Effect of in-plane fiber tow waviness in the strength characteristics of different fiber reinforced composites

EFFECT OF IN-PLANE FIBER TOW WAVINESS IN THE STRENGTH CHARACTERISTICS OF DIFFERENT FIBER REINFORCED COMPOSITES

A Thesis by

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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Mechanical Engineering.

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Rajeev Madhavannair, Committee Chair

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Ramazan Asmatulu, Committee Member

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Krishna Krishnan, Committee Member

DEDICATION

To my Loving Parents & Friends

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ABSTRACT

The purpose of this study was to investigate the strength and effectiveness of certain composite materials when induced by 'in-plane fiber tow waviness' in a composite ply. Fiber waviness is usually induced by infusion processes and inherent in fabric architectures. Composite structural details like ply drops and ply joints can cause serious fiber misalignment. These are usually dependent on parameters such as ply thickness, percentage of plies dropped, and location of ply drop, the gap between the plies, mold geometry and pressure, and pressure of the resin which slides the dry fibers during the resin transfer molding process. Fiber disorientation due to fiber tow waviness in „in-plane“ direction has been the subject of recent studies on wind turbine blade materials and other aerospace laminates with reports of compression strengths and failure strains that are borderline, depending upon the reinforcement architecture, matrix resin and environment. Waviness is expected to reduce compressive strength due to two primary factors. The fibers may be oriented in such a way that the geometry that results because of the orientation may exacerbate the basic fiber, strand, or layer buckling mode of failure. The waviness could also shift the fiber orientation of the axis of the ply longitudinal direction which eventually results in matrix dominated failures for plies normally orientated in the primary load direction (0^0). The longitudinal tension and compression behavior of unidirectional carbon fiber composite laminates of different materials (different grades of carbon, glass and Kevlar with different resins) were investigated using finite element analysis tool ABAQUS. Both global and local stress & strain values generated by the finite element model were validated by the traditional mechanical methods using ply/local stiffness matrix and global/reduced stiffness matrix. A precise geometry of waviness on different materials was modeled with different wave severity factor and a parametric study was conducted. Three different defects were modeled where the angle of misalignment ranged from 5 to 15 degrees with a wavelength ranged from 1 inch to 1.5 inches and amplitude which ranged from 0.05 inches to 0.1 inches. This revealed the effect of 'in-plane fiber tow waviness' on the stress distribution and loss of strength in carbon-reinforced composite materials. The results clearly show that the effect of 'in-plane fiber tow waviness' leads to resin rich areas which causes high stress concentrations and decrease in the strength ratio, leading to delamination's.

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CHAPTER 1

INTRODUCTION

1.1 Background

Composite materials are mostly used in Aerospace Structures until recently. Today these materials are used widely in other fields such as automotive, energy, turbine blades. Manufacturing of the composite materials is a difficult tasks to main the quality standards. There are many defects induced during the process of manufacturing of the composite panel. Most of the defects are due to a mismatch of coefficient of thermal expansion, improper fiber volume fraction, void contents, fiber misalignments or fiber waviness. For quite some time now, researchers have been trying to improve the manufacturing systems. Several fields of engineering evolved due to the efforts made into better usage, new advanced materials, and high precision manufacturing process.

For minimal fuel usage and to reduce weight every airplane manufactures utilize composites with varying degress. There is a huge gain in achieving the tailored properties by using composites and therefore manufacturing a defect-free composite is also becoming a challenging task. There are few major defects like delamination, porosity, resin rich areas, and voids which still cause for some concern.

Tow waviness can be unintentionally induced in a uni-directional dry carbon ply during the manufacturing process. This unintentionally induced waviness can be categorized into two types. The first one is in-plane waviness and the other is out-of plane waviness. In-plane waviness is a kind of fiber tow waviness which is induced within the lamina, where the fiber direction deviates from 0º to other angles at a particular location or throughout the lamina. Out of plane waviness is a kind of waviness which is induced through the plies in the thickness direction. In this thesis, we are concerned about the in-plane tow waviness and their severity in reducing the overall strength of the composites.

In-plane fiber waviness can be categorized mainly into two types, one is normal waviness which carries the wavy pattern through he lamina. This could occur due to the poor binder failure along the width of the lamina. The other type of in-plane waviness is called localized waviness. Here the tow will not only misaligned to their preferred direction, but also creates the resin rich packets which leads to uneven volume fraction in a composite structure. These are highly sensitive to the load, and creates the high stress near and around the resin rich areas.The Unidirectional dry carbon fiber ply is shown in the below figure 1.1.

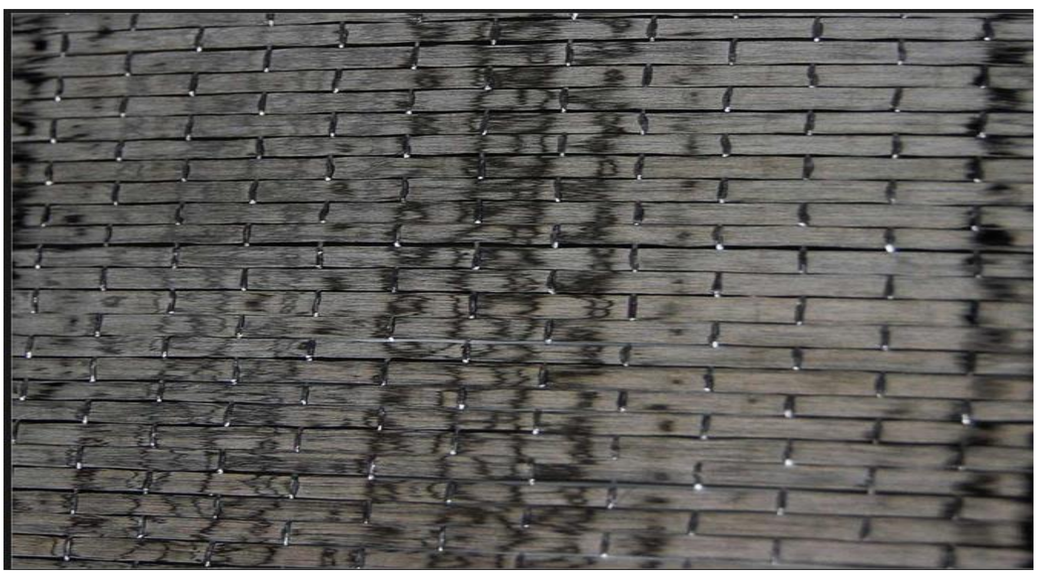


Figure1.1 Unidirectional Dry carbon fiber ply

The properties of the composite materials depend on the material properties which are used to make composite laminates and the distribution of the materials. The most important properties of the composite materials are its mechanical properties. The materials that are selected to make the composite panel should satisfy the application that usually requires strength, shape and rigidity. The mechanical properties of the composites can be predicted using the Rule of Mixture.

1.2 Literature Review

Fiber waviness received its attention over the past years. Most of the researches are concerned about the fiber waviness in unidirectional laminates while there is a less research on the in-plane waviness.

The first study was carried out by Rosen [1] on prediction of compressive strength of the laminate during micro bucking. He considered the kinking and buckling condition of the fibers inside the laminate and predicted the strength of the composite laminate during compression. Hsiao and Daniel [2] studied the effect of fiber waviness on stiffness and strength reduction in unidirectional composites under compressive loading conditions. The research primarily focused on the fiber waviness patterns which are generally found in the laminates.

Garnich and Karami [3] investigated the fiber waviness in the composite panel in a computational method. They considered the micro mechanical model of fiber and matrix unit cell as shown in the figure 1.2. The effect of stress in the wavy laminate was studied by considering several failure predictions. The stress distribution and its effects in the wavy laminate during axial loading and fiber waviness influence on the predictions for the failure, is also studied.

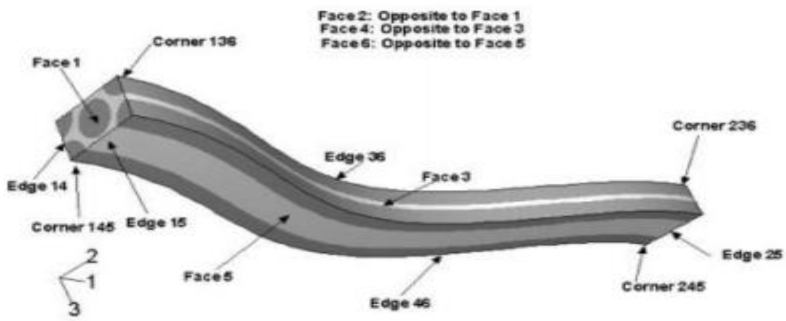


Figure.1.2 Micromechanical model used to study fiber waviness [3]

Lei Wang [4] identified the effects of in-plane fiber waviness on the static and fatigue strength of the fiberglass. They investigated the fiber failure and delamination‟s in a composite material when induced with in-plane waviness during tension. From this study, it was concluded that in-plane waviness causes a drastic strength reduction. As the severity of the waviness increases, there is a greater dropdown of the strength. The laminates with one surface and four layers of in-plane waviness are shown in figure 1.2.

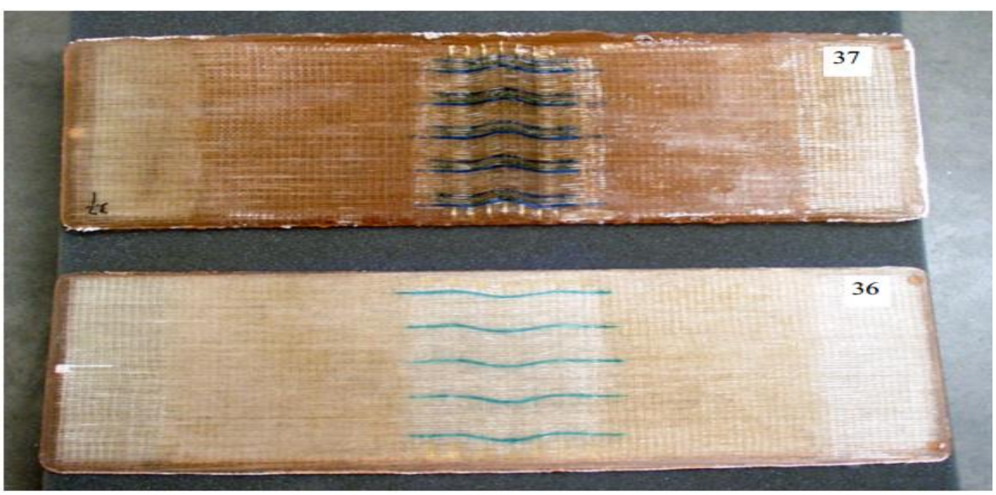


Figure 1.3 Laminates with In-plane Waviness [4]

Chun and Daniel [5] investigated the response of the laminated composites during tension and compression. They focused on the graded, uniform and local fiber waviness patterns which are found commonly in the laminates. The young‟s modulus along the longitudinal direction was found to be reduced as shown by the analytical model. It was also shown that the strength of the laminate will be gets influenced by the degree of fiber waviness, wavy fibers getting softened by the compressive loads and getting stiffer by the tensile loads. A recent study conducted by Joyce and Moon [6] focused on the effect of in plane fiber waviness in the strength reduction. They found that due to the fiber waviness, there is significant strength reduction and subsequent failure of the composite laminates due to the stress concentration factors that are developed near the tabbed region.

Kugler and Moon [7] investigated and found out the fiber waviness which is caused by the manufacturing and processing methods. They investigated the processing parameters like temperature at which the composite is gets cured, time duration of the curing process of composite laminates and external pressure that is applied on the surface of the composite during the curing process. The rate of sudden cooling the composite laminate undergoes after curing and the tool plate material which is used to layup the composite also leads to the fiber waviness. The mismatch of the thermal coefficient between the tool plate and the laminate composite was found to be the one of the potential reasons for the fiber waviness. Figure 1.3 shows the possible cases for the fiber waviness.

Nurhaniza, et al. [24] have studied the tensile test simulation for Carbon and Galss Reinforced materials using the finite element analysis tool Abaqus.

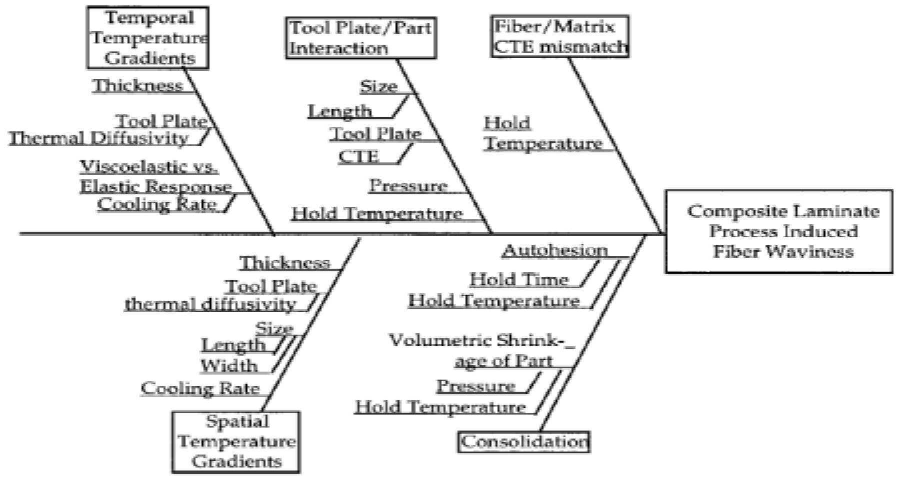


Figure 1.4 Potential causes for the fiber waviness during the manufacturing process [7]

Bogetti and Gillespie [8,9] have developed an analytical model in order to predict the effects of fiber waviness in a cross ply laminate which is shown in the figure1.5. The model was developed to predict the effect of waviness in the strength reduction and the stiffness in a composite laminate. The basis of their study to evaluate the structural response of the composite cylinder which is made with cross ply laminate during construction.

Martinez [10] studied the effects of misalignments in a fiber on the compression strength of composites by using glass/polyester laminate specimen. Misalignment of the fiber was introduced by the twisting of the fiber tows at a certain amount before the impregnation of the resin. It showed a reduction in the compressive strength with a misalignment angle which is greater than 10º for both carbon and glass fibers.

Mrse and Piggott [11] studied the effect of intentional and unintentional misalignments of the fiber on the compressive properties of unidirectional laminates. They considered unidirectional carbon fiber laminate for their study were unidirectional carbon fibers are made with AS4 carbon and reinforced with Polyether ether ketone (PEEK) prepreg which had been crimped to various degrees to change the waviness in the fiber. A Microscope was used to measure the wavelength and amplitude of the misaligned fibers and compressive strength and compressive modulus is correlated. Mandell and Samborsky [12,13] conducted research on fabric weave composite structures and found that the compressive strength of the composite reduced because of the through thickness waviness of the fibers, the tensile strength of the laminate remained high.

Poe, et al [14, 15] conducted tensile strength analysis on thick composite material which is filament wound carbon fiber solid rocket case of a motor that experienced low-velocity impact. They investigated the tensile strength of the damaged composite panel and found that it lead to a reduction of 39 % strength reduction than was expected. It was concluded that the strength of the composite laminate got reduced due to the fiber waviness in one of the plies, which got induced unintentionally during the manufacturing process.

Kar,et al. [16] did research on fractographic and microstructural examination of composites which are tested in compression. Their research shows that the resin rich areas will increase the moisture absorption and the fiber distribution inside the composite gets uneven which ultimately weakens the composite material.

Nirbhay, et al. [23] have developed 3D models to establish the simulation of composite specimens during a tensile test. This study enabled the understanding the strength of composites using finite element tool abaqus.

1.3 Objectives

The main objective of this thesis is to study the effect of in-plane fiber tow waviness and resign rich area in a composite ply and laminate, with different material systems and stacking sequence. Some more specific objectivies are mentioned below.

- To investigate the effect of minor, major and severe fiber tow waviness defects on the reduction of the strength of composite laminas of AS4/3501-6, IM7/977-3, Glass/Epoxy, and Kevlar/Epoxy.
- Validating the Abaqus® results with the equations used in mechanics materials approach.
- Calculating the first ply failure load along with the defects using Abaqus®
- Conducting a parametric study of the decrease in load carrying capacity in different material systems with the minor, major and severe fiber tow waviness defects within the lamina, cross ply laminate and angle ply laminate.
- Predicting the reduced strength ratio of the lamina and laminate with three different types of defects using the finite element analysis tool Abaqus®.

1.4 Methodology

The methodology used to investigate the effect of fiber waviness is shown in figure 1.5. The composite single ply is built using the finite element analysis tool Abaqus®. A composite lamina is a combination of a bunch of tows which are grouped together using binder threads. Tow is defined as a bunch of untwisted fiber filaments. Composite lamina is made out of combining the tows together, which includes resin that is impregnated with a defined volume fraction in each of the carbon/glass/kevlar material.

Fourteen tows are combined together to form a composite lamina, where the width and thickness of the each tow is considered as 0.07 inches and 0.0078 inches. The total width and thickness of the laminas are 0.98 inches and 0.0078 inches respectiviely.

Resin rich location is created by misaligning one of the following tows. The location of the resin rich area is modeled so that it is at the center of the composite lamina. The fiber waviness will be followed by the corresponding tows and depending on the angle of the wave the corresponding wavy tows gets terminated along the width of the lamina.

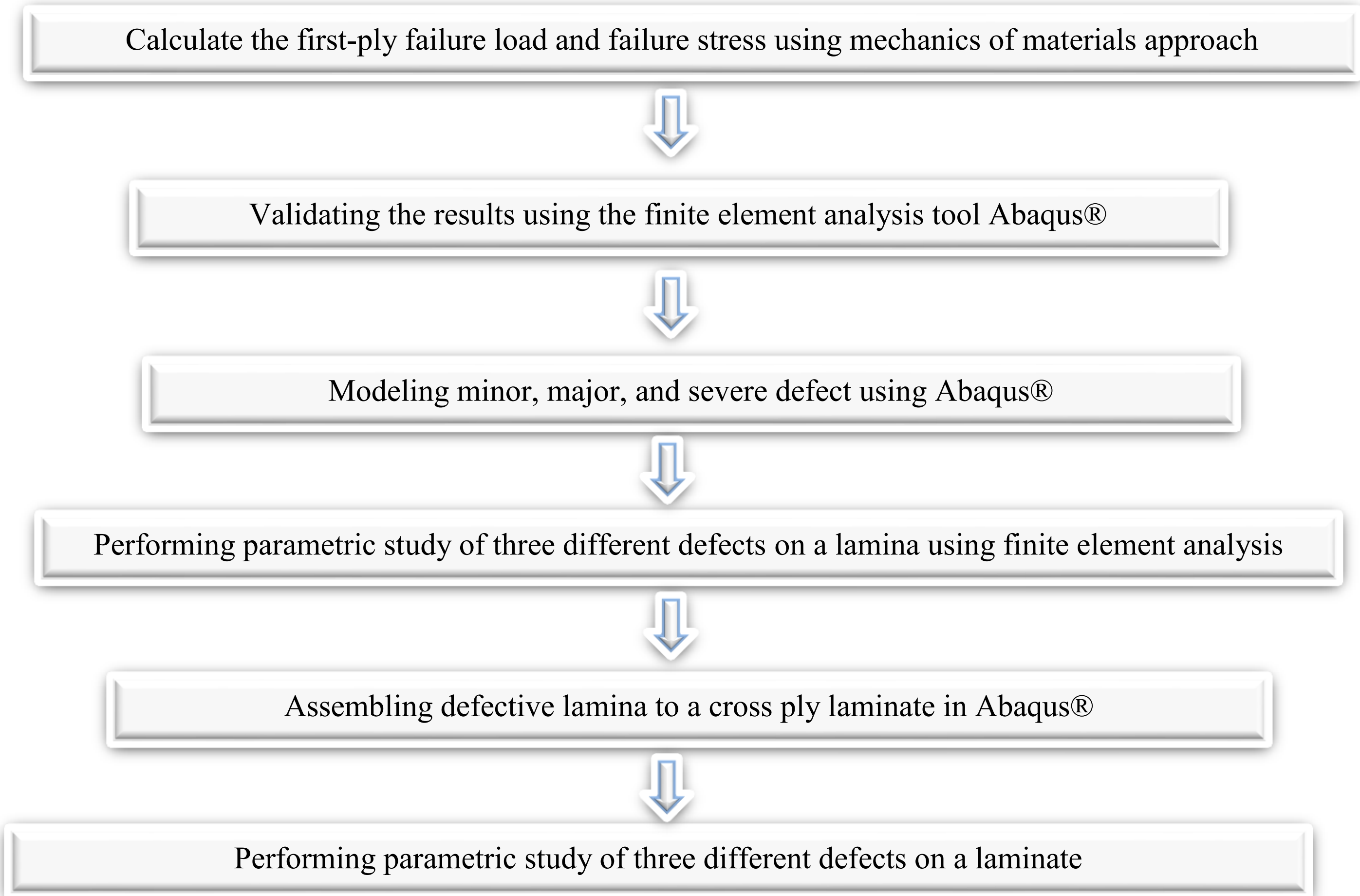


Figure 1.5 Methodology

CHAPTER-2

THEORETICAL FRAME WORK

2.1 Basic assumptions to simplify the approach of mechanics of materials

Few assumptions are considered to simplify the mechanics of materials approach in describring the interaction between fiber and matrix during tension and compression.

1. Fibers inside the composite lamina or laminate should be evenly distributed without any misalignments and uneven distribution [17].

2. There should be a fiber bonding between the fibers and the matrix.

3. During the process of layup or after the process the composite laminate should be free of voids.

4. The force that is applied on a laminate should be along the direction of the fibers.

5. There shouldn"t be any prior residual stress developed in the fibers and the matrix

6. Both the fiber and the matrix should be satisfying the linear elastic material relation.

2.2 Longitudinal tension

In the specific case of application of a longitudinal tensile load, this results in load acting parallel to the direction of the fibers. Considering there is a perfect bonding between the fiber and the matrix, the strain of the composite is equal to the strain of the fiber and the matrix.

$$\varepsilon_f = \varepsilon_m = \varepsilon_c \tag{2.1}$$

ε_f = longitudinal strains in fibers , ε_m = longitudinal strains in matrix, ε_c =longitudinal strains in composite

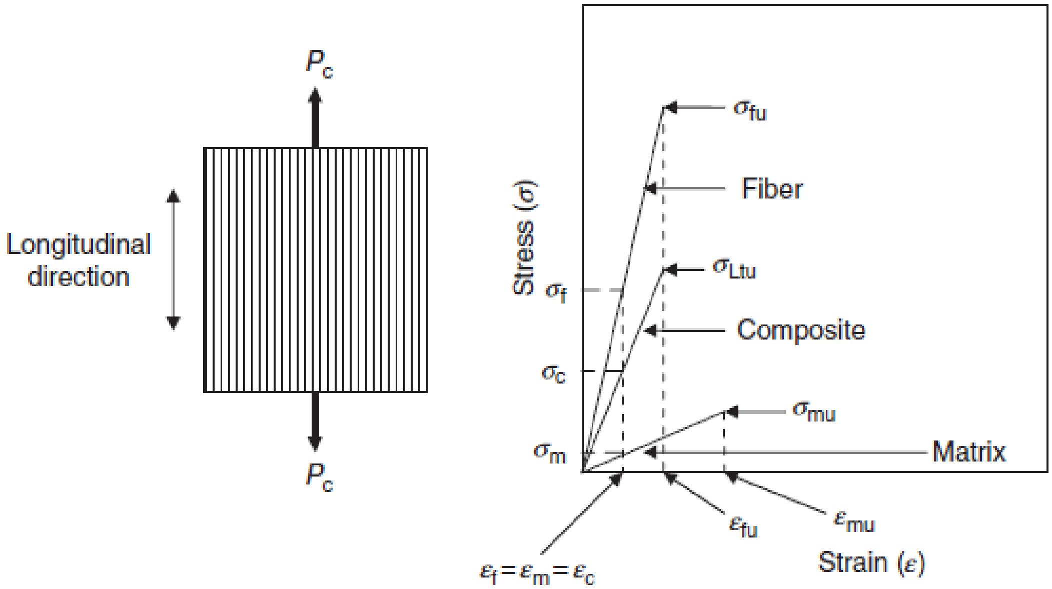


Figure: 2.1 Longitudinal tensile loading of a unidirectional continuous fiber lamina [17]

Since the two constituent fiber and matrix in the composites are elastic the longitudinal stress can be calculated as

$$\sigma_f = E_f \varepsilon_f = E_f \varepsilon_c \tag{2.2}$$

$$\sigma_m = E_m \varepsilon_m = E_m \varepsilon_c \tag{2.3}$$

The tensile force applied on the composite will be shared by the fiber and the matrix as shown in the equation below.

$$P_c = P_f + P_m \tag{2.4}$$

Equation 2.4 can be written as $\sigma_c A_c = \sigma_f A_f + \sigma_m A_m$ (2.5)

σ_c = Average tensile stress, A_c = cross-sectional area of the composite, A_m = cross-sectional area of the matix, A_f= Cross-sectional area of the fibers.

2.3 Stresses in each ply of a laminate

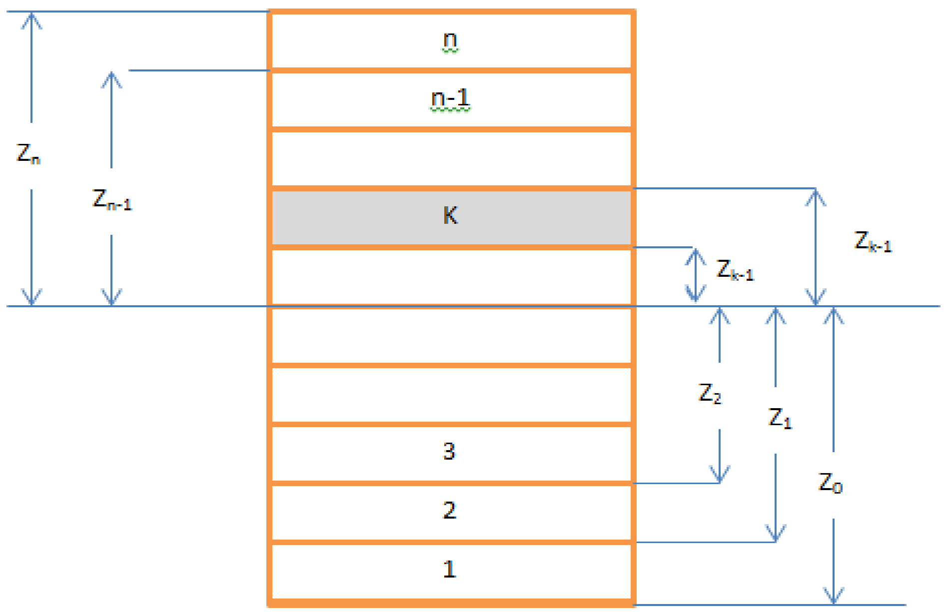


Figure 2.2 Lamina numbering and distance from the mid-plane

For the laminate analysis, we should need the distance of each ply from the mid plane. Distance of a lamina from the mid-plane is expressed by considering the top and bottom of each ply. If we need to analyze any one of the ply, for example K_{th} ply, it could be assumed anywhere between the plys. Z_n always represents the distance of mid plane to top of the ply which is nth ply. Z_1 represents the distance between the mid plane and top surface of the first ply which is counted from bottom. On the other hand Z_{n-1} would be the distance between the mid plane and bottom of the nth ply. The value of Z_0 is always considered as negative, which is always below the mid plane. Similarly Z_n will always be positive value and is equal to the one half of the total thickness of the laminate.

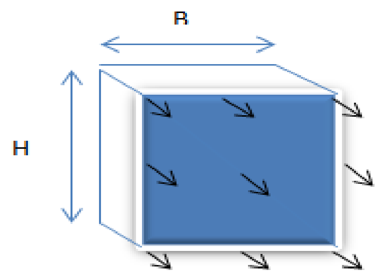


Figure: 2.3 Prismatic membrane with uniformly distributed loading

Let us consider the cross-section of a prismatic membrane of a lamina. There is a uniform distribution of stress on the cross-section as shown in figure 2.3. H is the height and B is the width. The magnitude of this distributed load is P, which contains units of Pounds/inch^2, N/m^2 or Pascal. To find the resultant of this prismatic member it is enough to multiply the distributed loading by the area of the member where loading is taking place. This gives the resultant force along the x direction which is represented as P *H * B which has units of force. Instead of multiplying the load with area if we multiply the depth, we get running load or a line load , (P *H) which contains units of force/length.

