and/or areas that can accept a mapped mesh.

3.13 STRUCTURAL STATIC ANALYSIS:

A static analysis calculates the effects of study loading conditions on a structure, while ignoring inertia and damping effects, such as those caused by time varying loads. A static analysis can however include steady inertia loads and time varying loads that can be approximated as static equivalent loads. Static analysis is used to determine the displacements, stresses, strains and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed, i.e. the loads and the structure’s responses are assumed to vary slowly with respect to time.

4. RESULTS AND DISCUSSION

4.1 WITHOUT LAYERED COMPOSITE

Meshed model

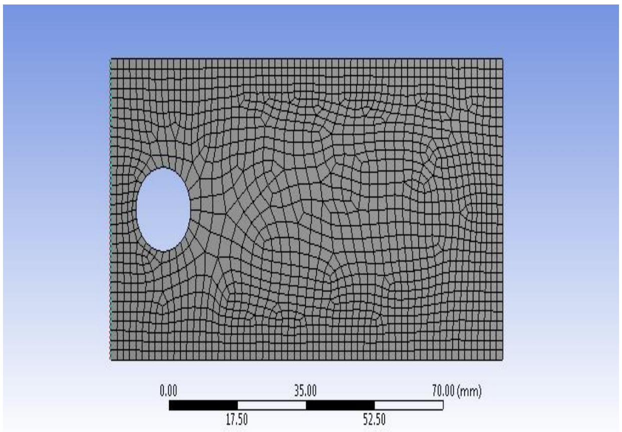


Fig 4.1 :The model is designed with the help of CATIA and then import on ANSYS for Meshing and analysis. The analysis by static approach is used in order to calculating stress profile and damage. For meshing, the fluid ring is divided into two connected volumes. Then all thickness edges are meshed with 360 intervals. A tetrahedral structure mesh is used. So the total number of nodes and elements is 3631 and 13595.

Total deformation

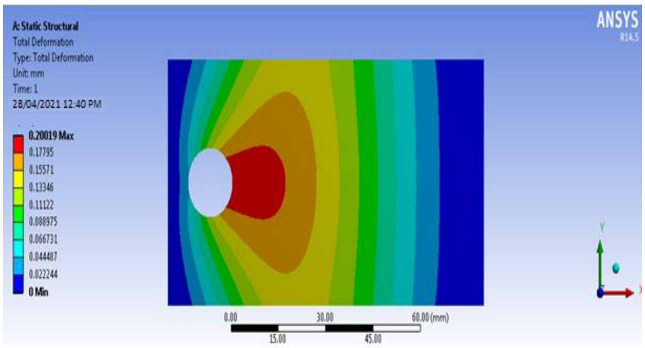


Fig 4.2 :According to the contour plot, the maximum deformation at fastener hole due to applied the loads. The maximum deformation is 0.20019mm and minimum is 0.022244 mm

Stress

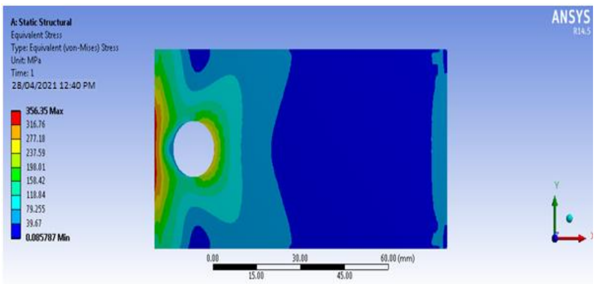


Fig 4.3 : According to the contour plot, the maximum stress at fastener hole due to applied the loads. The maximum stress is 356.35N/mm^2 and minimum is 0.085787 N/mm^2