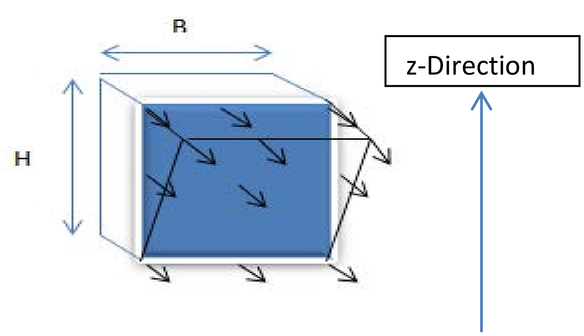


Figure: 2.4 Prismatic membrane with un-uniformly distributed load

Let us consider that the loading on the surface of the prismatic membrane is non-uniform. We can still deduce a resultant force P that various along Z direction P (Z) through the thickness H as shown in the figure 2.4. That we also come up with resultant line load, using the equation $\int_{-H/2}^{H/2} P(z)dz$. This equation applies whether it is a linearly applied load or a non-linearly applied load. Because loading is variable across the depth of membrane we not only have resultant line load, but also experience the resultant moment.

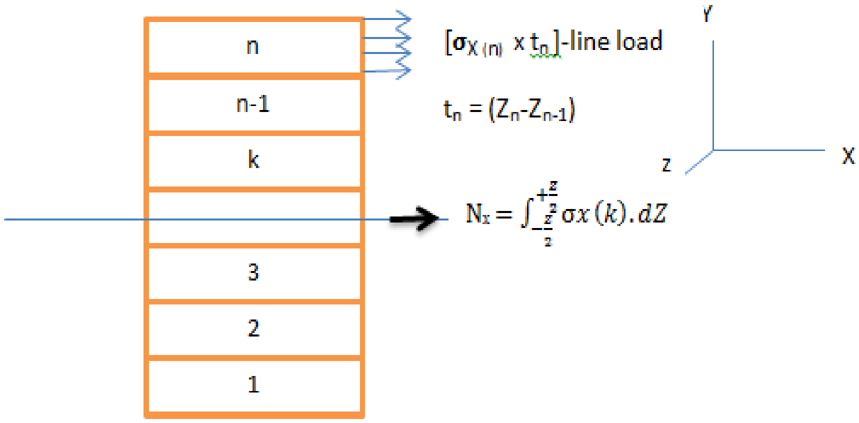


Figure: 2.5 Ply stresses and ply Resultants

Normal stress acting on the surface of any ply will be $\boldsymbol{\sigma}_x$. $\boldsymbol{\sigma}_x$ is uniform over any given ply ,but the values may differ corresponding to the surrounding plys. The value of stresses can change from ply to ply. We can always construe a resultant line load due to the distributed loading over individual plys. The resultant of the entire laminate will give the running load N_x. If the stresses are uniform over all the plies we can use the equation $\sum_{k=1}^{n} \sigma_{x_{(k)}} X\ t_k$.The units of Nx will be the units of pounds/inch or N/m. Similarly, if we consider $\boldsymbol{\sigma}_z$ along the z direction in each ply and take the resultant of all the plys it gives a resultant running load N_z. Along with the normal stresses, shear stress $\boldsymbol{\sigma}_s$ will be developed in each lamina as shown in figure 2.6

This causes the resultant of entire laminate to be the running load of $N_{s.}$ or $N_{xy.}$ Whenever there is a non- uniform stress distribution in addition to resultant force, we also have resultant moments M_x,M_y, $Ms_.$

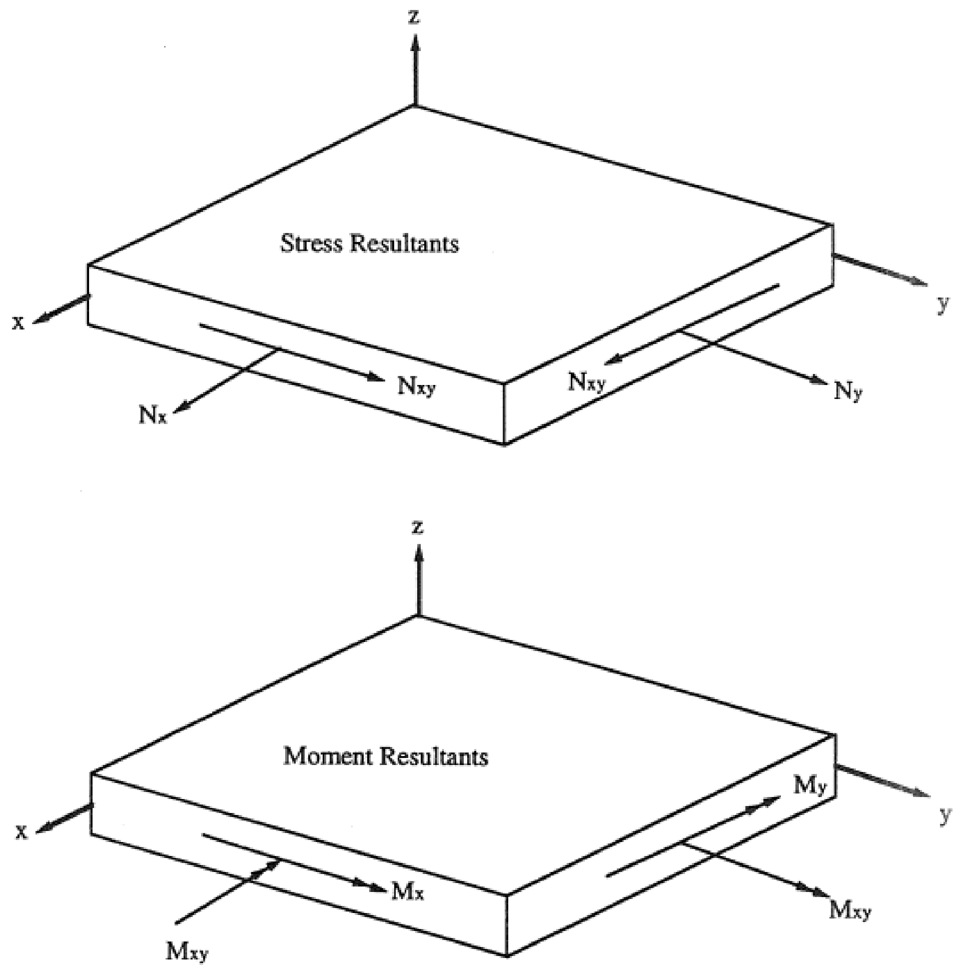


Figure 2.6 Stress resultants and Moment resultants [18]

In this study stresses developed in each ply will be calculated using the mechanics of materials approach. For the cross ply laminae classical lamination plate theory [19], is used to find the stresses in each ply of the laminate.

$$\begin{Bmatrix} N \\ M \end{Bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon_{xy}^0 \\ k_{xy} \end{Bmatrix}$$

.... (1)

In this research study we are concerned about balance and symmetric laminate because of non existence of coupling between the components, i.e $[B_{ij}]$ = 0. Since a uniaxial tension load is applied on the laminate, no bending and twisting moments are applied in our study. Hence the above matrix gets reduced.

$$[N] = [A]\ [\varepsilon_{xy}^0] \qquad \text{.. (2)}$$

Where N = Forces per Unit Length, ε_{xy}^0= Midplane Strains

The In-plane stiffness matrix [A] for entire laminate can be expanded as below

$$\begin{bmatrix} Nx \\ Ny \\ Ns \end{bmatrix} = \begin{bmatrix} A_{xx} & A_{xy} & A_{xs} \\ A_{xy} & A_{yy} & A_{ys} \\ A_{xs} & A_{ys} & A_{ss} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \Upsilon_s^0 \end{bmatrix} \qquad \text{..(3)}$$

$$N_x = (N_x)_1 + (N_x)_2 + (N_x)_3 + \ldots\ldots\ldots + (N_x)_n \qquad \text{...(4)}$$

$$N_x = (\sigma_x)_1(h_1 - h_0) + (\sigma_x)_2(h_2 - h_1) + (\sigma_x)_3(h_3 - h_2) + \ldots + (\sigma_x)_n(h_n - h_{n-1}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{..(5)}$$

Where h_1 = Distance between midplane and top surface of the bottom ply

h_0 = Distance between midplane and bottom surface of the bottom ply

$h_1 - h_0 = t_1$=Thickness of ply 1, t_k = Thickness of Kth ply

$$N_x = [Q_{xx} \quad Q_{xy} \quad Q_{xs}]_1 \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} t_1 + [Q_{xx} \quad Q_{xy} \quad Q_{xs}]_2 \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} t_2 + \ldots\ldots + [Q_{xx} \quad Q_{xy} \quad Q_{xs}]_n \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} t_n \text{......(6)}$$

$$N_x = \sum_{k=1}^{n} t_k \quad [Q_{xx} \quad Q_{xy} \quad Q_{xs}]_k \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{..(7)}$$

Similarly

$$N_y = \sum_{k=1}^{n} t_k \begin{bmatrix} Q_{xy} & Q_{yy} & Q_{ys} \end{bmatrix}_k \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} \quad \& \quad N_s = \sum_{k=1}^{n} t_k \begin{bmatrix} Q_{xs} & Q_{ys} & Q_{ss} \end{bmatrix}_k \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix}$$

The above three in-plane forces can be combined as below

$$\begin{bmatrix} N_x \\ N_y \\ N_s \end{bmatrix} = \sum_{k-1}^{n} \begin{bmatrix} Q_{xx} & Q_{xy} & Q_{xs} \\ Q_{xy} & Q_{yy} & Q_{ys} \\ Q_{xs} & Q_{ys} & Q_{ss} \end{bmatrix}_k \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} t_k = \begin{bmatrix} A_{xx} & A_{xy} & A_{xs} \\ A_{xy} & A_{yy} & A_{ys} \\ A_{xs} & A_{ys} & A_{ss} \end{bmatrix} \begin{bmatrix} \varepsilon_x^o \\ \varepsilon_y^o \\ \gamma_s^o \end{bmatrix} \quad \text{.........................(8)}$$

2.4 Failure modes of unidirectional composites during tension

The fiber strength throughout the composite will not be exactly same; strength may change from location to location within the composite structure [22].During the failure of the fibers, matrix takes the load from the failed fiber and transmits that load to the surrounding fibers along with the broken fibers.

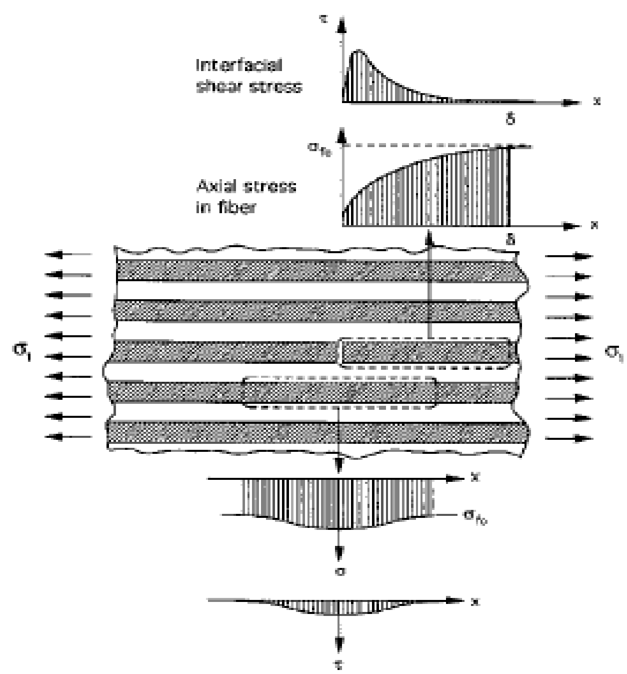
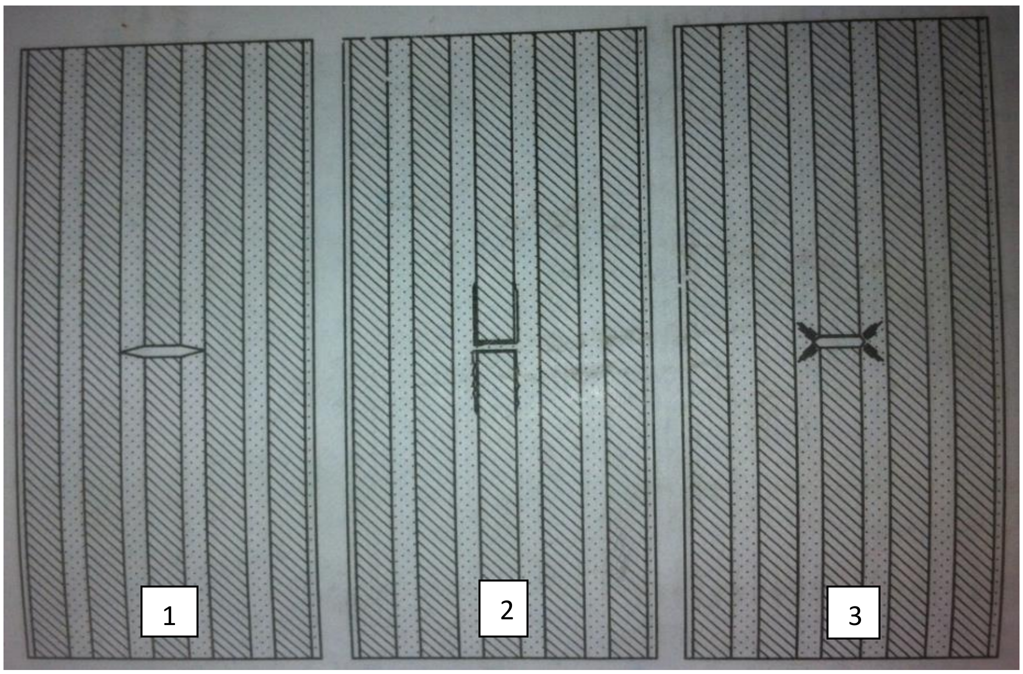


Figure 2.7 Stress distribution around the fiber break in a unidirectional composite under longitudinal tension [22]

Depending on the fiber and matrix material the fiber failure in the composite material produces different failure types as shown in figure 2.3.

1) The matrix material gets cracked transversely due to the brittle matrix and a strong interface.
2) Deboning between the fiber and the matrix due to the poor interface.
3) Conical shear fracture in matrix due to a ductile matrix and a strong interface



Transverse Debonding Conical shear

Figure 2.8 Failure mechanics around the fiber during failure [22]

2.5 Failure Criteria

„Max Stress" failure criteria is more applicable to this analysis. In the max. stress failure theory four independent failure modes are considered. The assumptions that these failure modes will not interact with each other. The representation of max stress theory is shown in figure 3 [20] below.

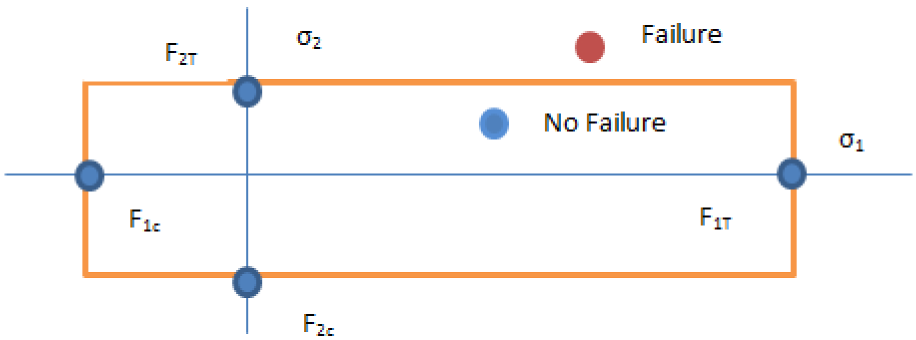


Figure: 2.9 Schematic representation of max stress theory

According to the max. Stress theory the failure occurs when at least one stress component along one of its principle material axes exceeds the corresponding strength in that direction.

F_{2T} – Failure in transverse tension

F_{2C} -Failure in transverse compression

F_{1C} -Failure in longitudinal compression

F_{1T} - Failure in longitudinal Tension

CHAPTER 3

EXPERIMENTAL STUDY

3.1 Wet lay-up Process

During the resin transfer molding several layers of dry fiber mats are arranged at the bottom half of the mold and the resin is injected through a spur which is placed on the top of the mold.The resin enters into the mold and spreads throughout the mold which fills space between the fiber yarns[17]. By this process entrapped air gets displaced through the air vents. Depending on the type of resin system used, curing takes place either at room temperature or in an oven. The Final cured part can be trimmed out as per requirements. The quality of the composite depends on the resin flow through the dry fibers. The potential problems encountered during the Resin Transfer Molding is incomplete filling of the resin, Non-Uniform resin distribution, void formation and improper curing temperature. A good flow of resin should be maintained in order to reduce the void content in the laminate. Fiber misalignment can be caused during the infusion of liquid resin into the mold, this type of defects happens, especially if the viscosity of the resin gets higher before it enters into a mold.The figure below shows the setup that was used for the wet layup process.

Figure 3.1: Setup of Vaccum Bagging for Wet lay-up Process

In our experimental approach, an attempt was made to disturb the fiber orientations manually. This approach would emulate the real case scenario of fibers being disturbed by the high viscosity of the resin. There were inconsistencies in the wet lay-up process like controllability and repeatability of the volume fraction of the fibers and resin accurately between laminate to laminate. The mechanical properties were varied laminate to laminate. This became a challenging problem because of difficulties in comparing the strengths of defective and non defective laminates. So, to simplify the analysis process and track the severity of the defect, finite element modeling technique was used in this study on carbon, glass, kevlar with different severities of waviness in the fiber. The porosity of the composite panel was measured to be more than 2%. The main cause for the high porosity is the lay-up process. A perfect and repeatable method is required to improve the wetlayup process, so as to get consistent volume fractions of the fiber and matrix without any porosity.

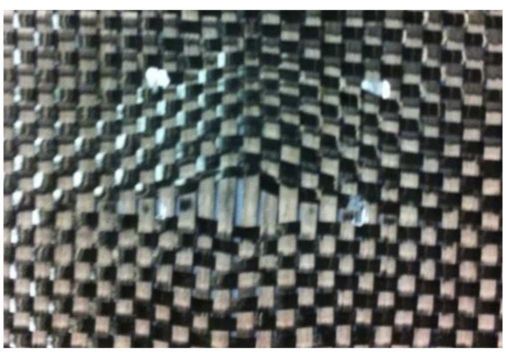


Figure 3.2: Single ply with misalligned tows

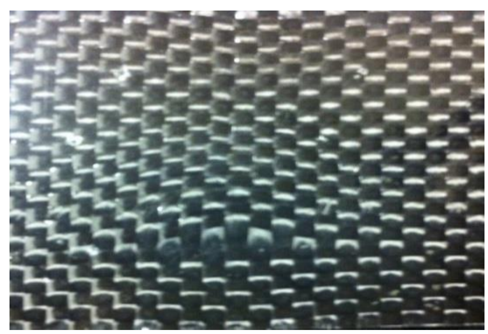


Figure 3.3: Fiber tow waviness on a plain weave laminate

3.2 Combine Loading Compression

Combine loading compression test was carried out to test the compression strength of the laminate. ASTM 6641 Standard was used to test the compression strength of the composite laminate . The dimensions of the test coupons were 140mm in the length and 12mm in width. A prease and accurate test coupons are be required in order for the coupons to fit the slot in the combine loading compression fixture as shown in the figure below.

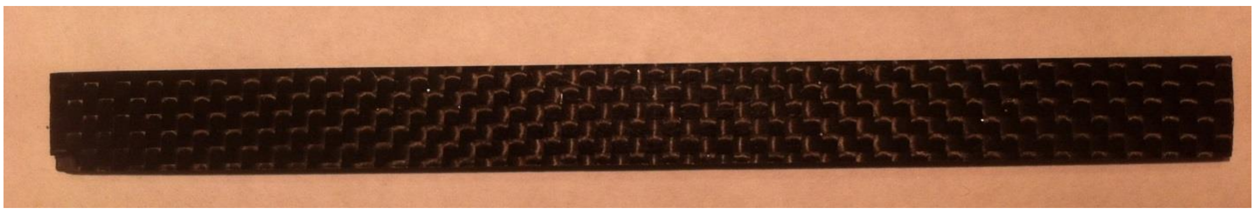


Figure 3.4 Coupon for the combine loading compression test

Figure 3.5 Defective coupon for the combine loading compression test

The test coupons are loaded into the fixture and bolted tightly to prevent slippage from the grips as shown in the figure below. The combine loading compression fixture is placed between the two platens , the bottom plate is fixed and the top plate is free to apply the load. The cross head is moved downwards to compress the fixture at a rate of 0.05 in/min. The material will resist the load and it fails at the weakest location. In our case, inplane fiber waviness is the point of the weakest loaction, but due to uneven thickness variation and improper machining all the coupons failed at the grips. To get the test results perfectly with out any flaws, sophisticated machinery should be used for the wet layup process and machining. This failure is due to improper precision in cutting the test coupons and uneven thickness of the coupons for both plain and defective cases. The failure locations of the test coupons are near grips and therefore the results are not recorded consistently during the combine loading compression test.

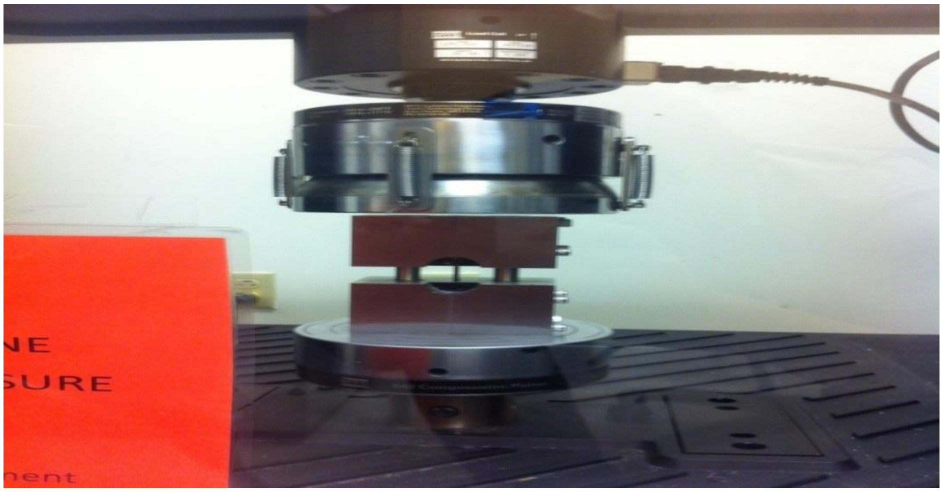


Figure 3.6 Experimental set up for combine loading compression

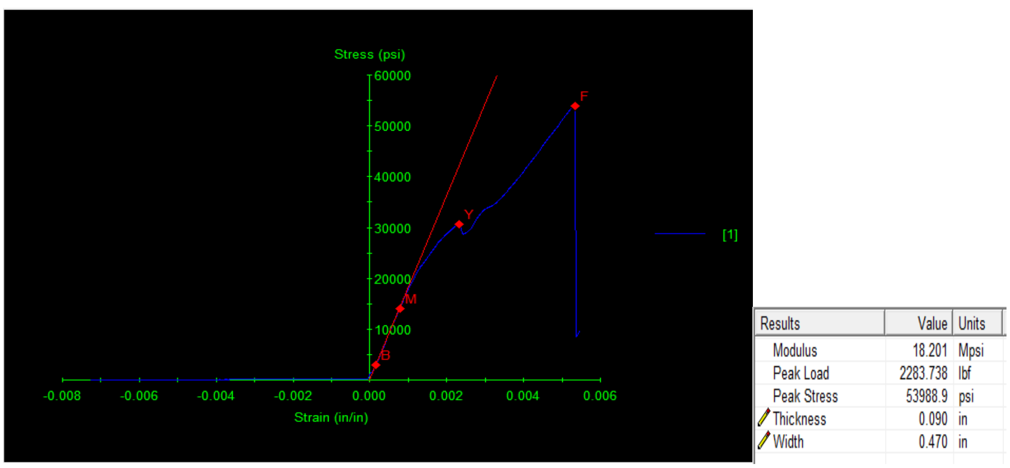


Figure 3.7 Stress vs strain plot

The compression strength results had variations due to the above mentioned irregularities in the coupons. Proper care need to taken in manufacturing and machining process to overcome this. The repeatability of the volume fractions cannot be achieved using a manual wet lay-up process. Intensive expertise manufaturing and machining process need to be followed in order to get consistent results.

CHAPTER-4

FINITE ELEMENT MODELLING AND ANALSIS OF A DEFECTIVE LAMINA

The main objective of this study is to analyze the effect of fiber waviness and resin rich areas in the strength of the single lamina and a laminate in tension using finite element analysis (FEA). The core research area is the study of magnitude and stress concentration on a lamina and laminate at the location of the fiber waviness and the resin rich areas. A comparative FEA analysis is used to study the three types of defects which are minor, major and severe. The analysis was carried out on single lamina with two grades of carbon and epoxy materials, glass/epoxy and kevlar/epoxy.

A three dimensional finite element model was built using the Abaqus tool to perform the structural analysis during tensile loading. The purpose of this study is to predict the load carrying capability of the composite lamina when induced with fiber waviness and resin rich areas combinedly. The failure stresses are post processed using Abaqus. Depending on the severity of the defects the lamina reaches its failure stress very soon and the load carrying capacity also gets reduced.

4.1 Description of Finite Element Model

The finite element model was built by modeling 14 tows (bunch of fibers) individually which are assembled together using tie constraints. A tie constraint ties the two surfaces of the fiber tows together and does not allow any relative motion between them [21]. The length and width of the each tow are 0.984 inch length and 0.07 inch width respectiviely. The 14 tows which are assembled together to create a single lamina are shown in the figure 4.1. The properties of AS4/3501-6 are considered for this analysis and later the analysis will be followed by IM7/997-3, glass and kevlar composite lamina. Material orientation for each tow is assigned as shown in the figure below. One side of the composite lamina is fixed in all degrees of freedom and the other side is applied to a load.

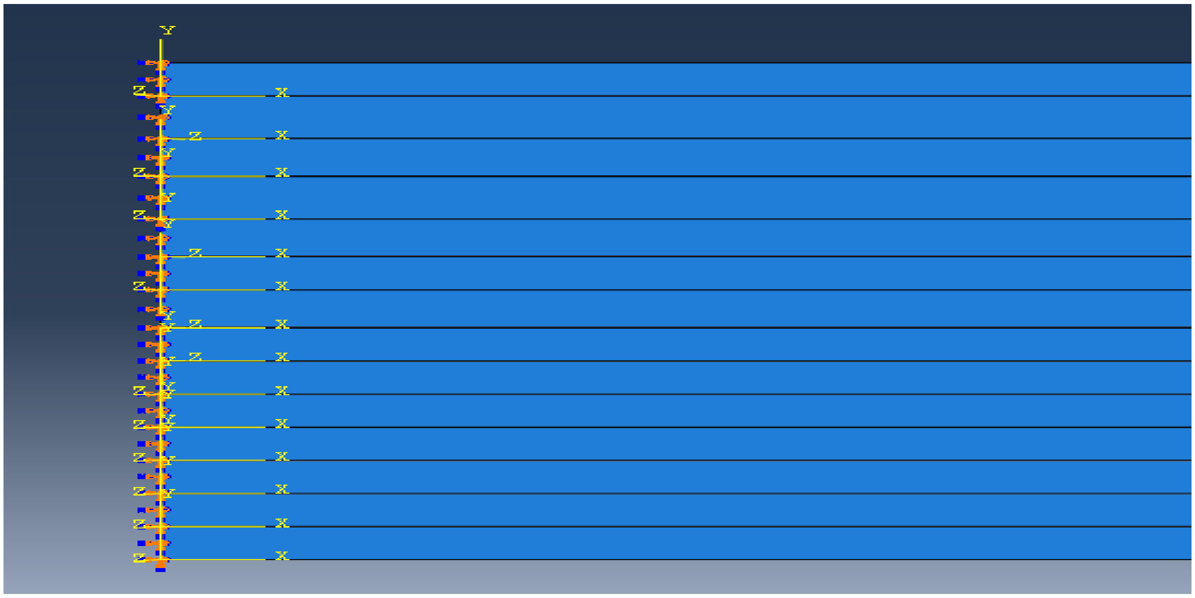


Figure 4.1 Lamina modeling in Abaqus

The waviness of the tow is modeled in the 7th tow from the bottom and the rest of the following tows are followed with 7th tow in the y-axis and gets terminated at edges as shown in figure 4.2. A termination point of the wavy tows is assumed in this analysis, because in a real time scenario, fiber tow waviness cannot be exactly symmetrical in geometry and it depends on the type of fiber, weave architecture, and density of the fiber tows which are combined together with binders. To simplify this analysis, the termination of the number of fiber tows will increase along with the increase in the angle of the waviness. The more the angle of misalignment, higher the chance that gets the following fiber tows to get terminated from waviness and become straight tows. The defect geometry‟s are listed in the table below.