Strain

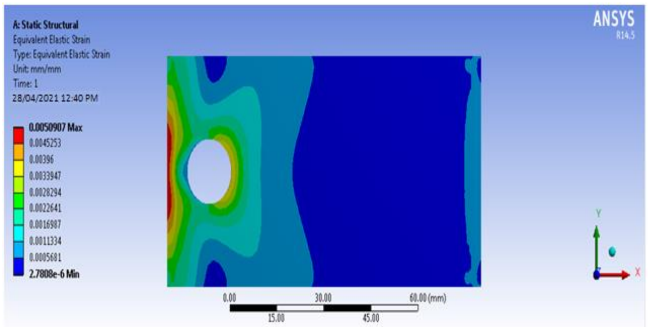


Fig 4.4 : According to the contour plot, the maximum strain at fastener hole due to applied the loads. The maximum stress is 0.005090 and minimum is 2.70e-6.

Shear stress

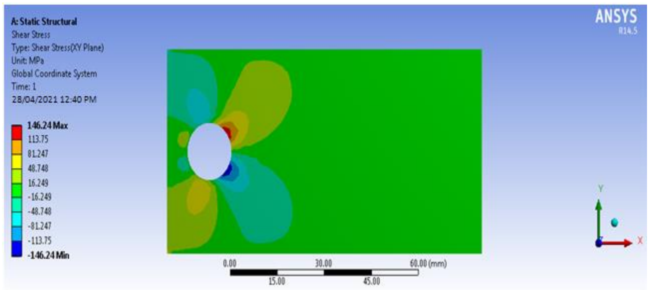


Fig 4.5 : According to the contour plot, the maximum shear stress at fastener hole due to applied the loads. The maximum shear stress is 146.24 N/mm^2 and minimum is 1.24 N/mm^2.

Life

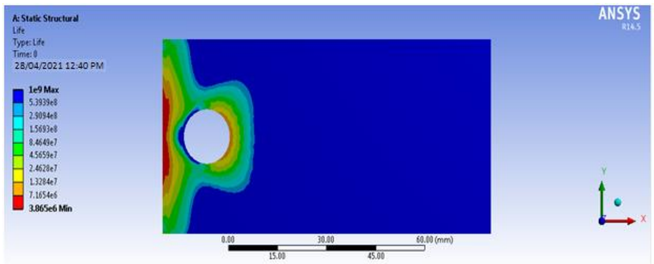


Fig 4.6 According to the plot, the maximum life at fastener hole and minimum at end of the specimen.

Damage

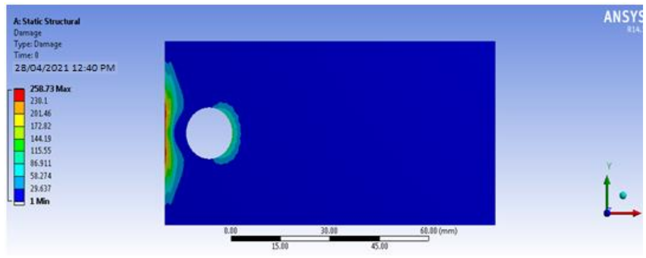
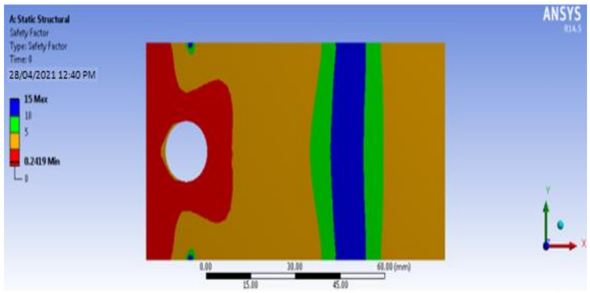


Fig 4.7 : According to the plot, the maximum damage at end of the specimen and minimum at fastener hole.