Since the fiber tows get misaligned, the material orientation of the fiber tow changes according with the direction of the fibers. So the misaligned tow is discretized into different sections to assign material orientation, creating local coordinate system of the misaligned fiber tows as shown in the figure: 4.2

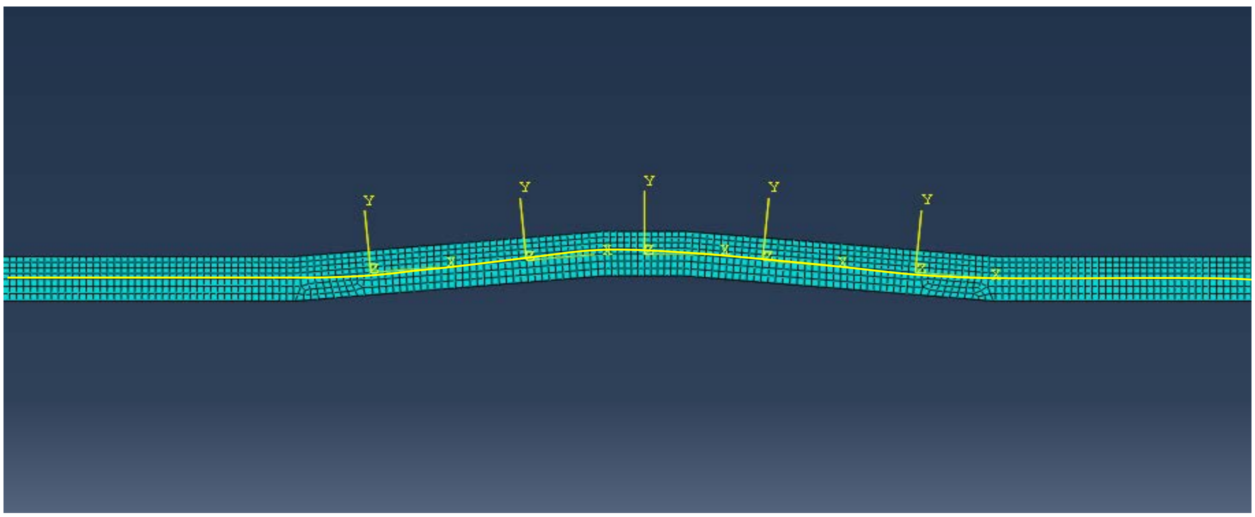


Figure 4.2 Material orientation of the single tow

Similarly material orientation is assigned to the all tows and assembled together using tie Constraints. The misaligned portion will be filled with resin and acts as resin rich area as shown in figure 4.3

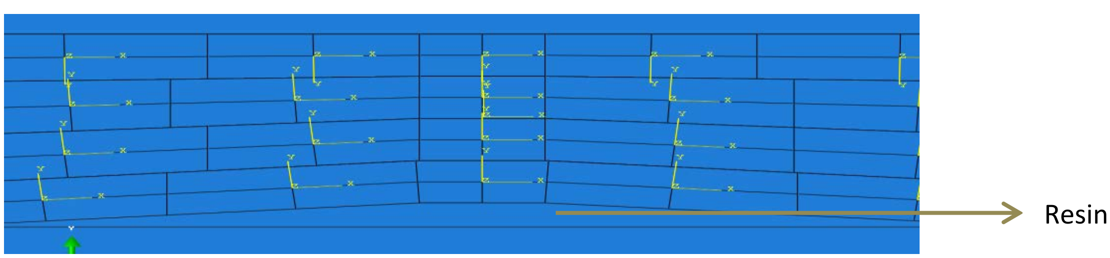


Figure 4.3 Resin rich area of the minor defect

Table 4.1: Wave parameter value for the defects

Defect	Wavelength (inch)	Amplitude(inch)	Angle(degrees)
Minor	1	0.05	5
Major	1.25	0.07	10
Severe	1.50	0.1	15

The perfect, minor, major and severe defects are shown in the figures below.

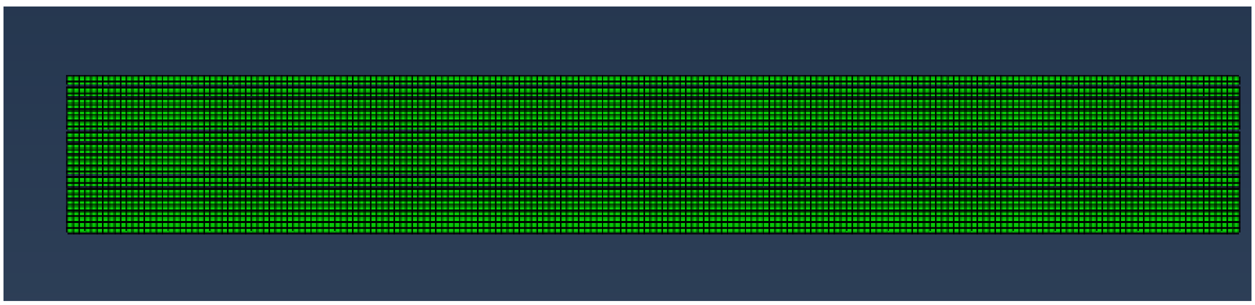


Figure 4.4 No defect

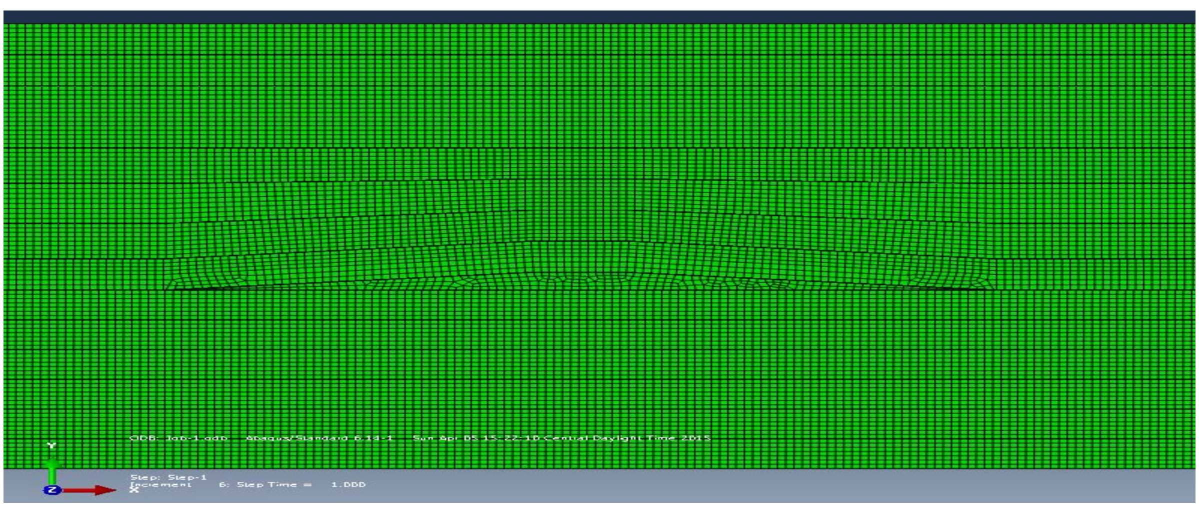


Figure 4.4.1 Minor defect with 1 inch wavelength, 0.05 inch amplitude and 5^0 angle

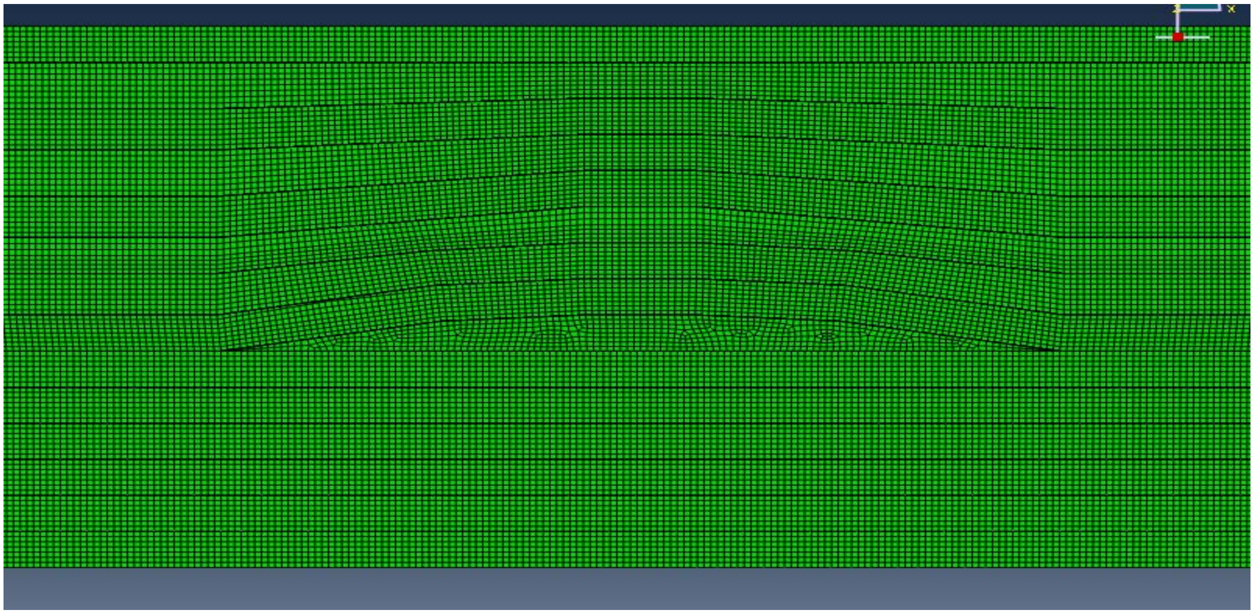


Figure 4.4.2 Major defect with 1.25 inch wavelength, 0.07 inch amplitude and 10^0 angle

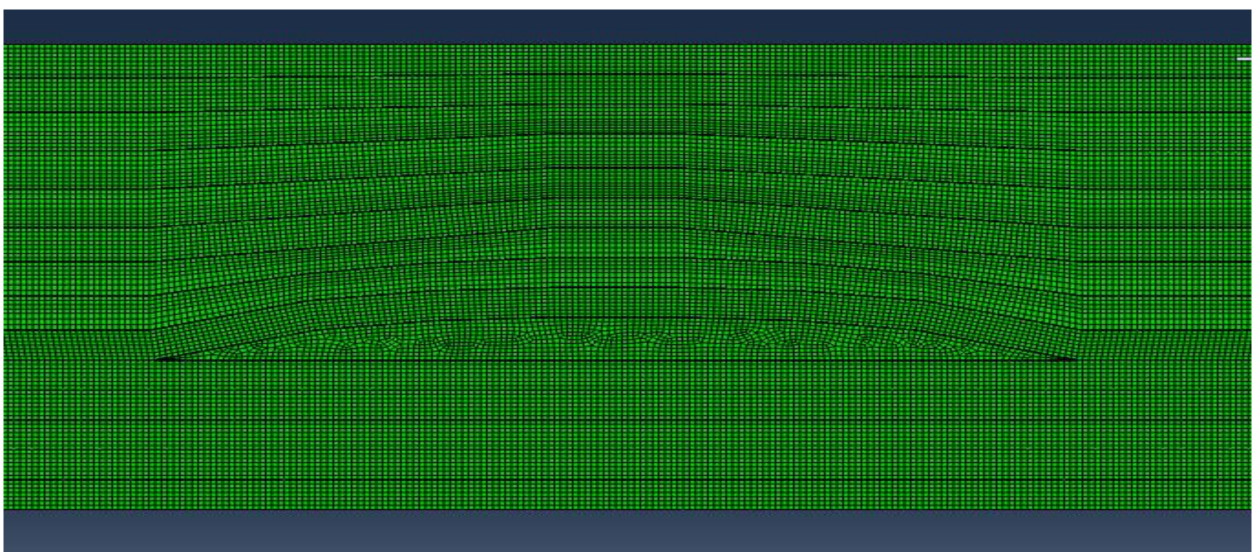


Figure 4.4.3 Severe defect with 1.5 inch wavelength, 0.1 inch amplitude and 15^0 angle

Mechanical properties are taken from the book by Daniel I.M., & Ishai O. "Engineering Mechanics of composite materials" [22]. The following table shows the mechanical properties of the materials.

Table 4.2 Mechanical properties of unidirectional composites

Property	**Carbon /Epoxy (AS4/3501-6)**	**Carbon /Epoxy (IM7/977-3)**	**Glass/Epoxy**	**Kevlar/Epoxy (Aramid 49)**
Volume Fraction (V_f)	0.63	0.65	0.55	0.60
Density (lb/in^3)	0.058	0.058	0.071	0.050
E_1(Msi)	21.3	27.7	6.0	11.6
E_2(Msi)	1.50	1.44	1.50	0.80
G_{12}(Msi)	1.00	1.13	0.62	0.31
υ_{12} Major Poisson ratio	0.27	0.35	0.28	0.34
υ_{21} Minor Poisson ratio	0.02	0.02	0.06	0.02
F_{1t} (Ksi) Longitudinal Tensile strength	330	470	165	205
F_{2t} (Ksi) Transverse. Tensile strength	8.3	8.9	5.7	4.2
F_6 (Ksi) In-plane Shear Strength	11.0	10.9	12.9	7.1

4.2 Finite Element Modeling Results for Single ply AS4/3501-6

Mechanics of materials equations were used to find approximate values of the maximum load that the (AS4/3501-6) plain lamina could carry to reach the maximum stress values,as given in table 4.2 and this value is validated using Abaqus. The surface traction force of 2418 (lb/in) is applied to one end of the plain lamina. This load is the maximum load that the lamina can resist before it reaches the failure stress value 330 Ksi. The load carrying capacity got reduced in these three defects gradually. The reduction in load carrying capacity for AS4/3501-6 is shown in the below figure: 4.5. The composite lamina with defects reaches the ultimate stress soon.

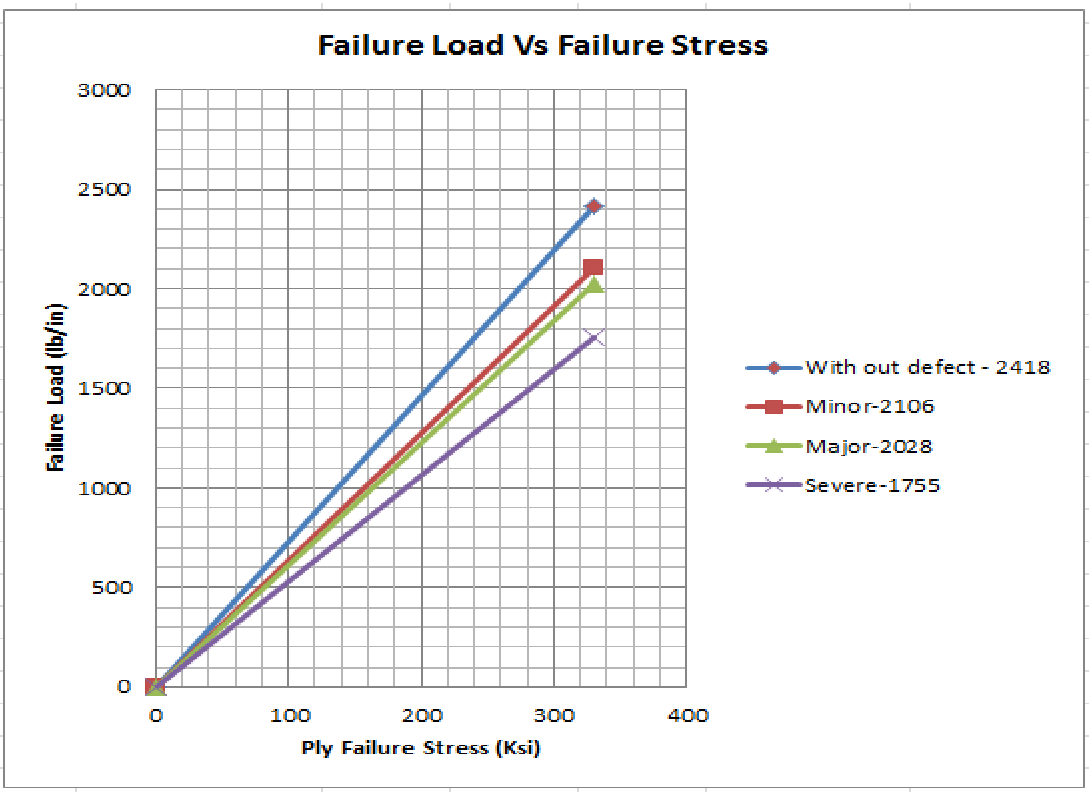


Figure 4.5 Reduction in the load carrying capacity

As we can absorb the above plot the material with no defect resisted the load of 2418 lb/in (traction load 310000 lb/in^2) during the maximum stress limit. The model with minor defect experienced the maximum value of stress when it reached reduced load of 2106 lb/in (traction load 270000 lb/in^2) which reduced the load carrying capacity to 13 %. Model with major defect experienced the maximum value of stress when it reached reduced load of 2028 lb/in (traction load 260000 lb/in^2) which reduced the load carrying capacity to 16%, and the model with severe defect reached reduced load drastically 1755 lb/in (traction load 225000 lb/in^2) which reduced the load carrying capacity to 27 % . These percentages are high because there are no other ply‟s surrounding to it to transfer the load.

1000 lb/in (128205 lb/in^2) load is applied on one side of the four models (contained one without defect and other three are defective models). Due to the resin rich area and the uneven distribution of volume fraction in the lamina, stress concentrations are developed at the weakest point. These stress values will get increased near the vicinity of the defect at the same loading conditions for the three different defects as shown in the below figure 4.6 and table 4.3

Table 4.3 Stress values and percentage Increase with applied load of 1000 lb/in

Cases	Defect	Stress (Ksi)	% Increase in stress
No defect	0	137	0
Minor	1	158	13
Major	2	162	15
Severe	3	187	27

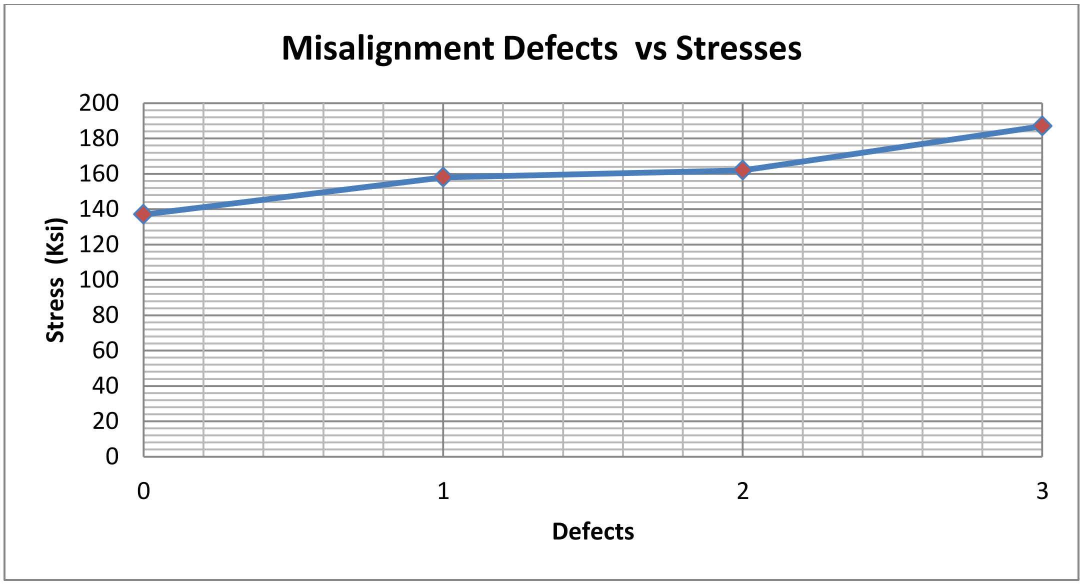


Figure: 4.6 Increase in the stress values along with increase in the severity in defects

4.3 Strength ratio of AS4/3501-6

When failure does not occur in the lamina, the stress is low enough to fail which shows strength ratio greater than 1. As the material approaches failure, the strength ratio will be less than one.

Strength Ratio = σ_a/σ_{Actual}

Where σ_a ~ Allowable Stress or maximum value of stress, σ_{Actual} ~ Actual Stress

A 1000 lb/in load is applied on one end of the surface of the lamina. The stress values get increased gradually as the severity of the defects gets increased. The allowable stresses or the maximum value of stress for AS4/3501-6 during tension is 330 ksi. The strength ratio drastically reduces from 2.42 (no defect) to 1.78 (severe defect) which is a 27 % reduction in strength. The strength ratios of the three defects and the one without defect is shown in the table 4.4 and figure 4.7

Table 4.4 Decrease in strength ratio

Cases	Defects	Strength Ratio	Stress (Ksi)
No defect	0	2.42	137
Minor	1	2.10	158
Major	2	2.05	162
Severe	3	1.78	187

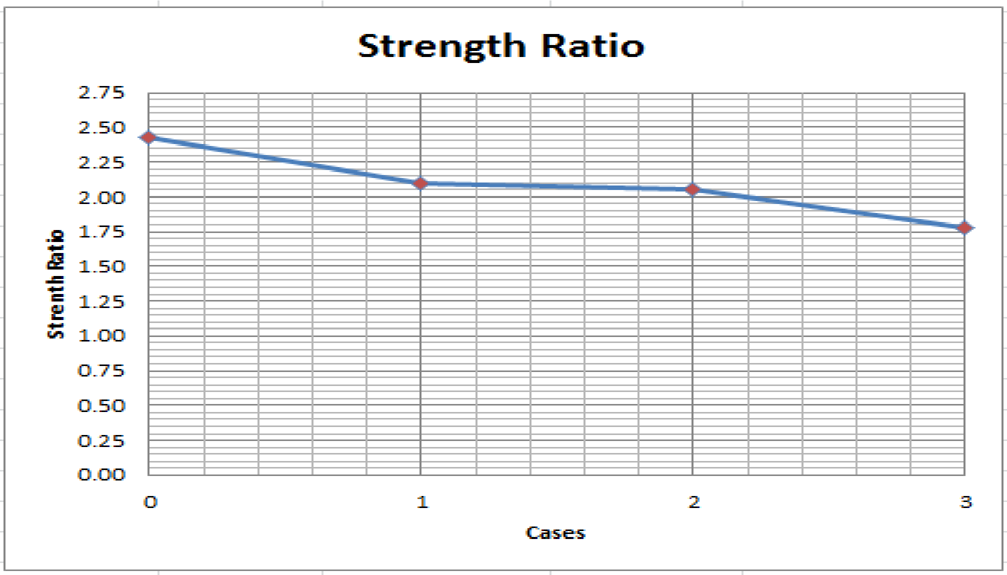


Figure 4.7 Decrease in strength ratio

4.4 Increase in Strain value as the severity of the defect Increases

Since there is a defect in a lamina, the strain value gets increased as the severity of the defect gets increased. Strain value gets increased due to the reduction in the stiffness of the lamina. The figure below shows the case when the strain values are increased at the failure load.

Table 4.5 Increase in strain values

Cases	Defects	Strain
No defect	0	0.0156
Minor	1	0.0187
Major	2	0.0209
Severe	3	0.026

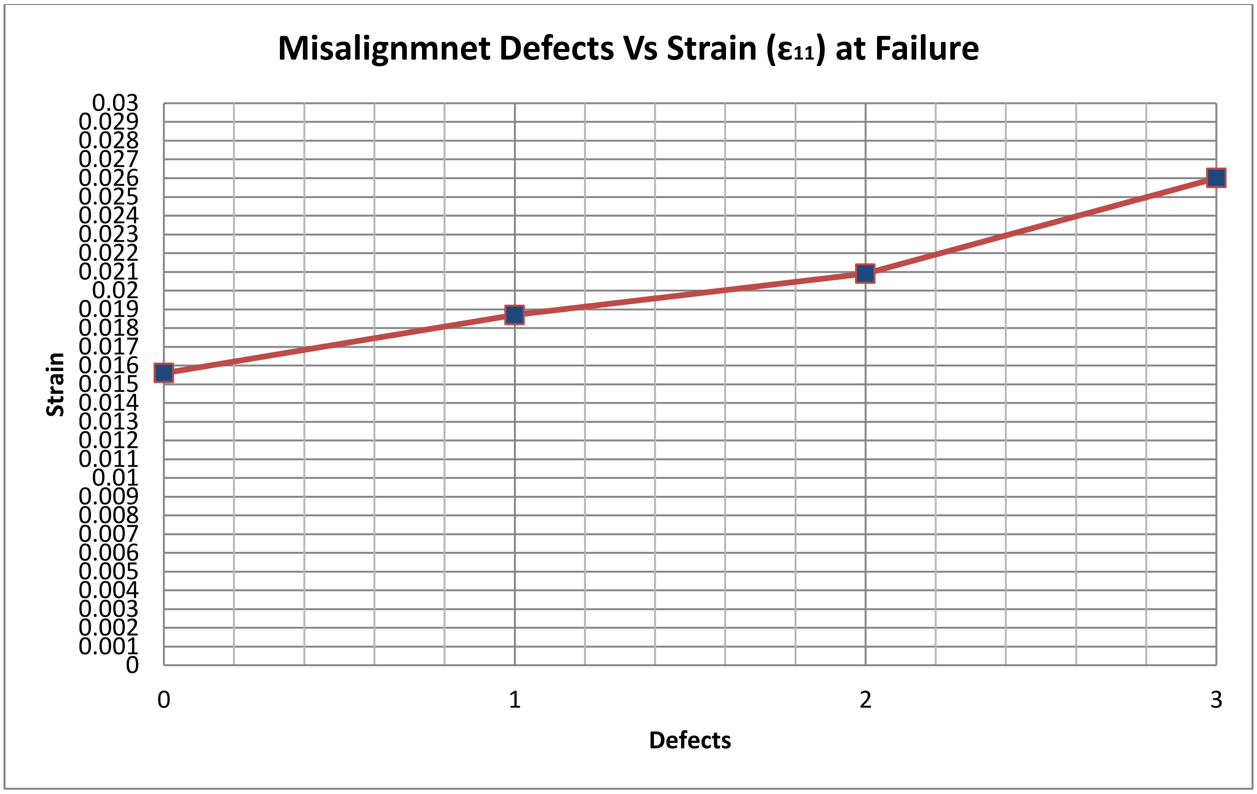


Figure 4.8 Increase in strain values

4.5 Stress distribution around the defect

It is observed that the load carrying capacity gets reduced as the severity of the defect increases. Accordingly, stress distribution of these three defects will be varied depending on the architecture of the defect. The snapshots of the results are taken when the model gets maximum stress values with the reduced loading condition. Figure 4.10 illustrates the stress values along the center of the defect in y-axis. In this plot, the x-axis represents the width of the model and the y-axis represents the stress values at the each nodal point.