Safety factor



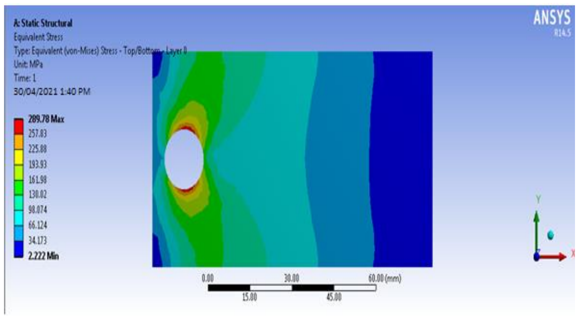
4.2 WITH LAYERED COMPOSITE

At -3 layers

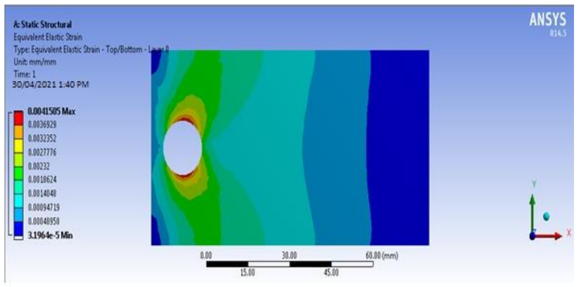
Layer	Material	Thickness (mm)	Angle (°)
(+Z)			
3	carbon fibers	2	90
2	carbon fibers	2	0
1	carbon fibers	2	-90
(-Z)			