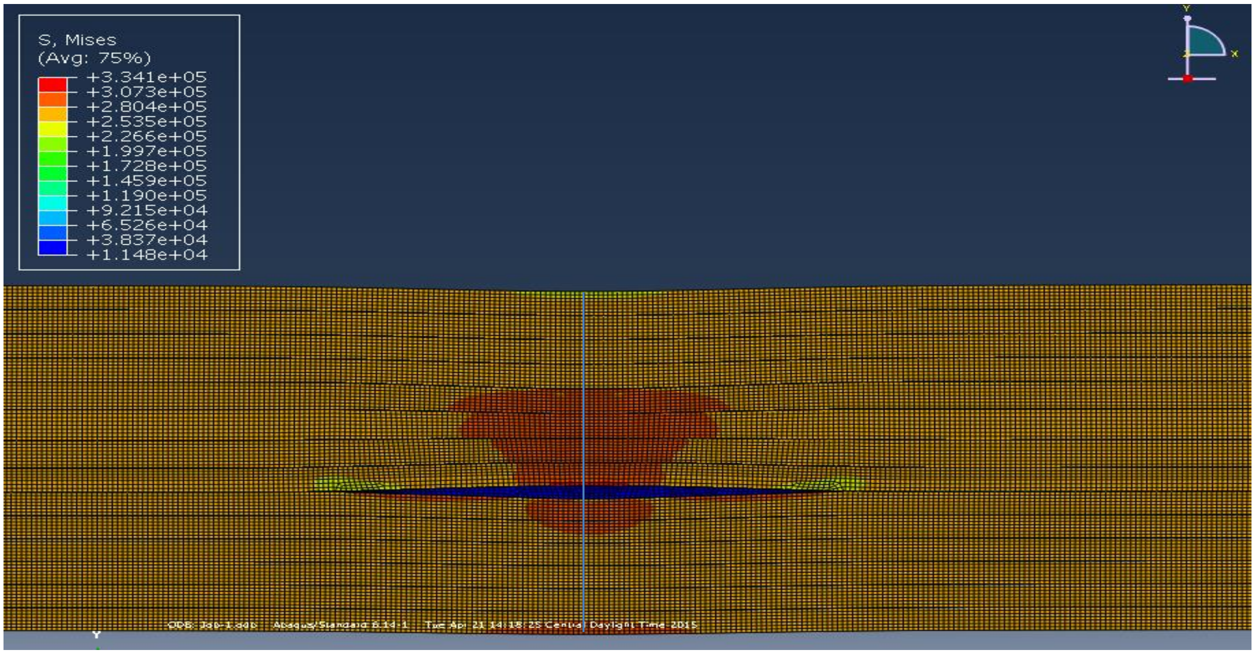


Figure 4.9 Stress distributions near the vicinity of the minor defect

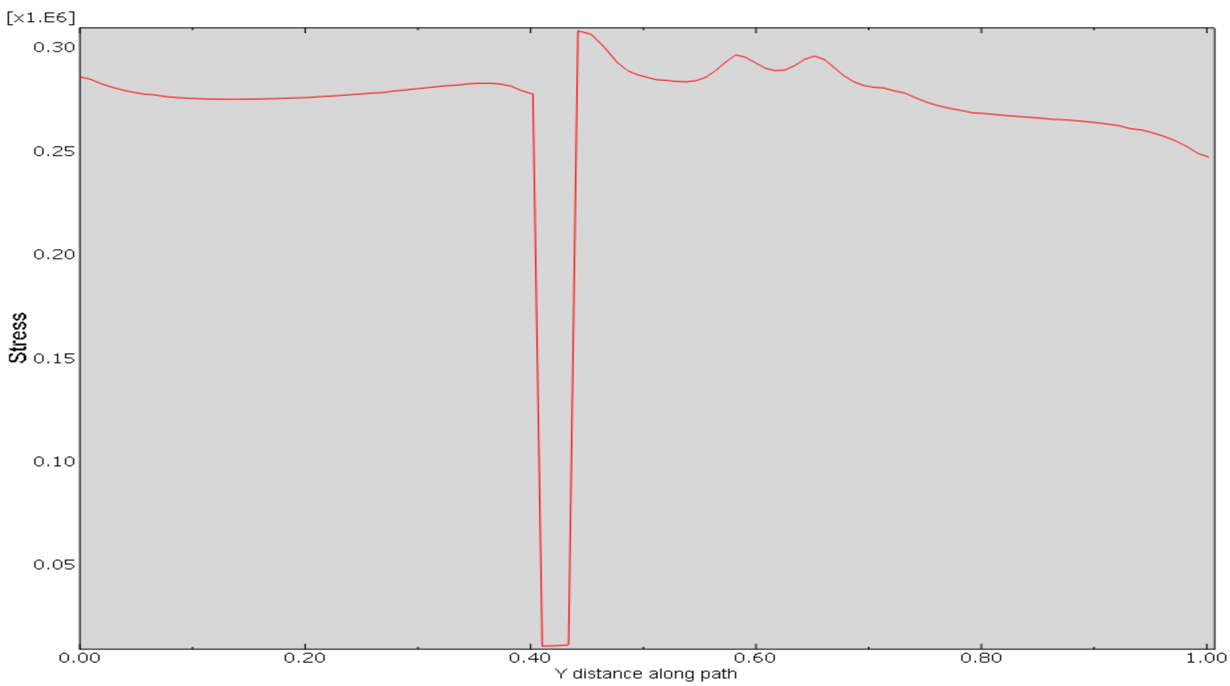


Figure 4.10 Stress distributions along the width of the minor defect

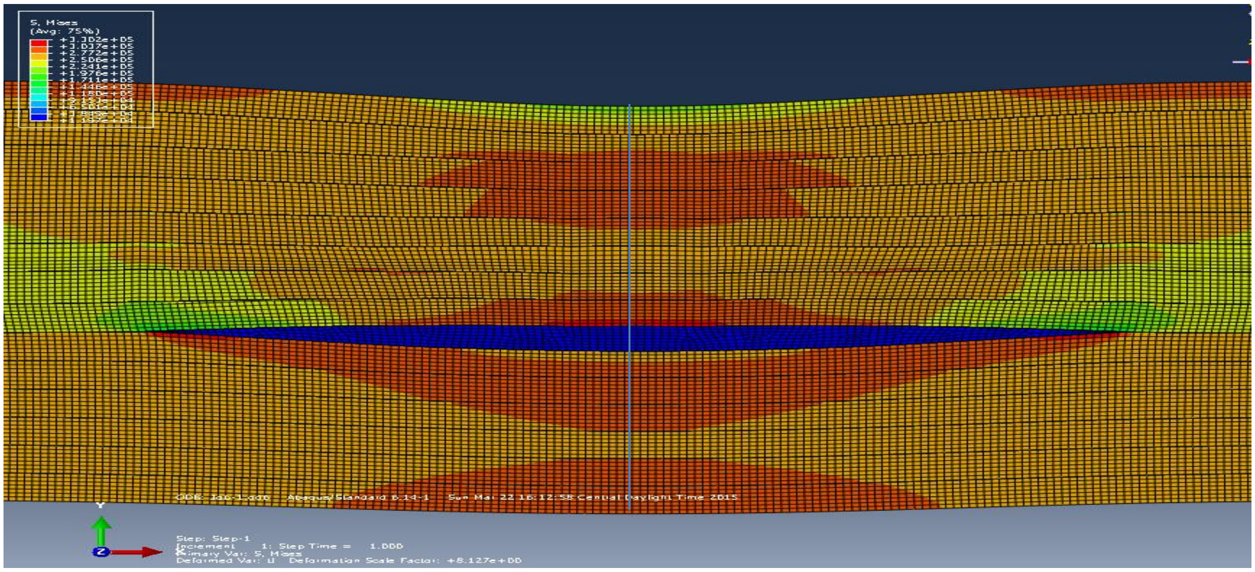


Figure 4.11 Stress distributions near the vicinity of the major defect

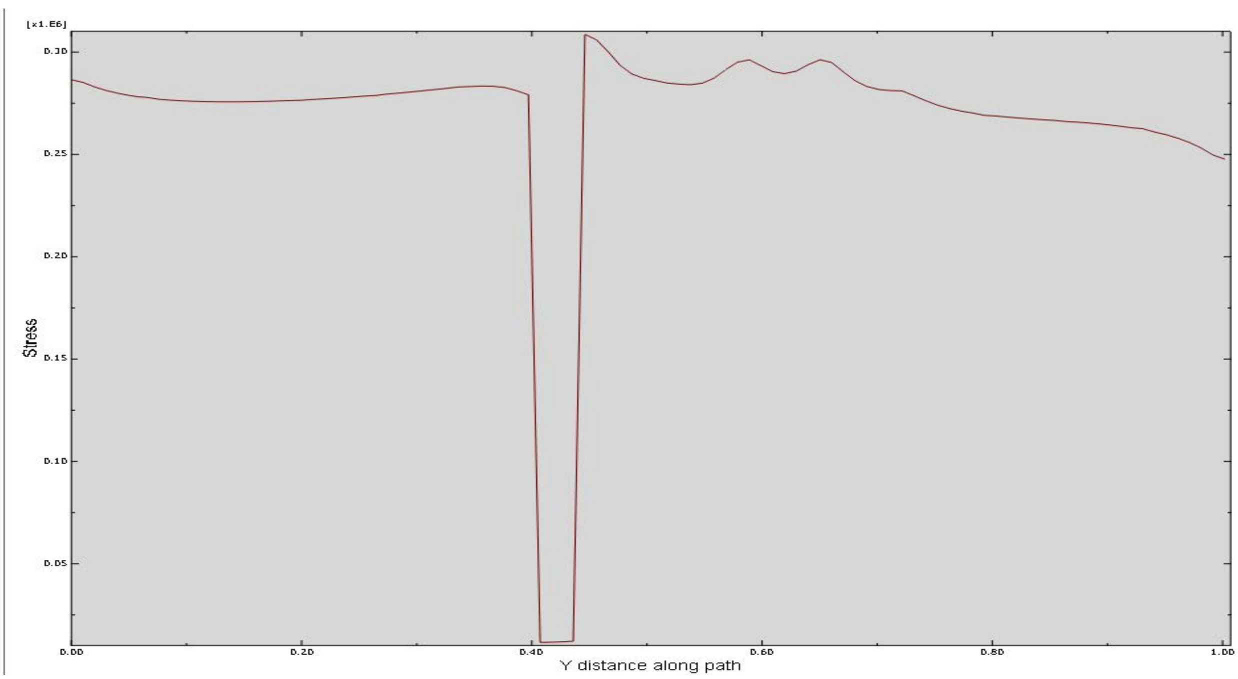


Figure 4.12 Stress distributions along the width of the major defect

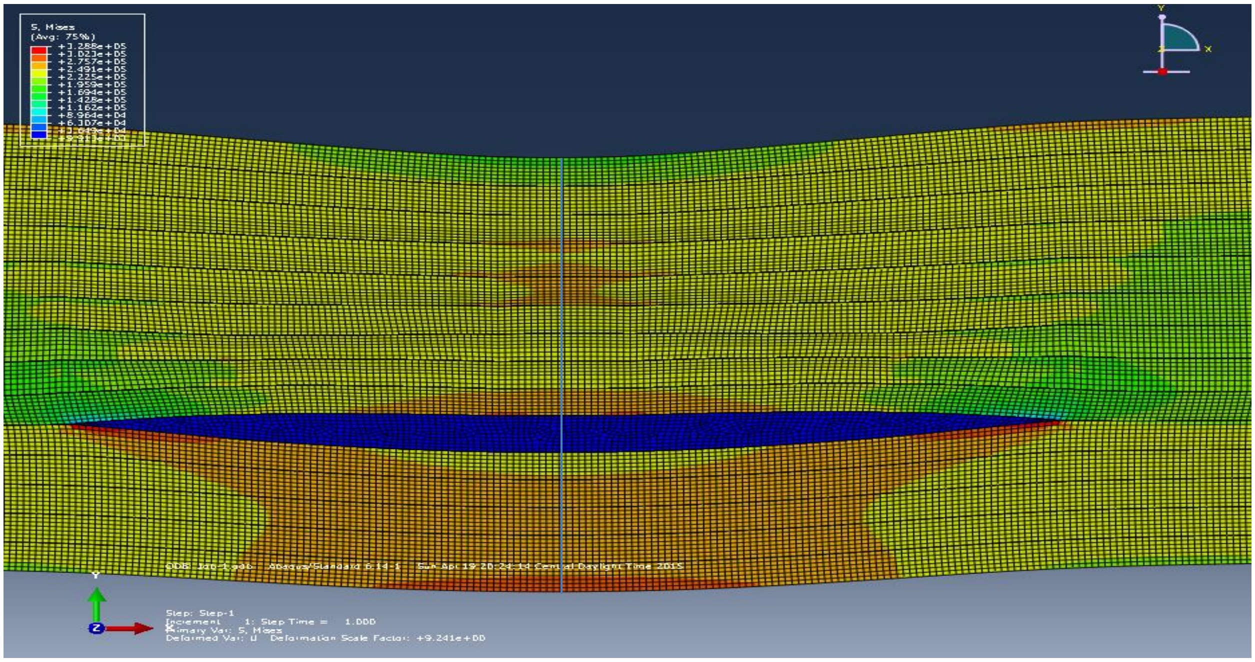


Figure 4.13 Stress distributions near the vicinity of the severe defect

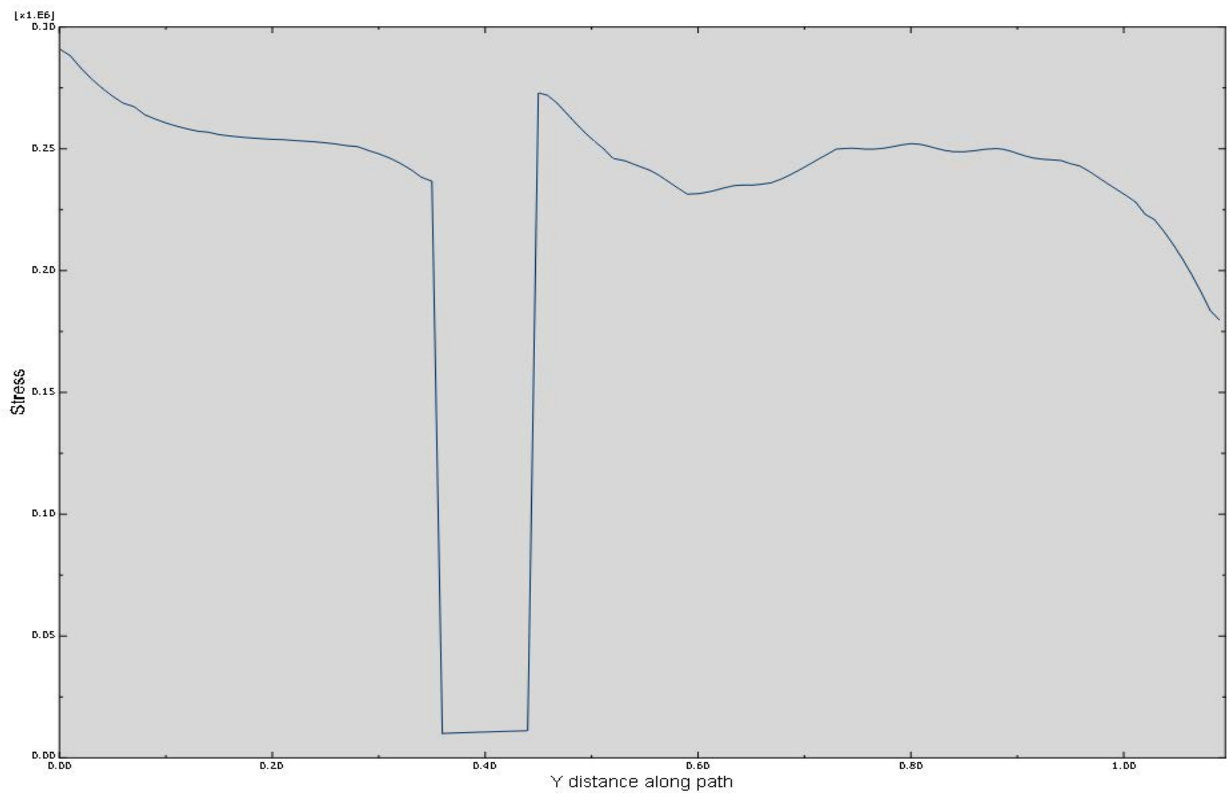


Figure 4.14 Stress distributions along the width of the severe defect

4.6 Finite Element Modeling Results for Single ply IM7/977-3

Mechanics of materials equations were used to find approximate values of the maximum load that the (IM7/977-3) plain lamina could carry to reach the maximum stress values as given in the table 3.2 and this value is validated using Abaqus. The predicted surface traction force of 3432 (lb/in) is applied to one end of the plain lamina. This load is the maximum load that the lamina can resist before it reaches the failure stress value 470 Ksi. The load carrying capacity got reduced in these three defects gradually. The reduction in load carrying capacity for IM7/977-3 is shown in figure: 4.15. The composite lamina with defects reaches the ultimate stress soon.

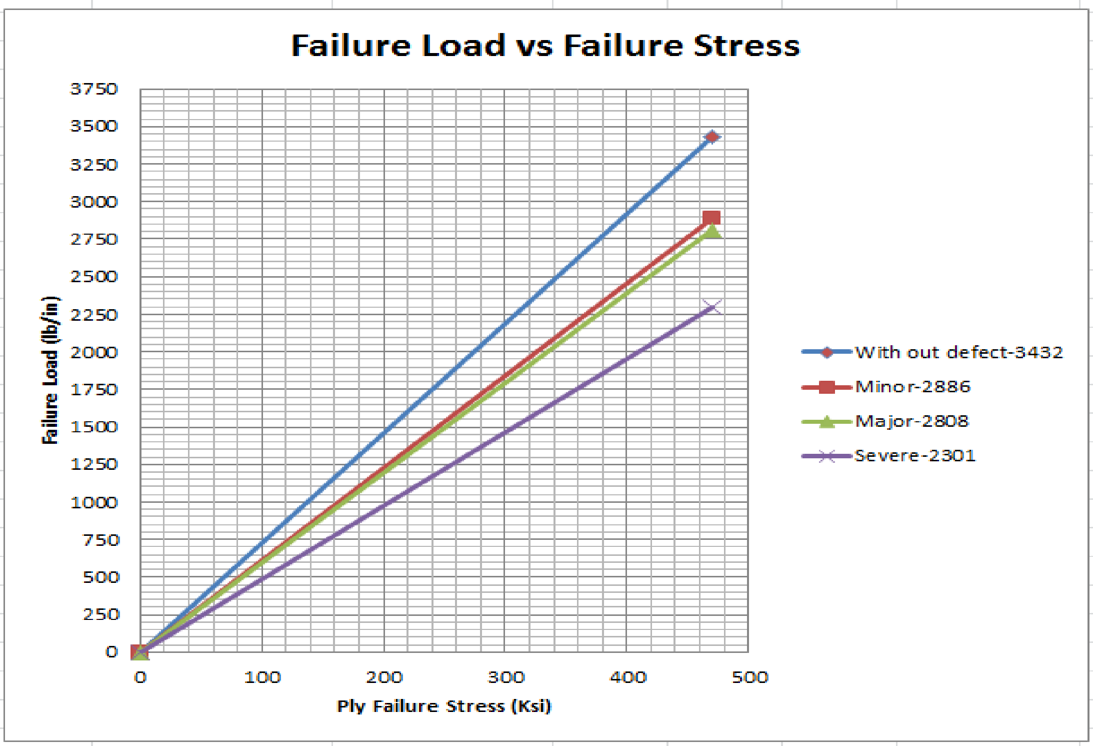


Figure 4.15 Reduction in the load carrying capacity

As we can absorb the above plot the material with no defect resisted the load of 3432 lb/in (traction load 440000 lb/in^2) during the maximum stress limit, the model with minor defect experienced the maximum value of stress when it reached reduced load of 2886 lb/in (traction load 370000 lb/in^2) which reduced the load carrying capacity to 16%. The model with major defect experienced the maximum value of stress when it reached reduced load of 2808 lb/in (traction load 360000 lb/in^2) which reduced the load carrying capacity to 17%, and the model with severe defect reached reduced load drastically 2301 lb/in (traction load 295000 lb/in^2) which reduced the load carrying capacity to 33% . These percentages are high because there are no other ply"s surrounding to it to transfer the load.

1000 lb/in (128205 lb/in^2) load is applied on one side of the four models contained one without defect and other three are defective models. Due to the resin rich area and the uneven distribution of volume fraction in the lamina, stress concentrations are developed at the weakest point. These stress values will get increased near the vicinity of the defect at the same loading conditions for the three different defects as shown in the below figure 4.16 and Table 3.6

Table: 4.6 Stress values and percentage increase with applied load of 1000 lb/in

Cases	Defect	Stress (Ksi)	% Increase in stress
No Defect	0	138	0
Minor	1	163	15
Major	2	167	17
Severe	3	204	32

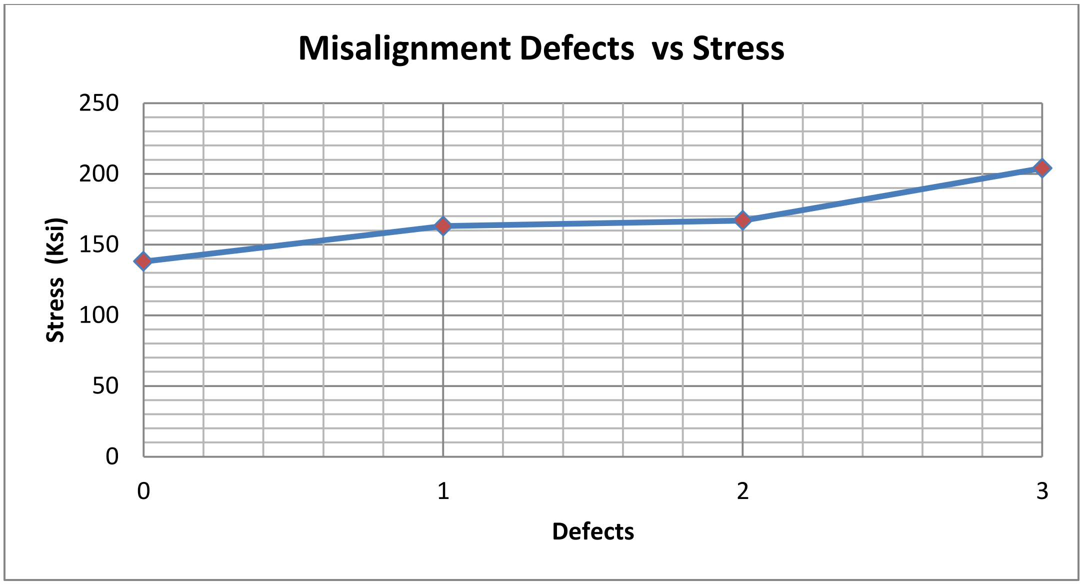


Figure: 4.16 Increase in the stress values along with increase in the severity in defects

4.7 Strength ratio of IM7/977-3

When failure does not occur in the lamina, the stress is low enough to fail which shows strength ratio greater than 1. As the material approaches failure, the strength ratio will be less than one.

Strength Ratio = σ_a/σ_{Actual}

Where σ_a ~ Allowable Stress or maximum value of stress, σ_{Actual} ~ Actual Stress

A 1000 lb/in load is applied on the surface of the lamina. The stress values get increased gradually as the severity of the defects gets increased. The allowable stresses or maximum value of stress for IM7/977-3 during tension is 470 ksi. The strength ratio drastically reduces from 3.41 (no defect) to 2.30 (severe defect) which is a 32 % reduction in strength. The strength ratios of three defects and without defect is shown in the below table 4.7 and figure 4.17

Table 4.7 Decrease in strength ratio

Cases	Defects	Strength Ratio	Stress (Ksi)
No defect	0	3.41	138
Minor	1	2.88	163
Major	2	2.81	167
Severe	3	2.30	204

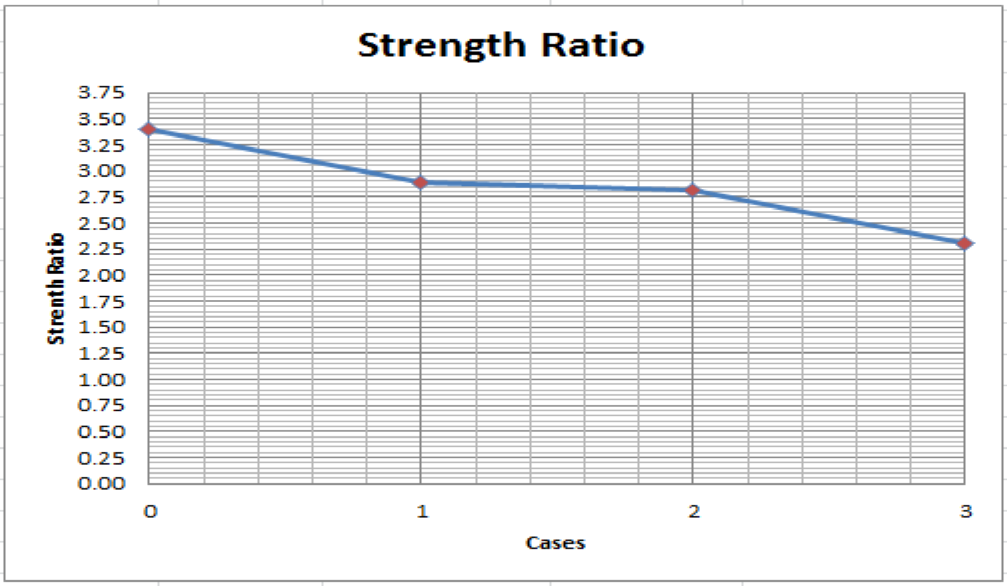


Figure 4.17 Decrease in strength ratio

4.8 Increase in Strain value as the severity of the defect Increases

Since there is a defect in a lamina the strain value gets increase as the severity of the defect gets increased. Strain value gets increased due to the reduction in the stiffness of the lamina. The figure below shows the plot where the strain values are increased at the failure load.

Table 4.8 Increase in strain values

Cases	Defects	Strain
No defect	0	0.017
Defect 1	1	0.021
Defect2	2	0.026
Defect 3	3	0.031

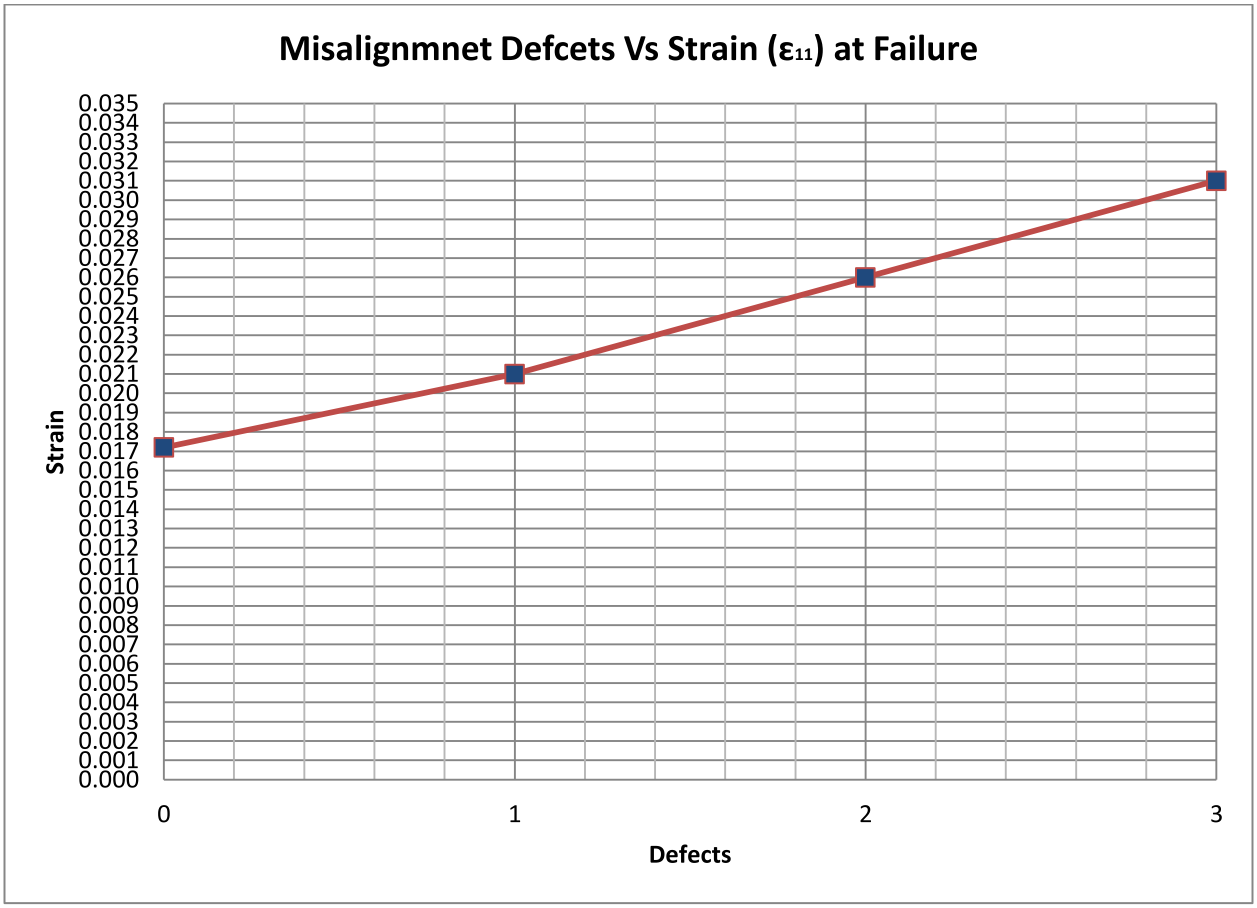


Figure 4.18 Increase in strain values

4.9 Stress distribution around the defect

The failure stresses are fixed, load is getting varied on the three models. It is observed that the load carrying capacity gets reduced as the severity of the defect increases. Accordingly stress distribution of these three defects will be varied depending on the architecture of the defect. The snapshots of the results are taken when the model gets maximum stress values with the reduced loading condition. Figure 4.19 illustrates the stress values along the center of the defect in Y-axis. In the plot the x-axis represents the width of the model and the y-axis represents the stress values at the each nodal point.

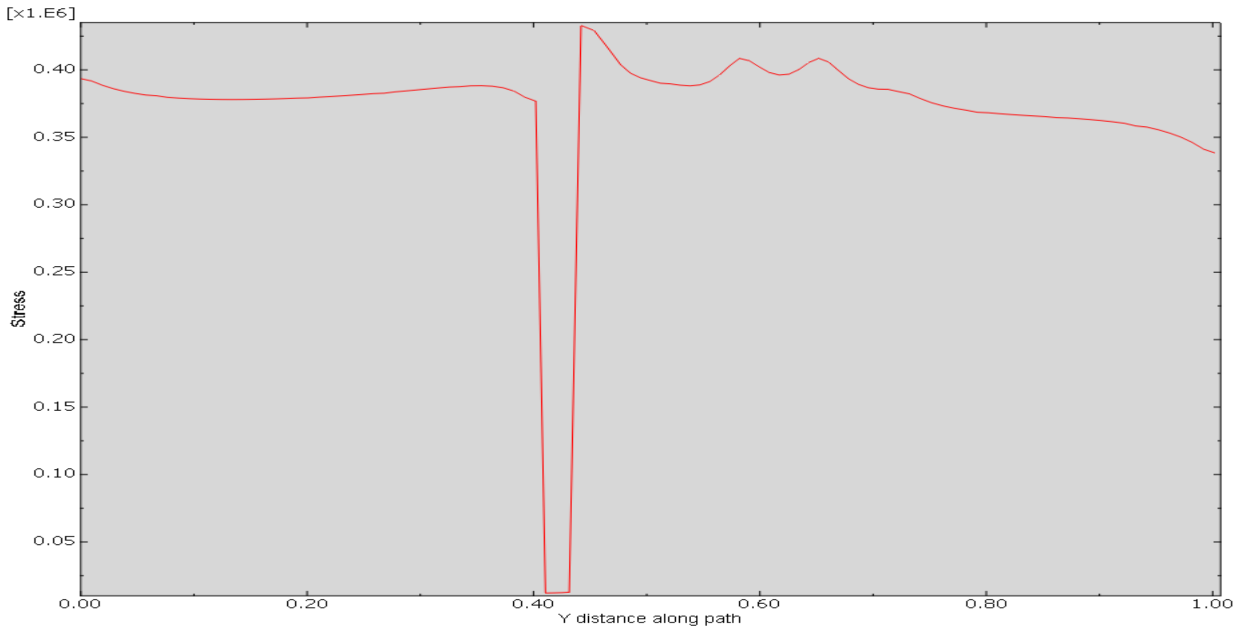


Figure 4.19 Stress distributions along the width of the minor defect

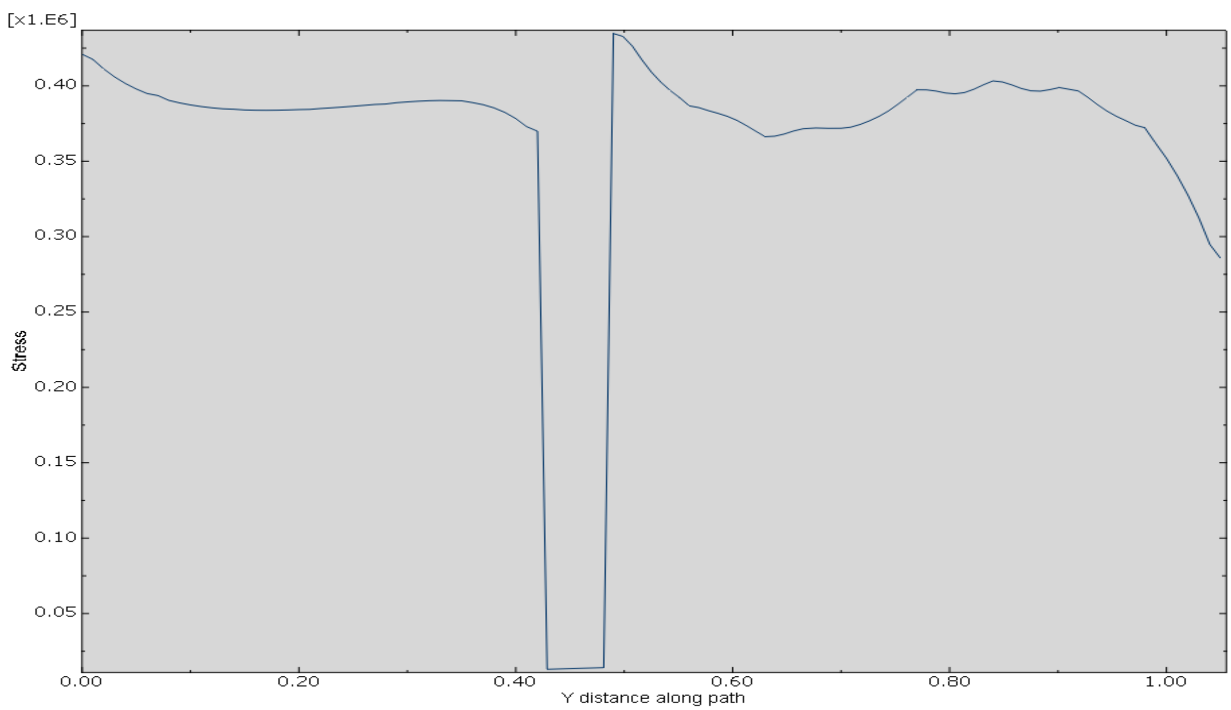


Figure 4.20 Stress distributions along the width of the major defect

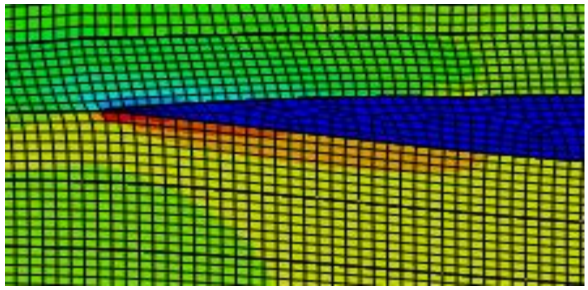


Figure 4.21 Stress distributions near the vicinity of the severe defect

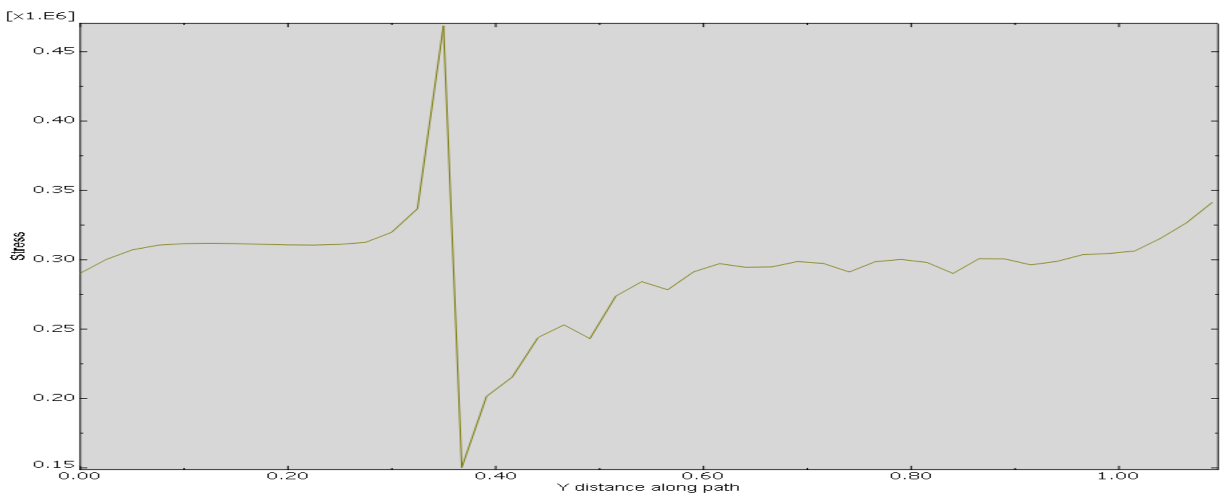


Figure 4.22 Stress distributions along the width of the severe defect through max. Stress location

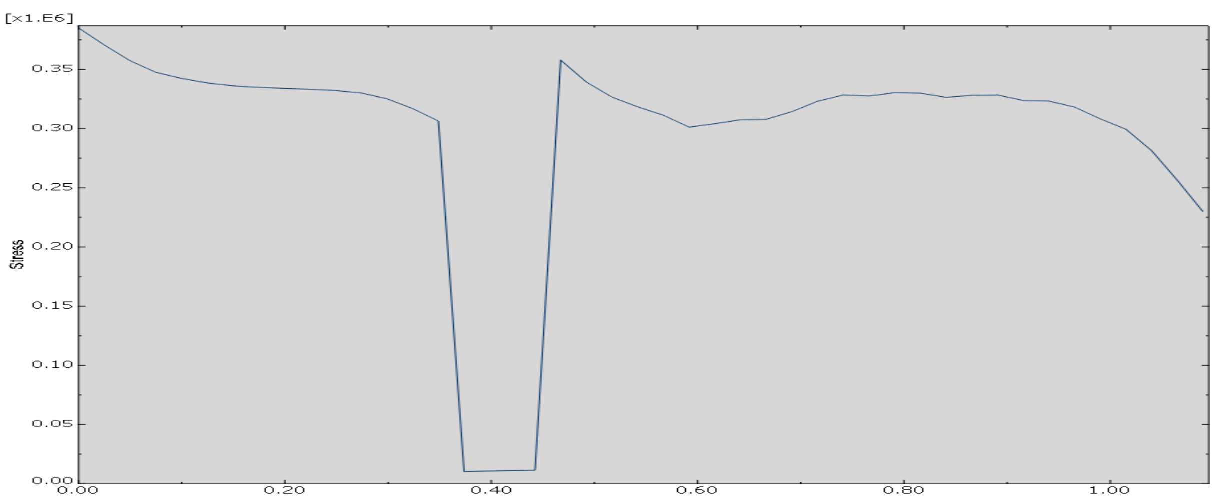


Figure 4.23 Stress distributions along the width of the severe defect

4.10 Finite Element Modeling Results for Single ply Glass/Epoxy

Mechanics of materials equations were used to find approximate values of the maximum load that the (glass/epoxy) lamina could carry to reach the maximum stress values as given in the above table 4.2 and this value is validated using Abaqus. The predicted surface traction force of 1140 (lb/in) is applied to one end of the plain lamina. This load is the maximum load that the lamina can resist before it reaches the failure stress value 165 Ksi. Since the stiffness of the glass/epoxy is very less compared to carbon/epoxy. High stresses are developed near the vicinity of the boundary conditions. The reduction in load carrying capacity for glass/epoxy is shown in the figure: 4.24. Since glass is a highly brittle material there will be an uneven stress distribution, but the max stress values are not developed near the vicinity of the defect when compared to carbon, but the load carrying capacity gets reduced. The three defective models failed almost at the same load because failure stresses are developed near the vicinity of the boundary conditions. The defective model experiences a low load carrying capacity, but there is no drastic change in the load carrying capacity as the severity of the defect is getting increased, because the maximum stress is developed near the vicinity of the boundary conditions.

The load carrying capacity of the glass/epoxy with minor, major and severe defect is reduced from 1140 lb/in (surface traction of 146100 lb/in^2) to 865.8 ksi (surface traction of 111000 lb/in^2) for minor defect, 861 ksi (surface traction of 110500 lb/in^2) for major defect and 854 ksi (surface traction of 109500 lb/in^2) for severe defect. The load carrying capacity of the lamina drastically reduces to 24 % for minor defect, 24.5% for major defect, and 25% for severe defect.

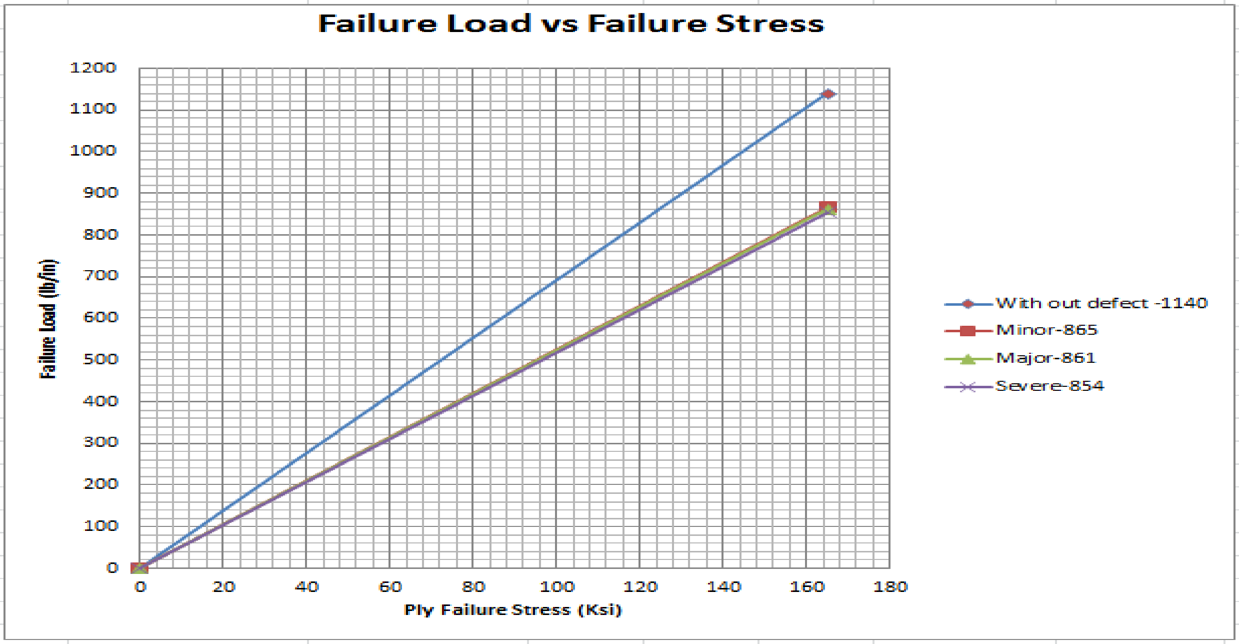


Figure 4.24 Reduction in the load carrying capacity

800 lb/in (102564 lb/in^2) load is applied on one side of the four models contained one without defect and other three are defective models. These stress values will get increased as shown in figure 4.25 and table 4.9

Table: 4.9 Stress values and percentage Increase with applied load of 800 lb/in

Cases	Defect	Stress (Ksi)	%Increase in stress
No defect	0	115	0
Minor	1	153	25
Major	2	153.5	25
Severe	3	154.7	26

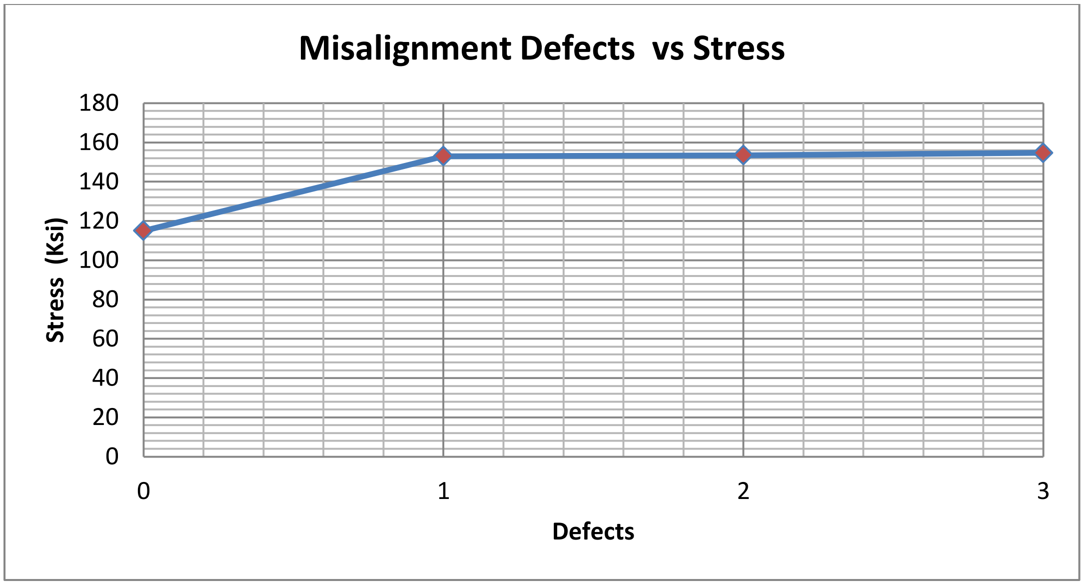


Figure: 4.25 Increase in the stresses

4.11 Strength ratio of Glass/Epoxy

When failure does not occur in the lamina, the stress is low enough to fail which shows strength ratio greater than 1. As the material approaches failure, the strength ratio will be less than one.

Strength Ratio = σ_a/σ_{Actual}

Where σ_a ~ Allowable Stress or maximum value of stress, σ_{Actual} ~ Actual Stress

800 lb/in load is applied on the surface of the lamina. The Allowable stresses or Maximum value of stress for glass/matrix during tension is 165 ksi. The strength ratio drastically reduces from 1.43 (No Defect) to 1 (Severe Defect) which is a 26 % reduction in strength. Since the strength ratio is equal to 1, the minor, major, severe defective lamina fails at around 800 lb/in. The strength ratios of three defects and without defect is shown in the table 4.10 and figure 4.26

Table 4.10 Decrease in strength ratio

Cases	Defects	Strength Ratio	Stress (Ksi)
No defect	0	1.43	115
Minor	1	1.08	153
Major	2	1.07	153.5
Severe	3	1.07	154.7

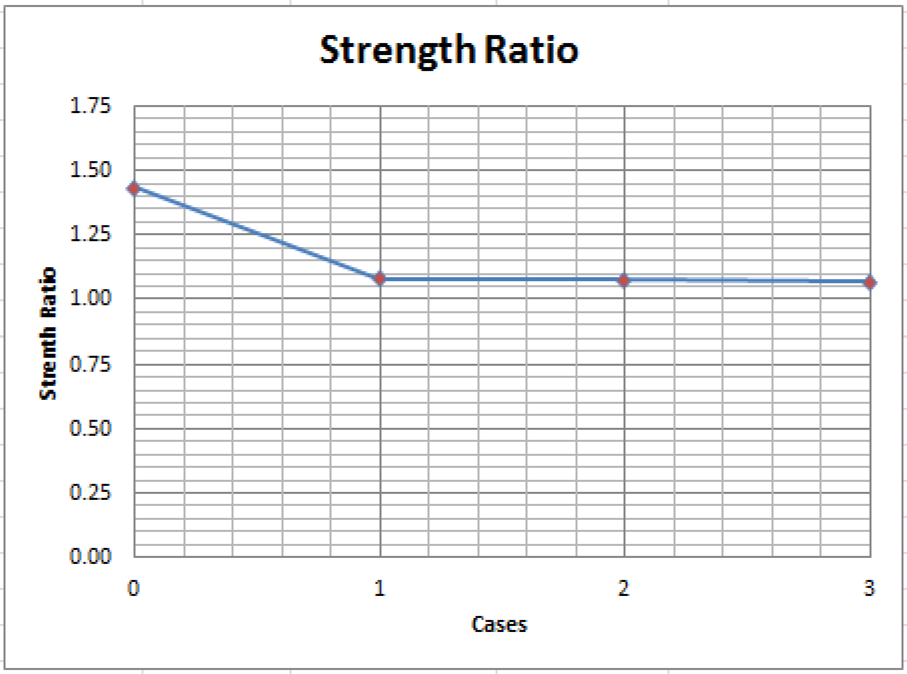


Figure 4.26 Decrease in strength ratio

4.12 Stress distribution around the defect

The failure stresses are fixed and hence the load is getting varied on the three models. It is observed that the load carrying capacity gets reduced as the severity of the defect increases. Accordingly stress distribution of these three defects will be varied depending on the architecture of the defect. The figure 4.27 illustrates the stress values along the center of the defect in Y-axis. In the plot the x-axis represents the width of the model and the y-axis represents the stress values at the each nodal point.

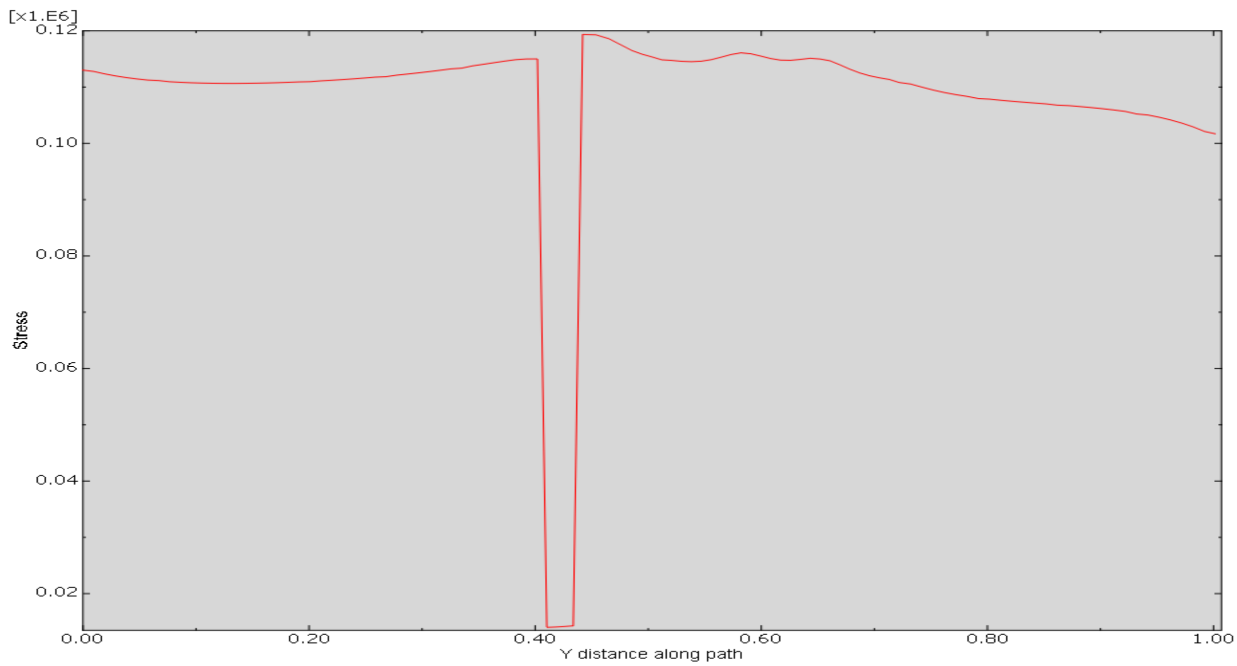


Figure 4.27 Stress distributions along the width of the minor defect

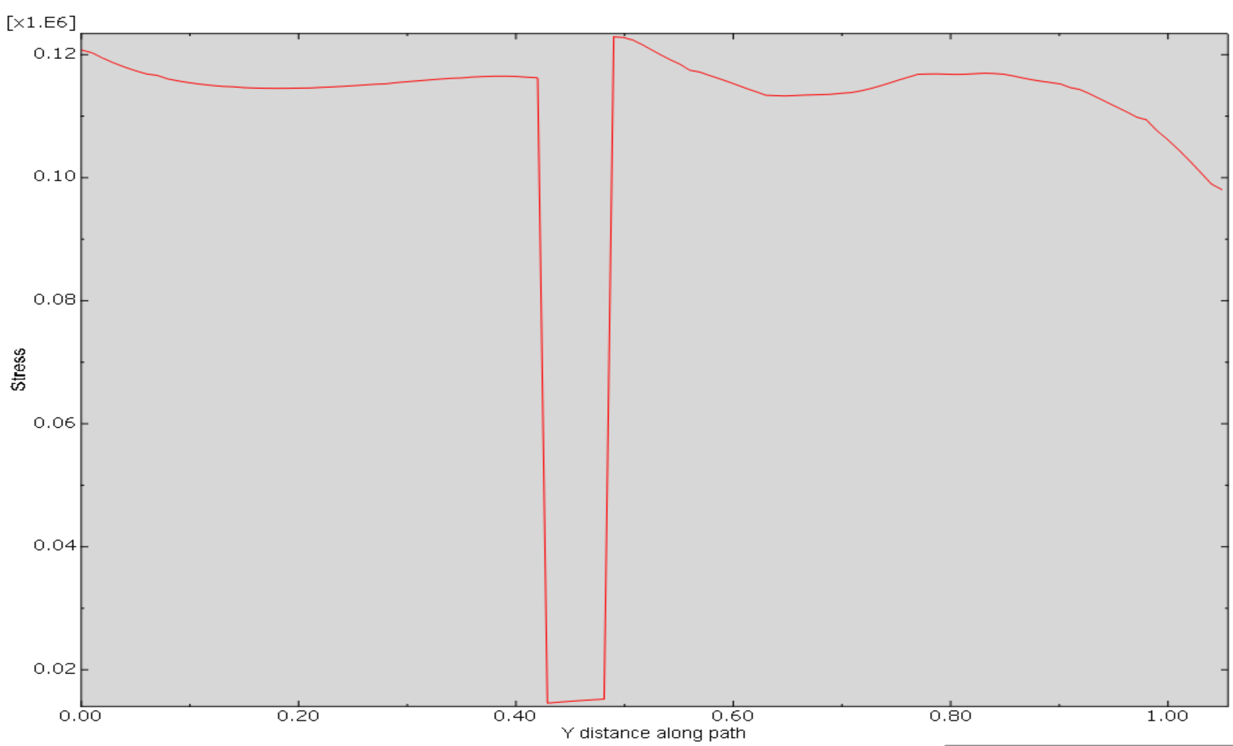


Figure 4.28 Stress distributions along the width of the major defect

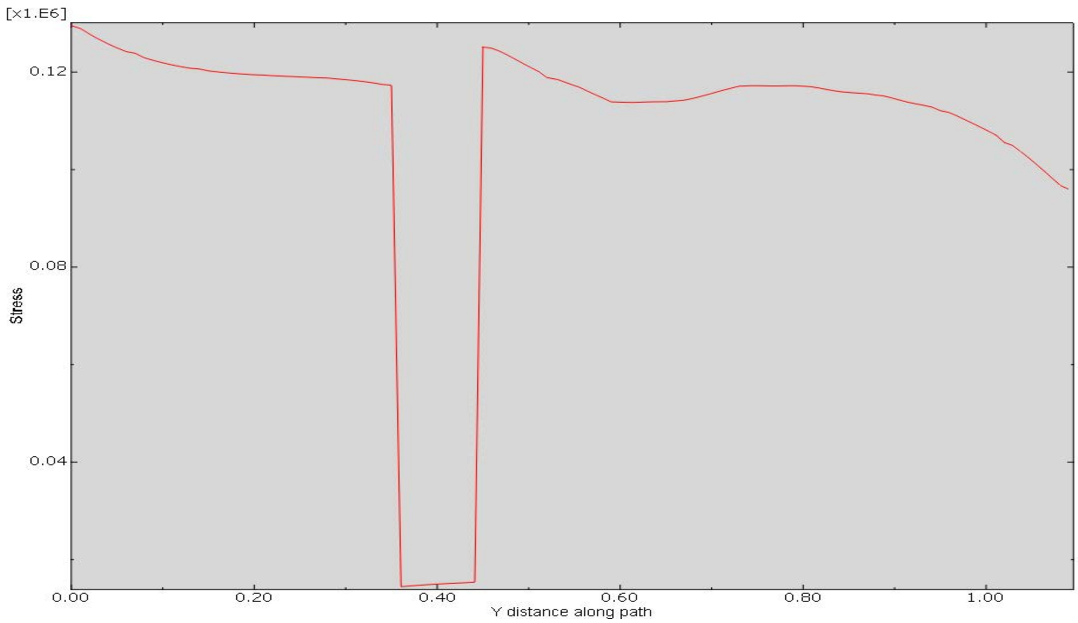


Figure 4.29 Stress distributions along the width of the severe defect

4.13 Finite Element Modeling Results for Single ply Kevlar®/Epoxy

Mechanics of materials equations were used to find approximate values of the maximum load that the (kevlar/epoxy) plain lamina could carry to reach the maximum stress values as given in table 4.2 and this value is validated using Abaqus. The predicted surface traction force of 1505 (lb/in) is applied to one end of the plain lamina. This load is the maximum load that the lamina can resist before it reaches the failure stress value 205 Ksi. The load carrying capacity got reduced in these three defects gradually. The reduction in load carrying capacity for kevlar/epoxy is shown figure: 4.30. The composite lamina with defects reaches the ultimate stress immediately after that.