Total deformation

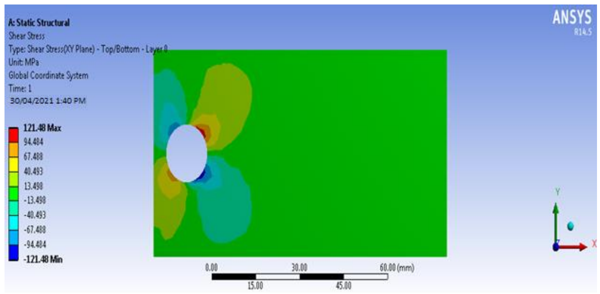
Stress



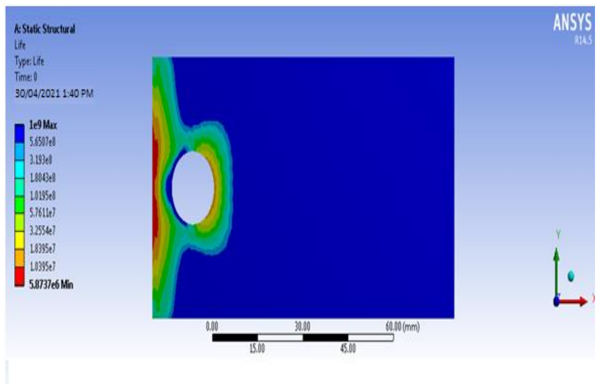
Strain



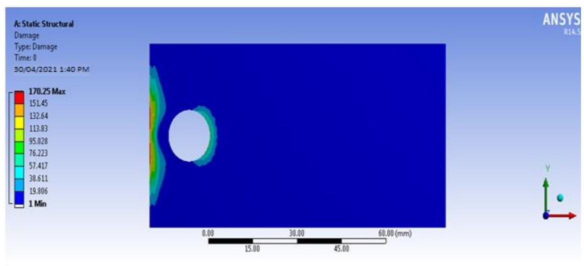
Shear stress



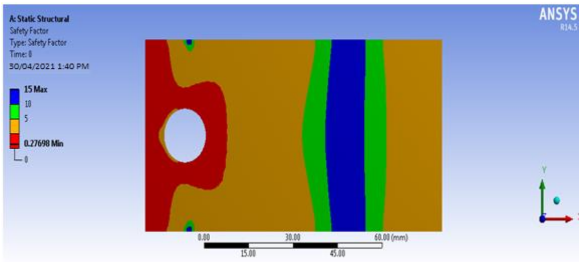
Life



Damage



Safety factor



5 RESULTS AND CONCLUSION

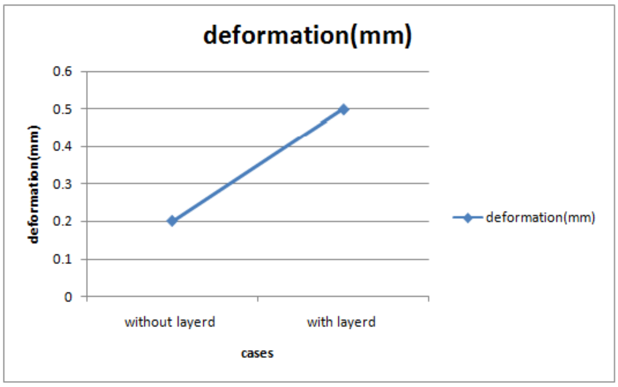


Fig 5.1 : Above plot shows, the maximum deformation versus cases such as without layered and with layered.

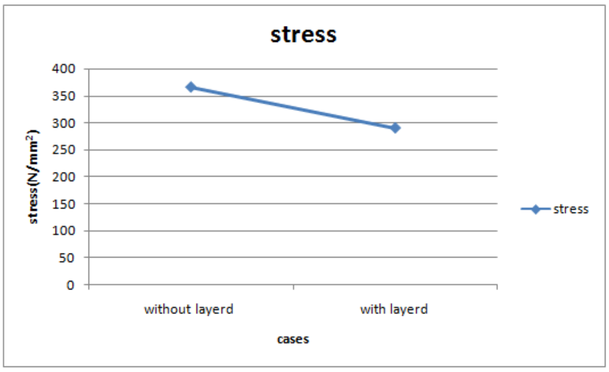


Fig 5.2 Above plot shows, the maximum stress versus cases such as without layered and with layered.

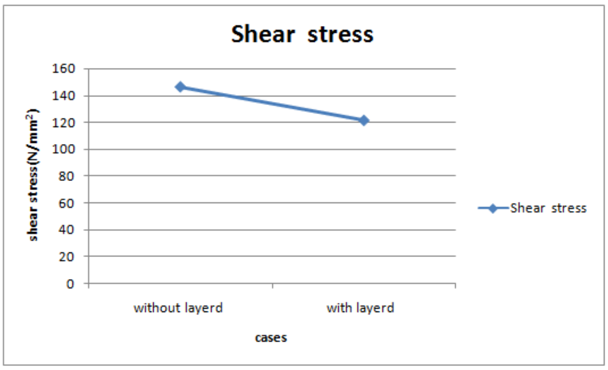


Fig 5.3 Above plot shows, the maximum shear stress versus cases such as without layered and with layered.

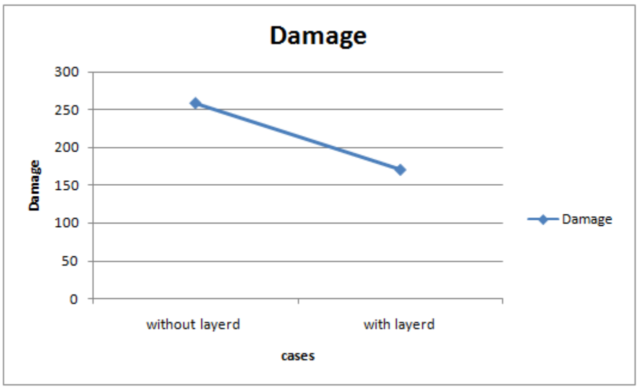


Fig 5.4 : Above plot shows, the maximum damage versus cases such as without layered and with layered.

In this work a numerical study on the failure load and failure mode investigations of pin loaded composite joints are presented. Special attention is paid to failure load and mode analyses in composites with stacking sequence [0/ ± 90]s. For the verification of the proposed FEA, composite laminated joints with layered and without layered composite structure. It can be seen that the results obtained analytically.

By observing the static analysis results, the stress and shear values are less at layered composite structure fastener hole.

By observing the fatigue analysis results, the damage values are less at layered composite structure fastener hole.

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