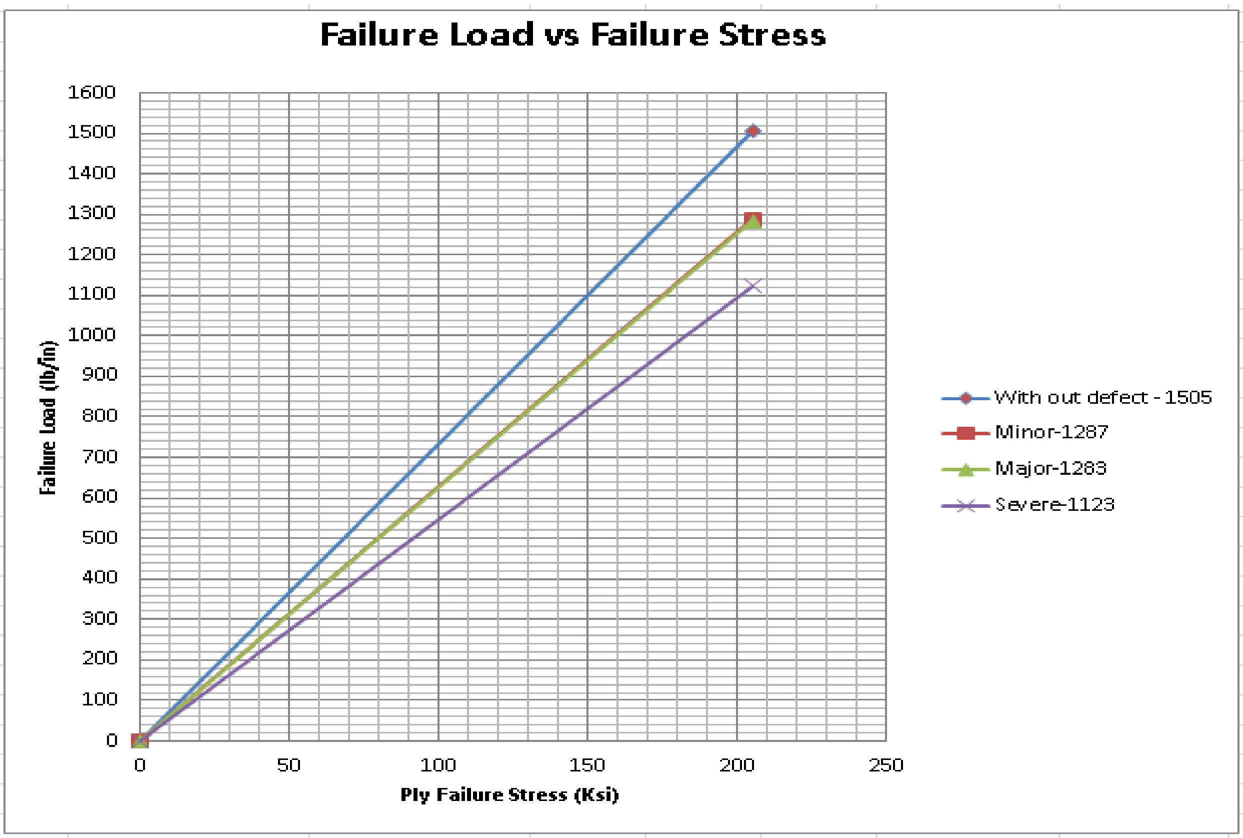


Figure 4.30 Reduction in the load carrying capacity

As we can absorve from plot above the material with no defect resisted the load of 1505 lb/in (traction load 193000lb/in^2) during the maximum stress limit, the model with minor defect experienced the maximum value of stress when it reached a reduced load of 1287 lb/in (traction load 165000 lb/in^2) that hence reduced the load carrying capacity to 14% , model with major defect experienced the maximum value of stress when it reached reduced load of 1283lb/in (traction load 164500 lb/in^2) that hence reduced the load carrying capacity to 15%. Both the minor and major defects exhibited the same level of stresses. The kevlar/epoxy material fails on same predicted load for the major and minor defect geometry. The model with severe defect have reached reduced load drastically at 1123 lb/in (traction load 144000 lb/in^2) that reduced the load carrying capacity to 26%. These percentages are high because there are no other plys surrounding to it to transfer the load.

1000 lb/in (128205 lb/in^2) load is applied on one side of the four models (contained one without defect and other three are defective models). Due to the resin rich area and the uneven distribution of volume fraction in the lamina, stress concentrations are developed at the weakest point. These stress values will get increased near the vicinity of the defect at the same loading conditions for the three different defects as shown in figure 4.31 and table 4.11

Table: 4.11 Stress values and percentage Increase with applied load of 1000lb/in

Cases	Defect	Stress (Ksi)	%Increase in Stress
No Defect	0	136	0
Minor	1	159	14
Major	2	160	15
Severe	3	184	26

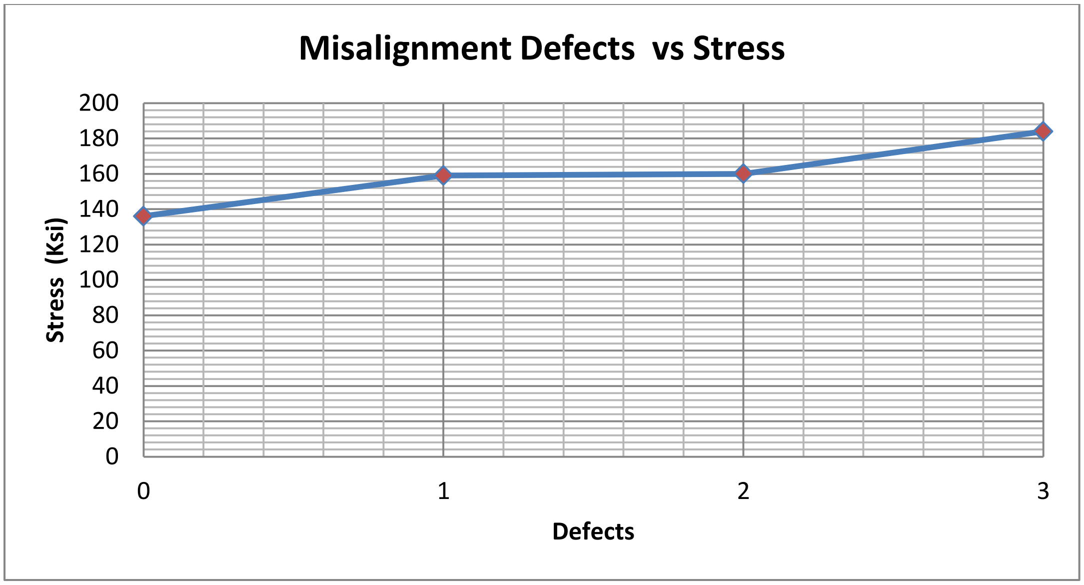


Figure: 4.31 Increase in the stress values along with increase in the severity in defects

4.14 Strength ratio of Kevlar/Epoxy

When failure does not occur in the lamina, the stress is low enough to fail which shows strength ratio greater than 1. As the material approaches failure, the strength ratio will be less than one.

Strength Ratio = σ_a/σ_{Actual}

Where σ_a ~ Allowable Stress or maximum value of stress, σ_{Actual} ~ Actual Stress

A 1000 lb/in load is applied on the surface of the lamina. The stress values get increased gradually as the severity of the defects gets increased. The allowable stresses or maximum value of stress for kevlar/epoxy during tension is 205 ksi. The strength ratio drastically reduces from 1.51 (no defect) to 1.11 (severe Ddefect) which is a 32 % reduction in strength. The strength ratios of three defects and without defect is shown in table 4.12 and figure 4.32.

Table 4.12 Decrease in strength ratio

Cases	Defects	Strength Ratio	Stress (Ksi)
No defect	0	1.51	136
Minor	1	1.29	159
Major	2	1.28	160
Severe	3	1.11	184

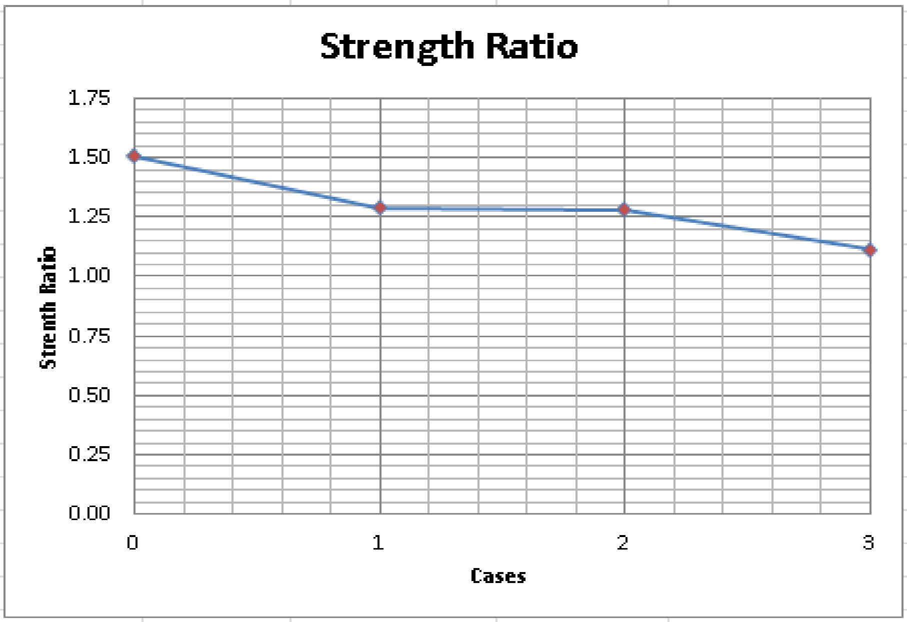


Figure 4.32 Decrease in strength ratio

4.15 Increase in strain value as the severity of the defect increases

Since there is a defect in a lamina the strain value gets increased as the severity of the defect gets increased. Strain value gets increased due to the reduction in the stiffness of the lamina. The figure below shows the plot where the strain values are increased at the failure load.

Table 4.13 Increase in strain values

Cases	Defects	Strain
No defect	0	0.01775
Defect 1	1	0.02144
Defect2	2	0.02465
Defect 3	3	0.02947

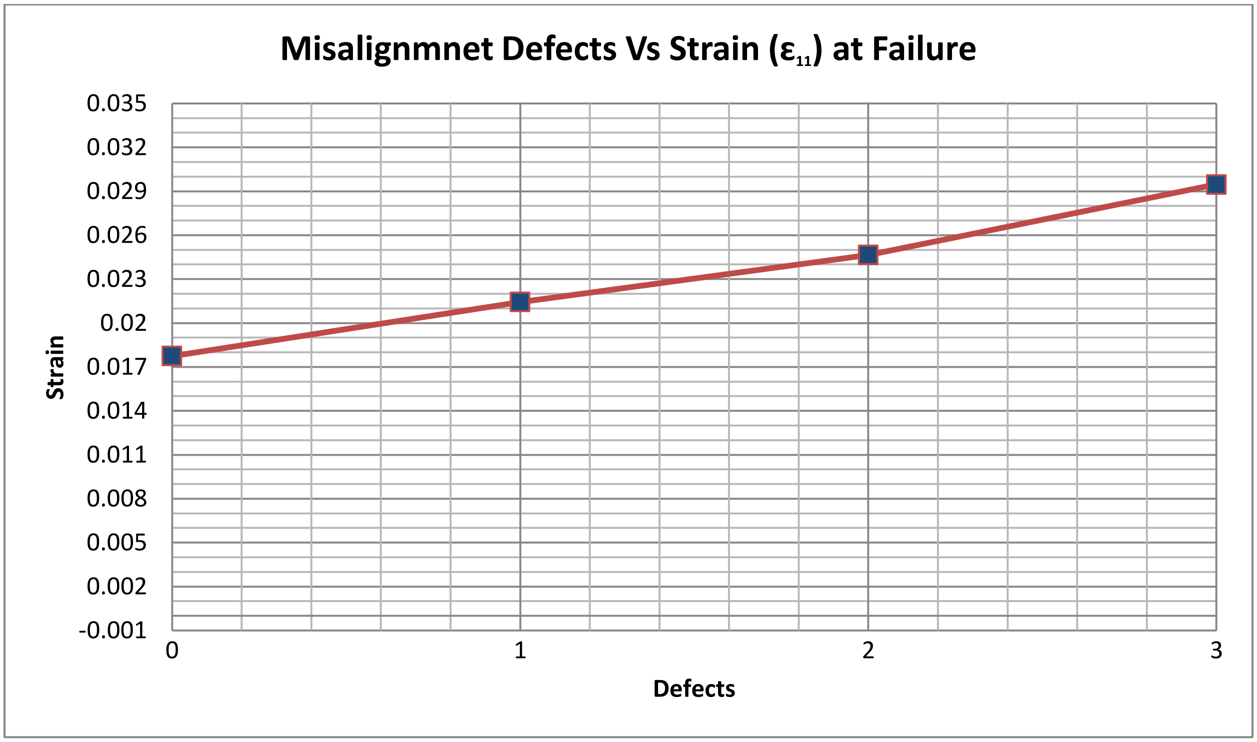


Figure 4.33 Increase in Strain Values

4.16 Stress distribution around the defect

As the failure stresses are fixed, the load varies on the three models. It is observed that the load carrying capacity gets reduced as the severity of the defect increases. Accordingly stress distribution of these three defects will be varied depending on the architecture of the defect. The snapshots of the results are taken when the model gets maximum stress values with the reduced loading condition. Figure 4.35 illustrates the stress values along the center of the defect in Y-axis. In this plot, the x-axis represents the width of the model and the y-axis represents the stress values at the each nodal point.

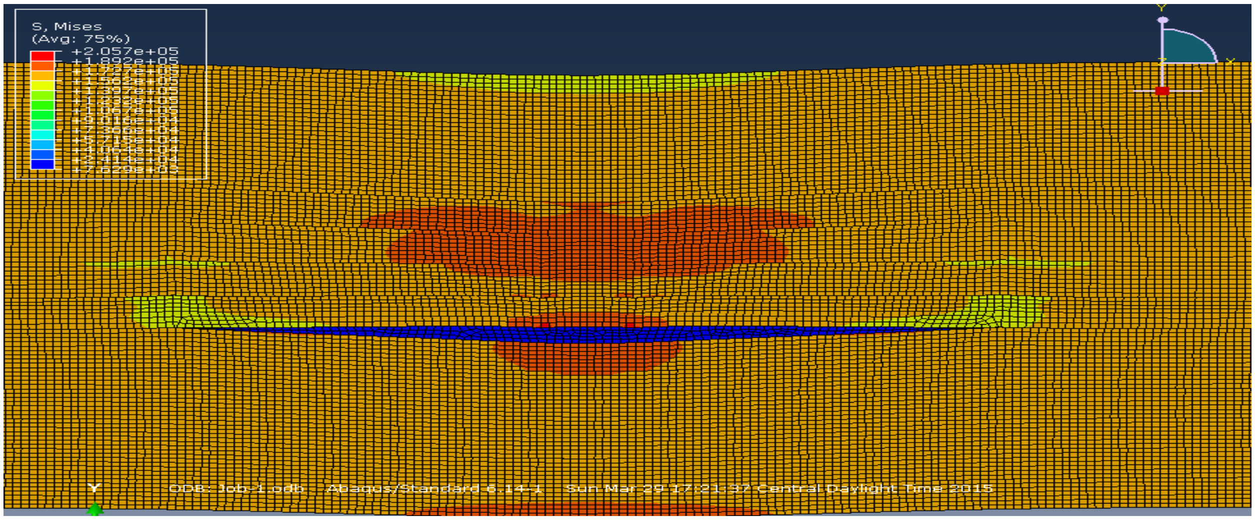


Figure 4.34 Stress distributions near the vicinity of the minor defect

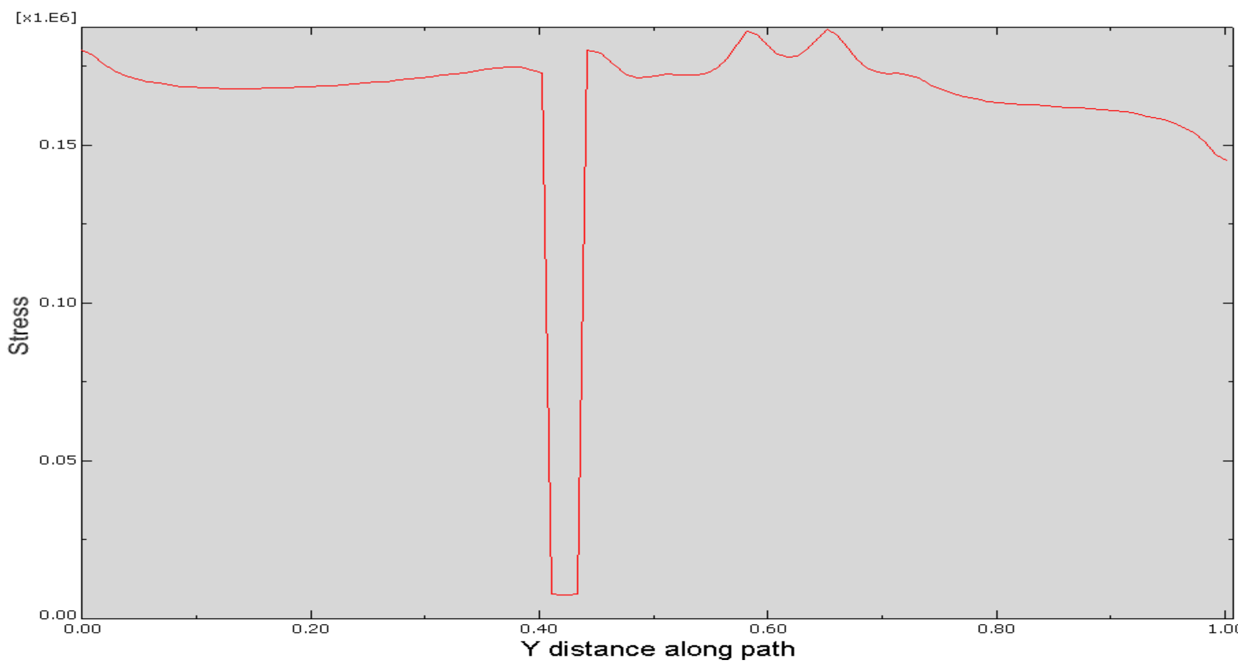


Figure 4.35 Stress distributions along the width of the minor defect

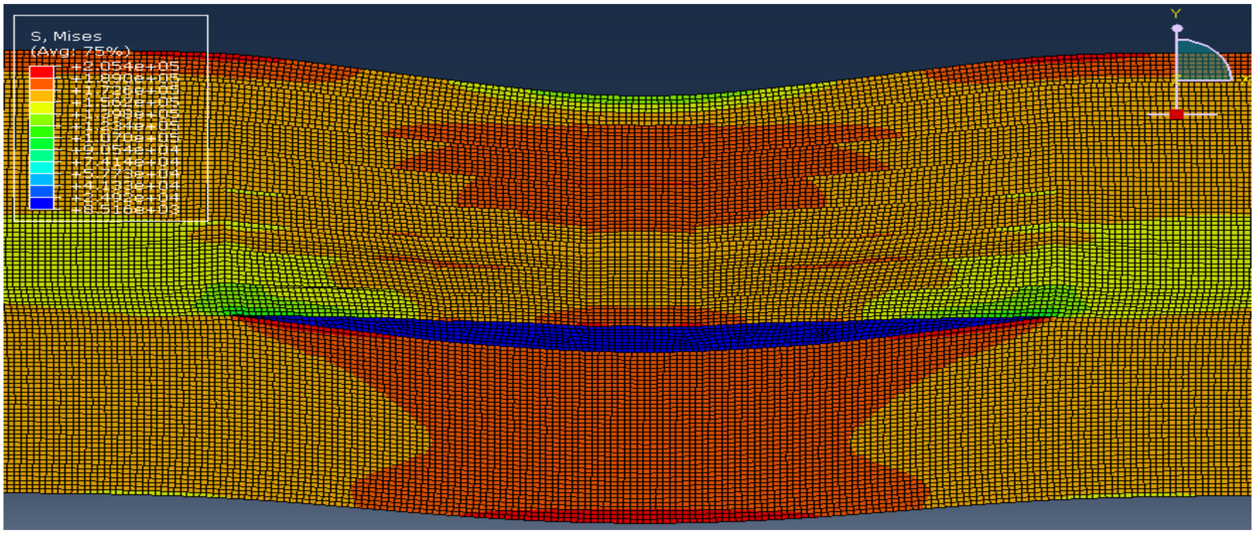


Figure 4.36 Stress distributions near the vicinity of the major defect

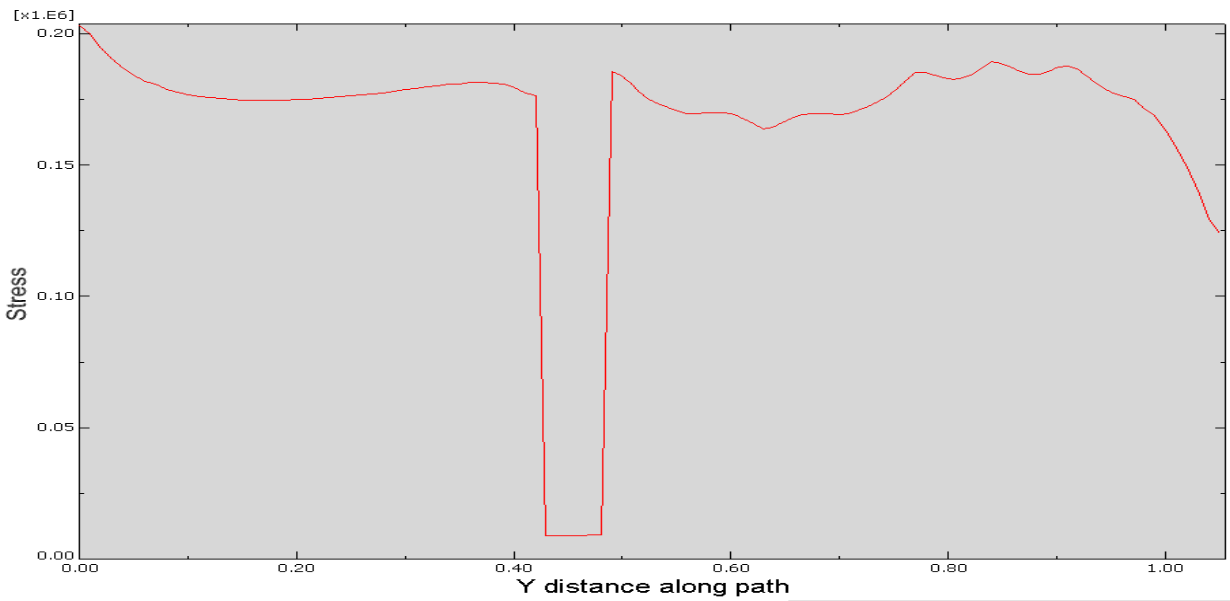


Figure 4.37 Stress distributions along the width of the major defect

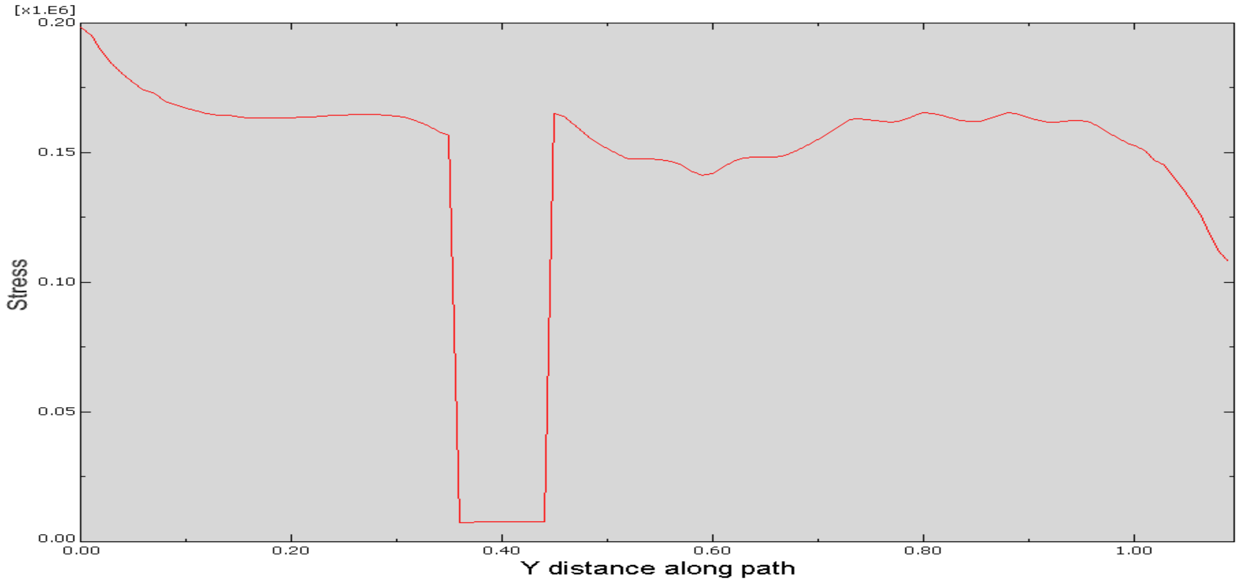


Figure 4.38 Stress distributions along the width of the severe defect

CHAPTER 5

FINITE ELEMENT ANALYSIS OF A DEFECTIVE LAMINATE

5.1 Laminate

If we have a single layer of an orthotropic material it is called as the lamina. When this is assembled together, it is called a laminate. Laminate is a stack of laminas bonded to each other. In this study, the bonding is assumed to be perfect with infinite stiffness and infinite strength, but in reality that may not be the case. These individual laminas could have same orientations or different orientations. Fiber direction in each ply could be different whatever the design requirement dictates. It could also be designed laminas made with different materials and that means that reinforcement material could be more than one in a single laminate. If the matrix is significantly different from layer, to layer it can be accepted as far as the matrix is chemically compatible to each other. If they are chemically incompatible, perfect bonding cannot be created.

In this study, finite element analysis of a laminate with a defective ply is analyzed. Finite element analysis will be conducted in a simple laminate assembly to analyze parametric values. $[0/90]_s$ stacking sequence is considered which is made with AS4/3501-6 material. The defective lamina will be assembled on the top surface of the laminate in this study as shown in the Figures 5.1.

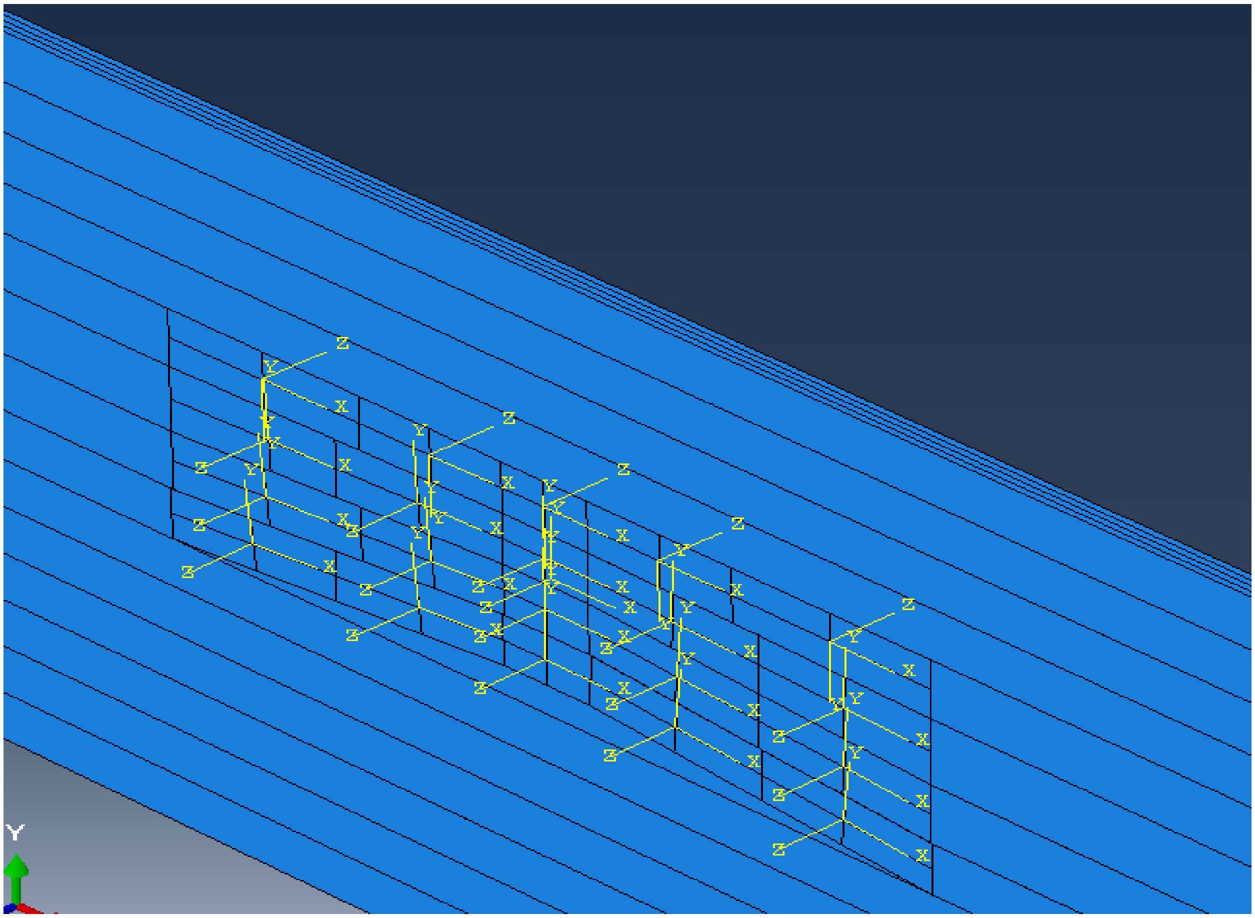


Figure 5.1 Assembly of a defective lamina

The reduction in the load carrying capacity and the locations of the stress concentrations is varied depending on the severity of the defect in a laminate. The influence of the defective ply in this case will not drastically reduce the load carrying capacity of the laminate but the maximum stress concentration is developed around the vicinity of the defect due to uneven volume fractions. Since 0 degree plys takes a max load during tension. The stress distribution in the 0 degree defective ply will be differing from the normal 0 degrees ply.

First ply failure loads are predicted using the mechanics of material equations, these values are validated using Abaqus results. For $[0/90]_s$ one of the 0^0 lamina is defective. For [0/90] s, the predicted first ply failure surface traction force of 1859 (lb/in) is applied to one end of the laminate. This load is the maximum load that 90^0 lamina can resist before it fails and reaches the global maximum stress value 8.3 Ksi with the strength ratio 1 and the global stress of 118 ksi is predicted in the 0^0 ply with a strength ratio of 2.7. The mode of failure in the 90^0 ply is a matrix in tension. The mode of failure in 0^0 ply is fiber in tension. First 90^0 plys fails and then the load gets evenly distributed to the surrounding 0^0 plys. Load carrying capacity gets reduced in these three defects gradually. The reduction in load carrying capacity for AS4/3501-6 is shown in the figure: 5.2 below.

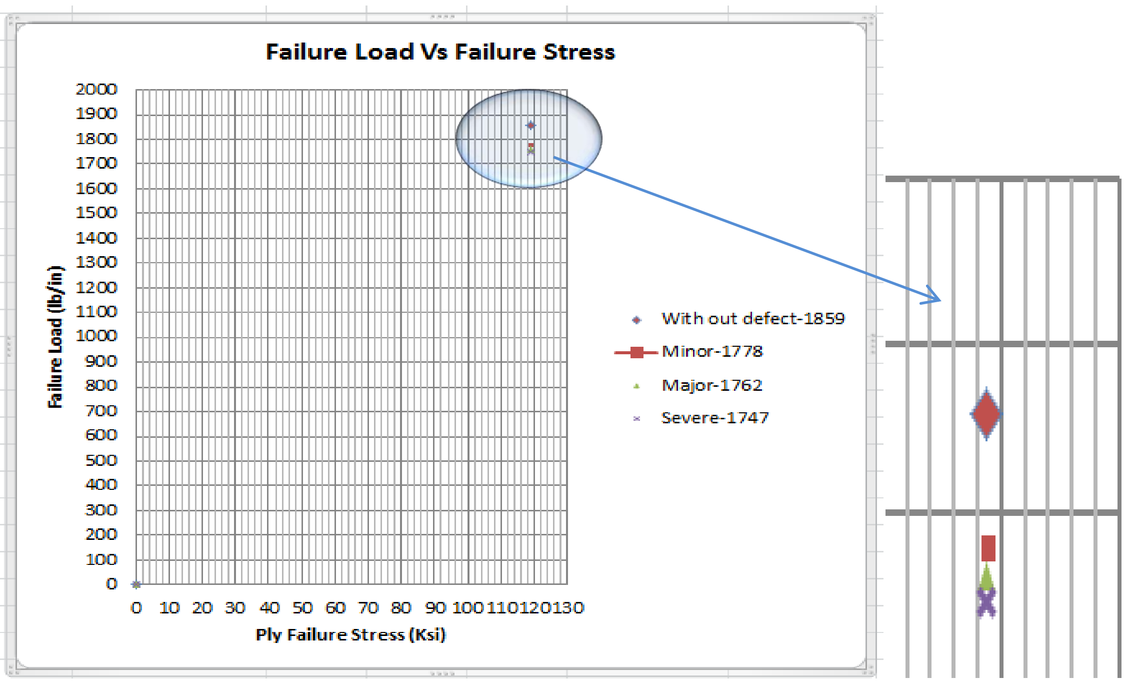


Figure 5.2 Reduction in the load carrying capacity

As we can absorve from the above plot the 0^0 lamina in a laminate with no defect resisted the load of 1859 lb/in (traction load 59589 lb/in^2), when 0^0 lamina reached the stress 118 ksi, and the laminate with minor defect on 0^0 lamina experienced the 118 ksi stress when it reached reduced load of 1778 lb/in (traction load 57000 lb/in^2) which reduced the whole laminate load carrying capacity to 4.3%. Similarly Laminate with major defect, reduced to 5.2% and severe defect 6.0 % reduction in load carrying capacity, which does not show much difference in the reduction of strength because the percentage variation in severity of these three different defects around 17-20 %.

1000 lbs/in (32051 lb/in^2) load is applied on one side of the four laminates contained (one without defect and other three are defective models). Due to the resin rich area and the uneven distribution of volume fraction in the lamina, stress concentrations are developed at the weakest point in a laminate. These stress values will get increased near the vicinity of the defect at the same loading conditions for the three different defects as shown in figure 4.3 and table 5.1

Table: 5.1 Stress values and percentage increase with applied load of 1000 lb/in

Cases	Defects	Stress (Ksi)	% Increase in stress
No defect	0	63	0
Minor	1	66	5
Major	2	67	6
Severe	3	68	7

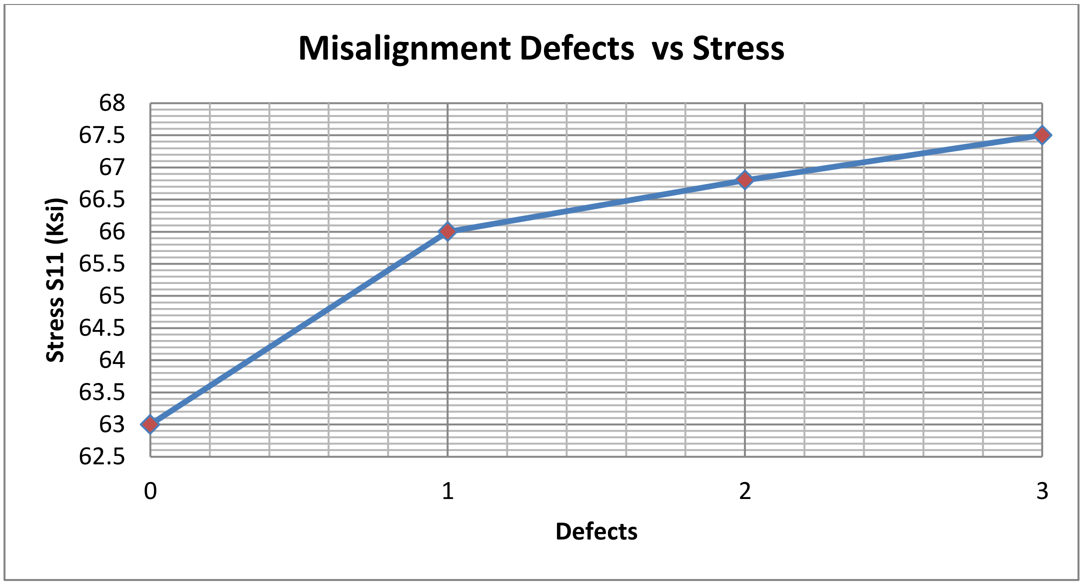


Figure: 5.3 Increase in the stress values in 0^0 ply along with an increase in the severity in defects

5.2 Strength ratio of (AS4/3501-6) Laminate

When failure does not occur in the lamina, the stress is low enough to fail which shows strength ratio greater than 1. As the material approaches failure, the strength ratio will be less than one.

Strength Ratio = σ_a/σ_{Actual}

Where σ_a ~ Allowable Stress or maximum value of stress, σ_{Actual} ~ Actual Stress

A 1000 lb/in load is applied on the surface of the laminate. The stress values get increased gradually as the severity of the defects gets increased. Since the applied load is less we may not abserve the failure, but the strength ratio gets decreased as the severity of the defective lamina gets increased in a laminate. The allowable stresses or Maximum value of stress for AS4/3501-6 during tension is 330 ksi. The actual stresses which are developed for the fixed load on a laminate are shown in table 5.1 above. The strength ratio reduces from 5.24 (no defect) to 4.89

(severe defect) which is a 7% reduction in strength. The strength ratios of three defects and without defect of a laminate is shown in table 5.2 and figure 5.4

Table 5.2 Decrease in strength ratio

Cases	Defects	Strength Ratio	Stress (Ksi)
No defect	0	5.24	63
Minor	1	5.00	66
Major	2	4.94	66.8
Severe	3	4.89	67.5

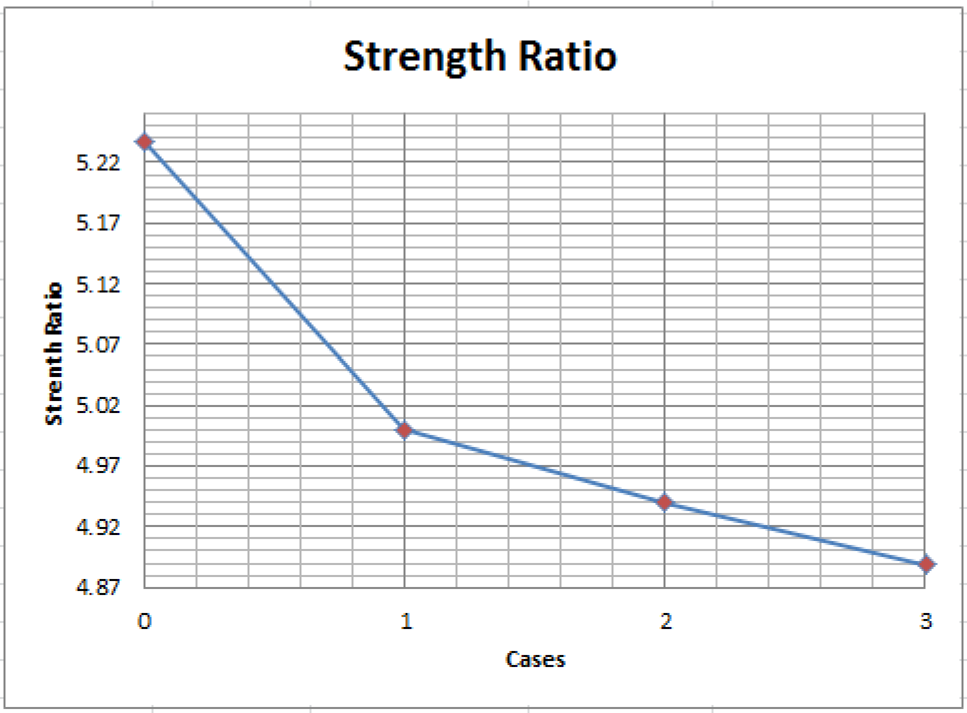


Figure 5.4 Decrease in strength ratio

5.3 Increase in strain value as the severity of the defect increases

Since there is a defect in a lamina the strain value of whole laminate gets increased as the severity of the defect gets increased. Strain value gets increased due to the reduction in the stiffness of the laminate. The figure below shows the plot where the strain values are increased at the failure loads.

Table 5.3 Increase in strain values

Cases	Defects	Strain
No defect	0	0.0055
Minor	1	0.0055
Mjor	2	0.0056
Severe	3	0.0068

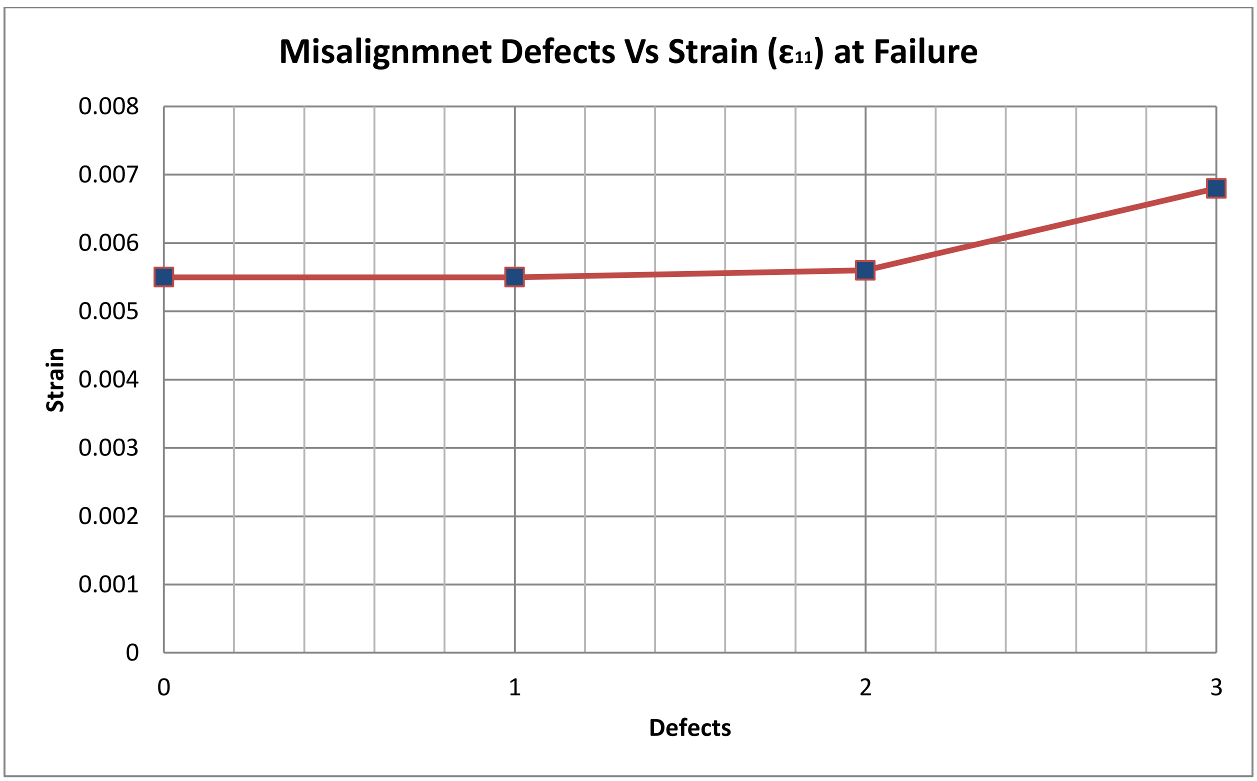


Figure: 5.5 Increase in strain values

5.4 Stress distribution around the defect

As the failure stresses are fixed, load gets varied on the three laminates. It is observed that the load carrying capacity gets reduced as the severity of the defect increases. Accordingly stress distribution of these three defects will be varied depending on the architecture of the defect. The snapshots of the results are taken when the model gets maximum stress values with the reduced loading condition. Figure 5.6 illustrates the stress values along the center of the defect in Y-axis in a laminate. In the plot the x-axis represents the width of the model and the y-axis represents the stress values at the each nodal point.

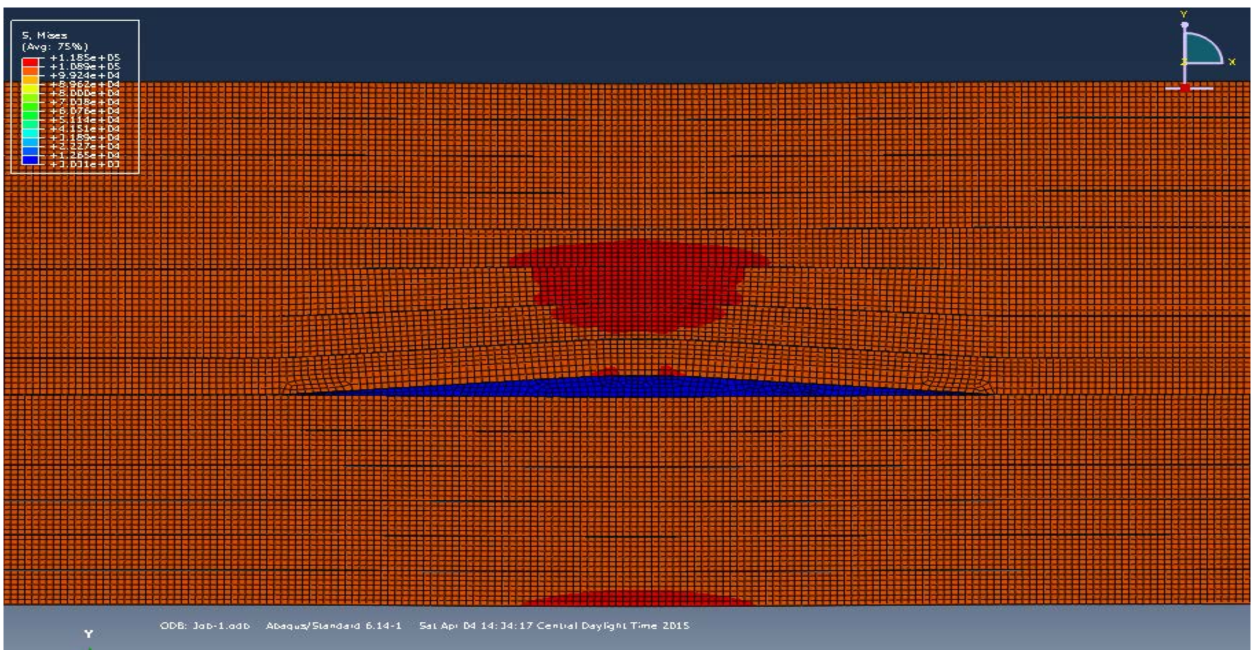


Figure 5.6 Stress distributions near the vicinity of the minor defect

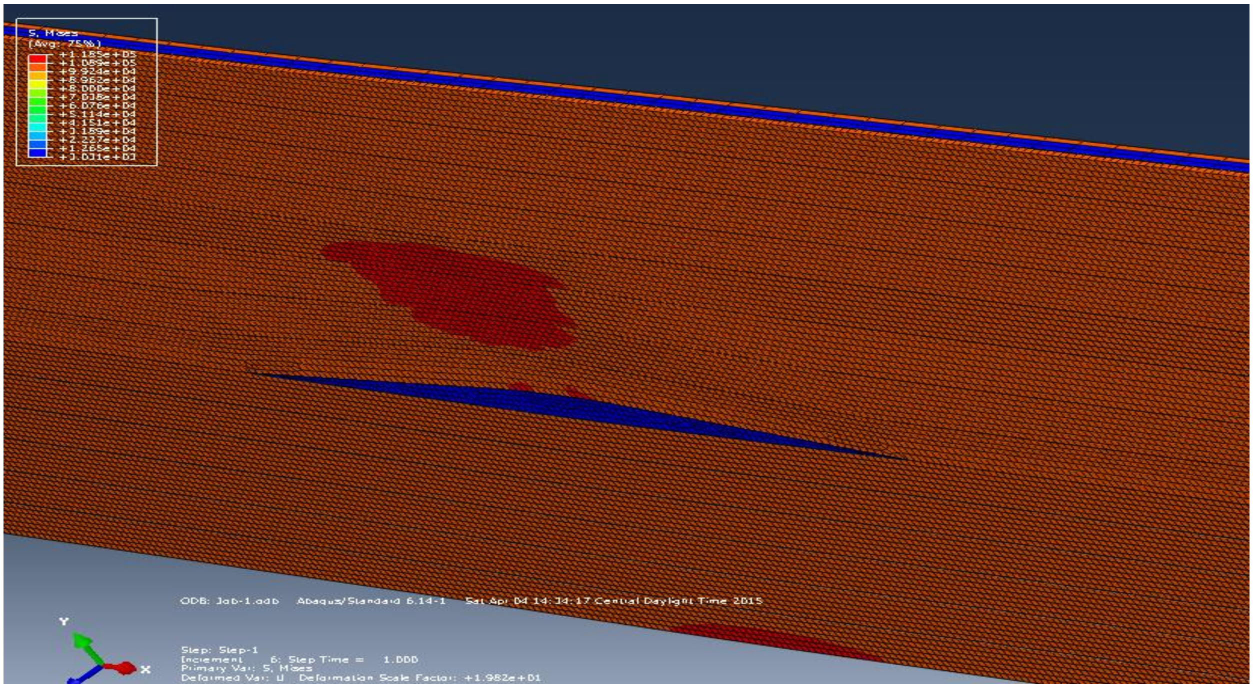


Figure 5.7 Stress distributions near the vicinity of the minor defect

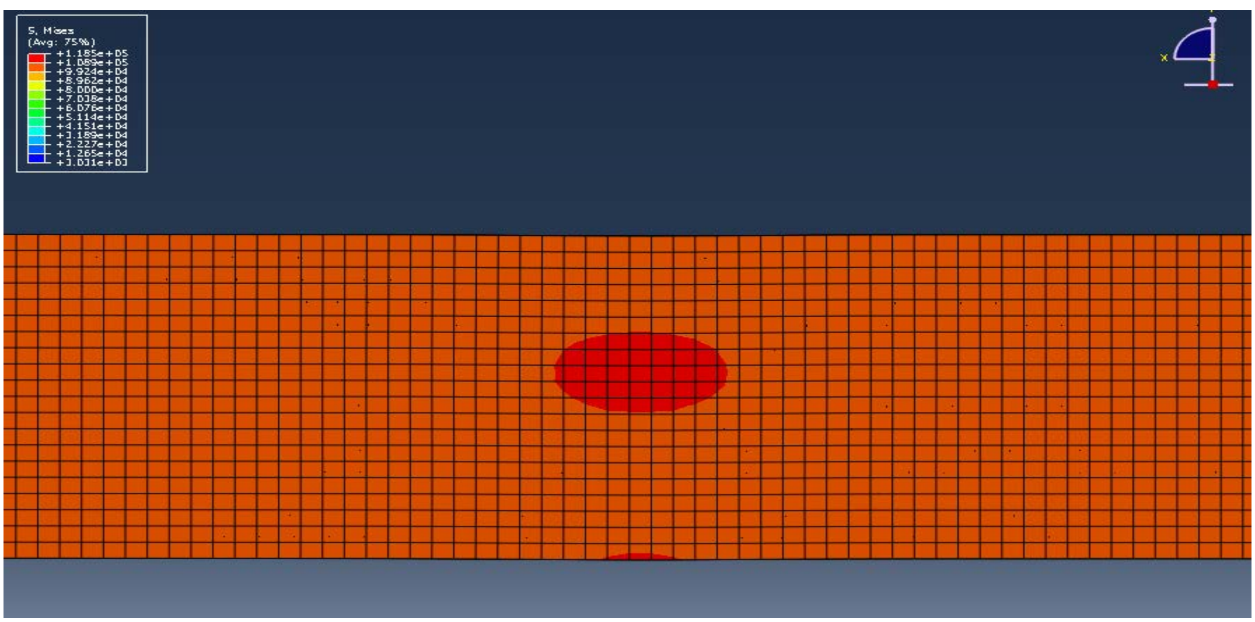


Figure 5.8 Stress distributions on the opposite side of the laminate

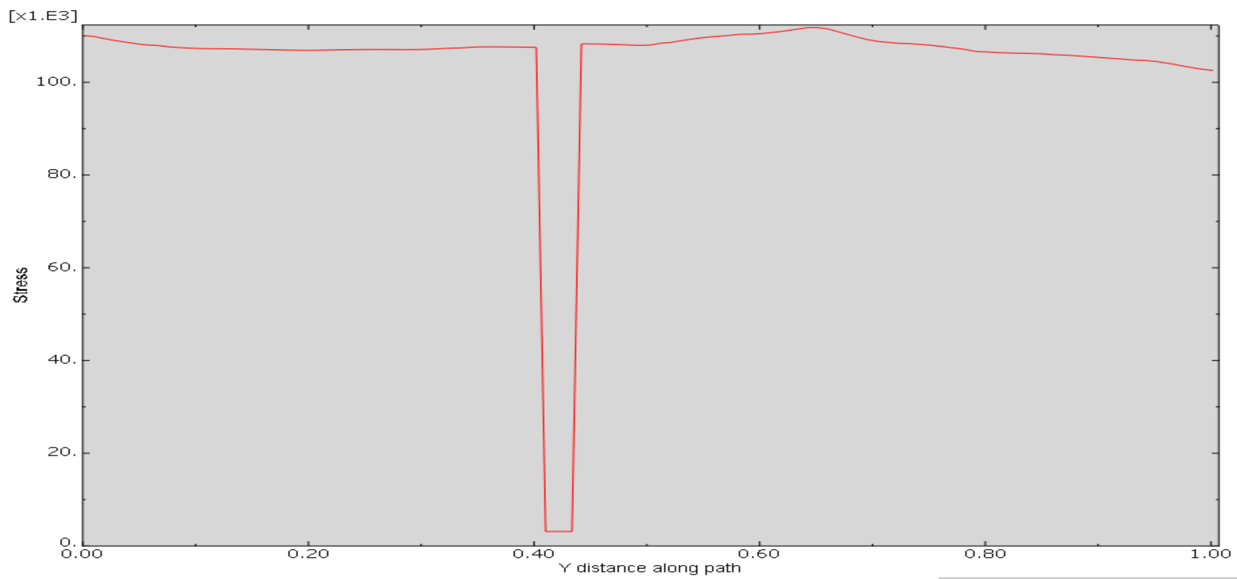


Figure 5.9 Stress distributions along the width of the minor defect

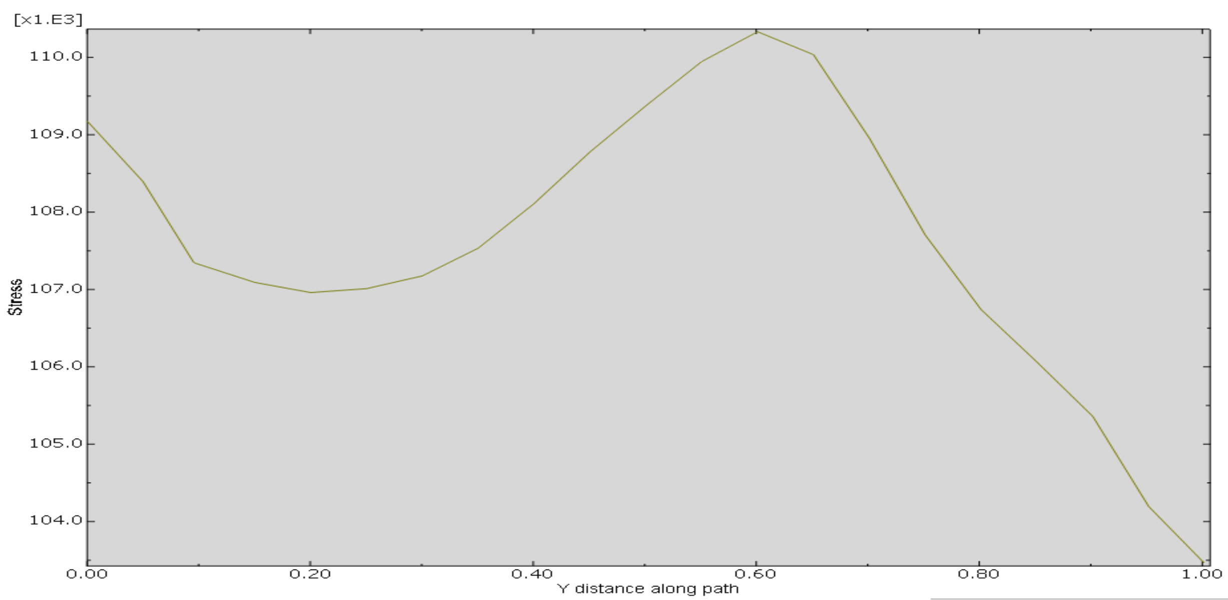


Figure 5.10 Stress distributions along the width of the minor defect on the opposite side of laminate

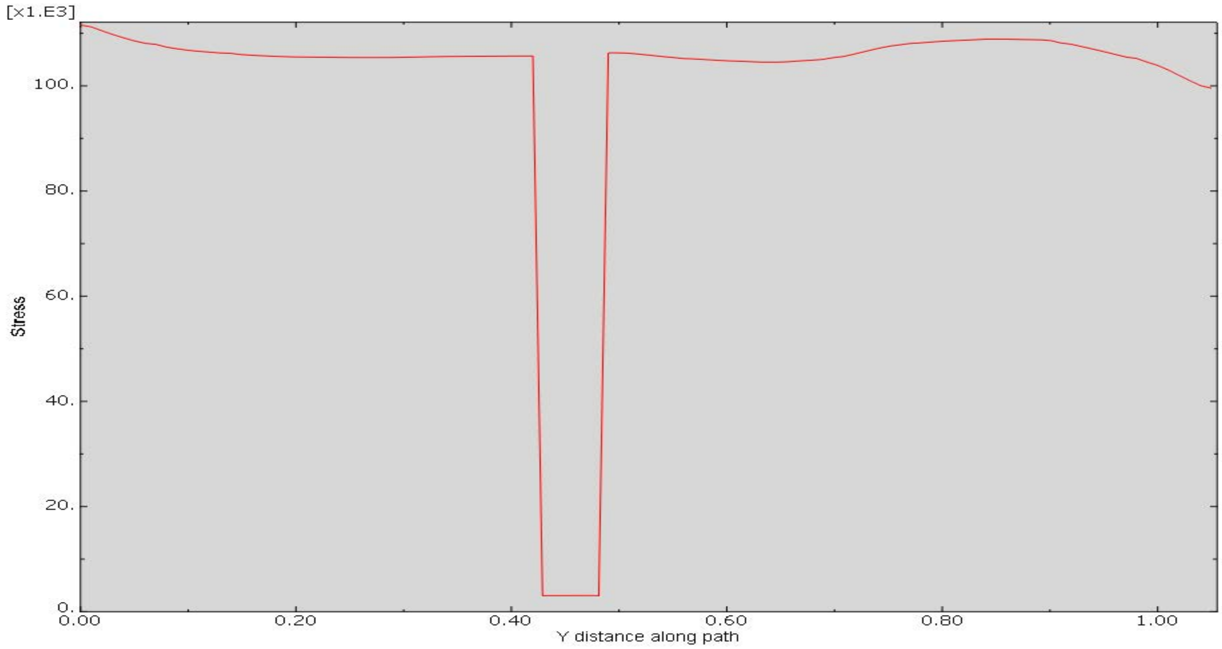


Figure 5.11 Stress distributions along the width of the major defect

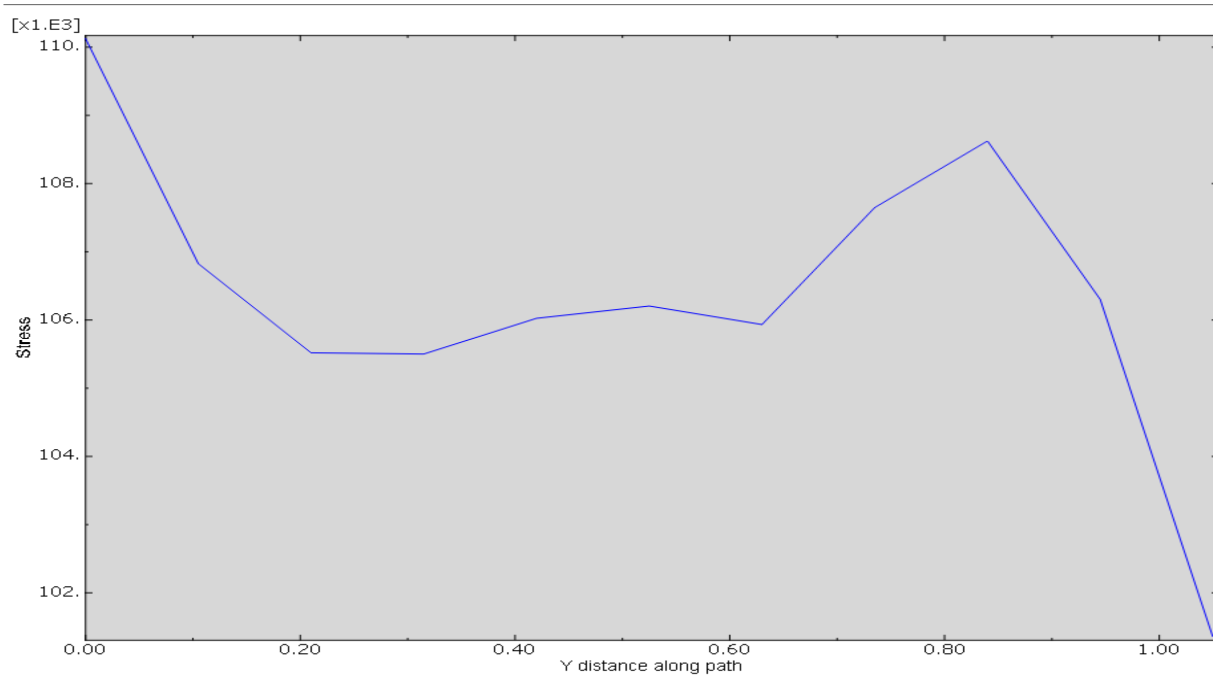


Figure 5.12 Stress distributions along the width of the major defect on the opposite side of laminate

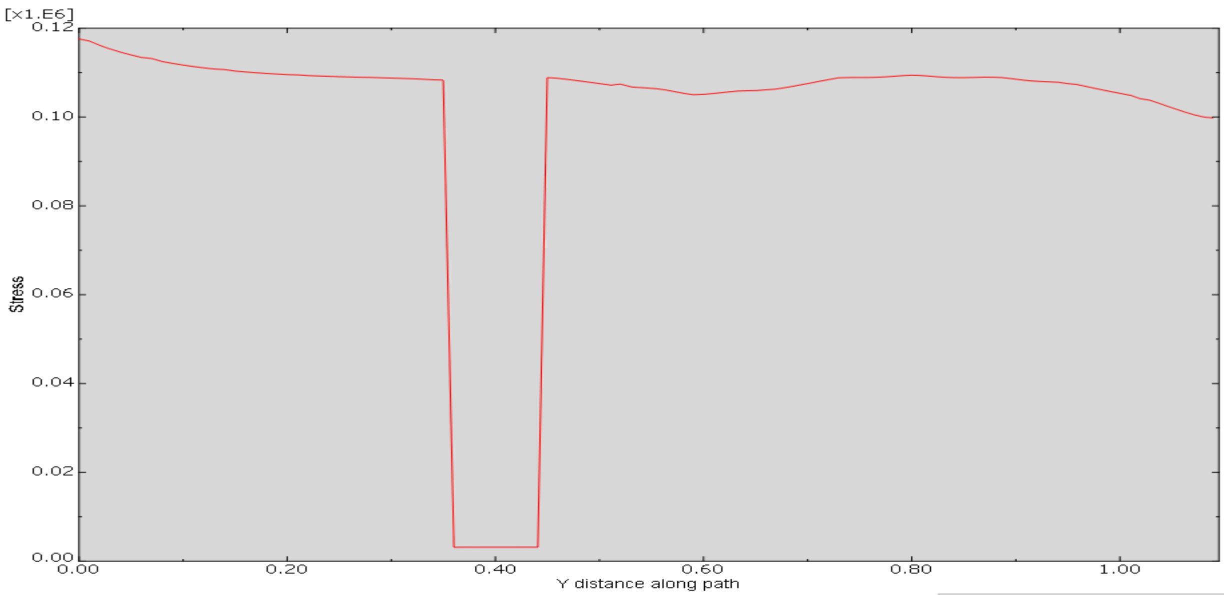


Figure 5.13 Stress distributions along the width of the severe defect

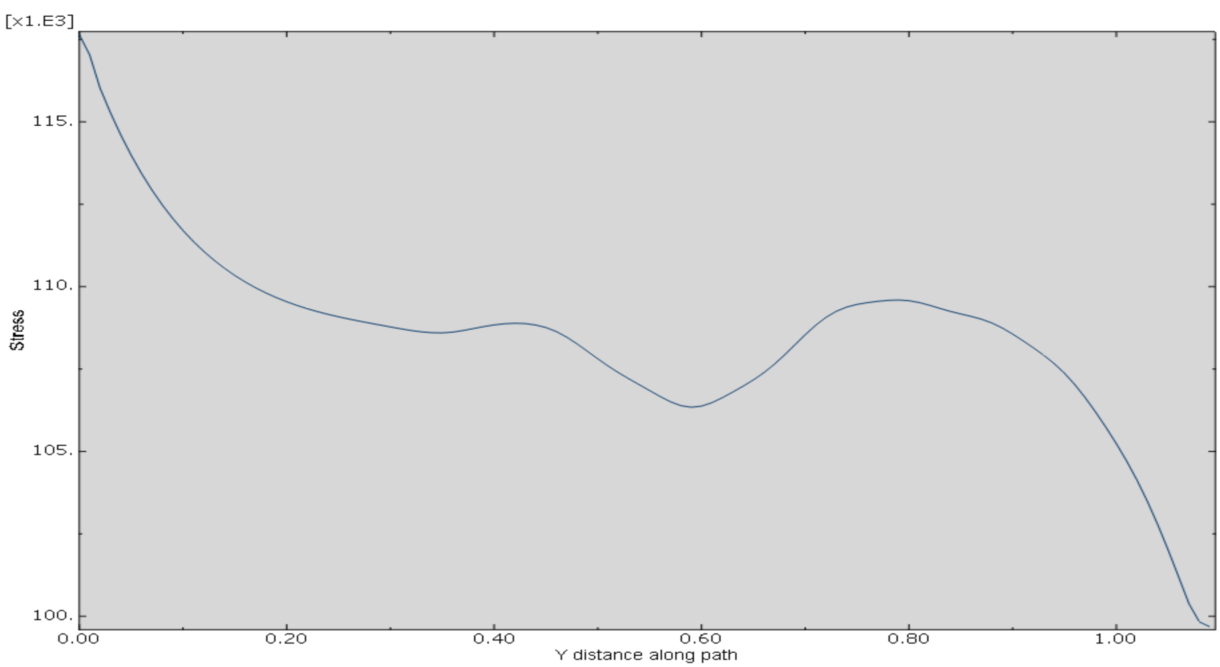


Figure 5.14 Stress distributions along the width of the severe defect on the opposite side of laminate

CHAPTER 6

FINITE ELEMENT ANALYSIS OF A DEFECTIVE LAMINA ASSEMBLED TO A LAMINATE $[0/90/45/-45]_s$

6.0 Laminate

In this analysis, a constant predicted load of 2184 lb/in (Surface traction load 35000 lb/in^2) is applied on the surface of four laminates, where one is without defect and other three are minor, major and severe defective 0^0 laminas which are assembled at top ply of the laminate as shown in the figure 6.1 In this study finite element analysis is used to analyze a laminate with a defective ply. Finite element analysis is performed in a simple laminate assembly to analyze parametric values. $[0/90/45/-45]_s$ stacking sequence is considered which is made with AS4/3501-6 material.

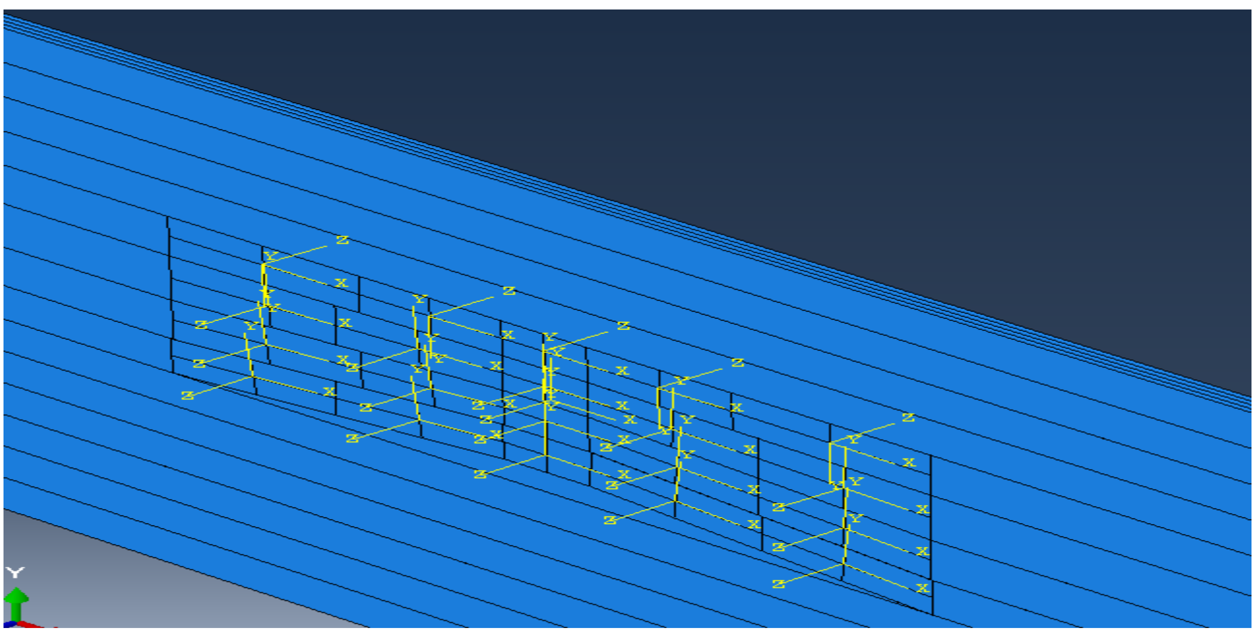


Figure 6.1 Assembly of a defective lamina

The reduction in the load carrying capacity and the locations of the stress concentrations is varied depending on the severity of the defect in a laminate. The influence of the defective ply in this case will not drastically reduce the load carrying capacity of the laminate but the maximum stress concentration is developed around the vicinity of the defect due to the uneven volume fractions, since 0 degree plys takes a maximum load during tension. The stress distribution in the 0 degree defective ply will be differ from the normal 0 degrees ply.

First ply failure loads are predicted using the mechanics of material equations and these values are validated using Abaqus results. For $[0/90/45/-45]_{s,}$ one of the 0^0 lamina is defective. For [0/90/45/-45] s, the predicted first ply failure surface traction force of 2184 (lb/in) is applied to one end of the laminate. This load will be kept fixed in this analysis to study the stress distribution on the three defective lamiantes. This load is the maximum load that the 90^0 lamina can resist before it fails and reaches the global Maximum Stress value 8.3 Ksi with the strength ratio 1. The global stress of 127 ksi is predicted in the 0^0 ply with a strength ratio of 2.6 and the global stress in 45/-45 is 33 ksi. The mode of failure in the 90^0 ply is a matrix in tension. The mode of failure in 0^0 ply is fiber in tension. First 90^0 plys fails and the load will be evenly distributed to the surrounding 0^0 plys. In this analysis most of the load is carried by the 0 plys, but the maximum stress locations are developed near the boundary conditions which are completely fixed in all the degrees of freedom. But on the other hand, there is an uneven stress distribution displays near the vicinity of the defect and the maximum stress values gets increased as the severity of the defect increases at the same load for all the three defective laminates. The increase in stress values are not much higher for minor and major defects but for severe one, the stress values are increased up 7 %. The stress increases rate is shown in the figure 6.2. The rise in stress levels are shown in table 6.3 and figure:6.4

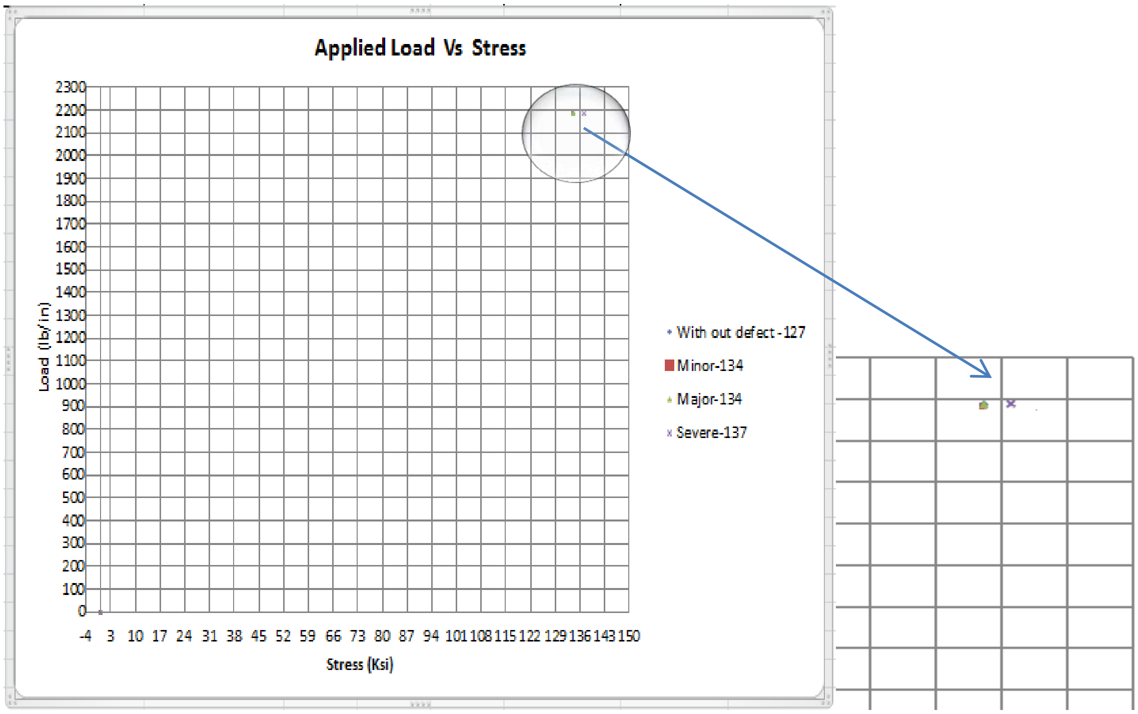


Figure 6.2 Stress increases in fixed load

Table: 6.1 Stress values and percentage Increase with applied load of 2184 lb/in

SL.No	Defect	Stress (Ksi)	% Increases
No defect	0	127	0
Minor	1	134	5
Major	2	134	5
Severe	3	137	7

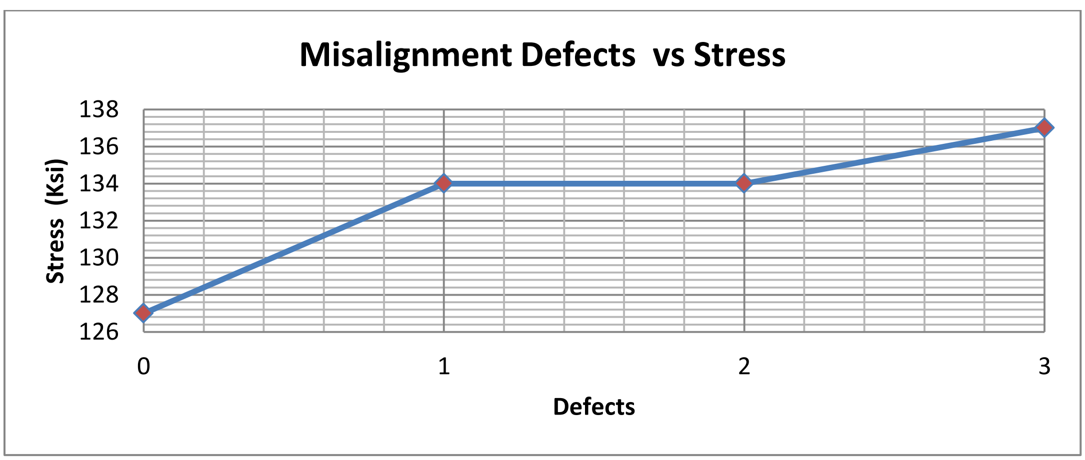


Figure: 6.3 Increase in the stress values in 0^0 ply along with an increase in the severity in defects

Table 6.2 Reduction in strength Ratio

Defects	Cases	Strength Ratio	Stress (Ksi)
No defect	0	2.60	127
Major	1	2.46	134
Major	2	2.46	134
Severe	3	2.41	137

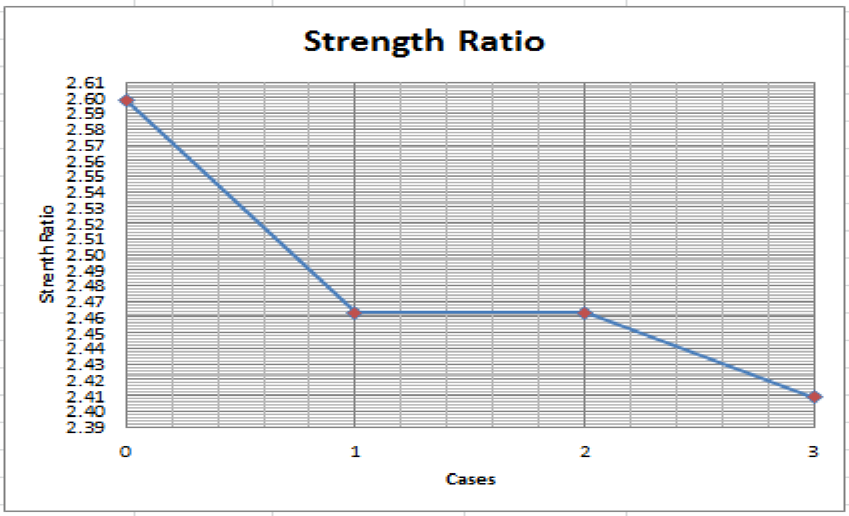


Figure 6.4 Reduction in Strength Ratio

As shown in the above plot strength ratio of the lamina got reduced from 2.60 to 2.41 wih an minimum application of load 1000 lb/in.

CHAPTER-7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The effect of in-plane fiber waviness is studied by creating laminates and analyzing them computationally by modeling both in-plane fiber tow waviness and resin rich pockets using finite element tool Abaqus. It concludes that, the effect of the defect in a lamaina will depend on the properties of the material and as the severity of the defect increases the load carrying capacity of both the lamina and laminate reduces.

AS4/3501-6

- The effect of major, minor, and severe fiber waviness and the resin rich area were analyzed in a lamina made with AS4/3501-6
- The load carrying capacity of the single lamina got reduced 13% for minor defect. 15% for major defect and 27% of severe defect.
- High stress concentrations are developed near the vicinity of the defect, the stresses are increased from 137 ksi to 187 ksi at an application of fixed load 1000ksi on the three laminas,
- The strength ratio of the lamina got reduced from 2.42 (no defect) to 1.78 (severe defect) at an applied load of 1000 lb/in
- Strain values got increased to 40 % as the severity of the defect increases at the failure loads of the lamina.

IM7/977-3

- The effect of major,minor, and severe fiber waviness and the resin rich area were analyzed in a lamina made with IM7977-3

- The load carrying capacity of the single lamina got reduced 15% for minor defect. 17% for major defect and 32% of severe defect.
- High stress concentrations are developed near the vicinity of the defect, the stresses are increased from 138 ksi to 204 ksi at an application of fixed load 1000ksi on the three laminas.
- The strength ratio of the lamina got reduced from 3.41 (no defect) to 2.30(severe defect) at an applied load of 1000 lb/in
- Strain values got increased to 45 % as the severity of the defect increases at the failure loads of the lamina.

Glass/Epoxy

- The effect of major, minor, and severe fiber waviness and the resin rich area were analyzed in a lamina made with glass/epoxy
- The failure was occurring in the boundary conditions, but the uneven stress distributions were developed near the vicinity of the defect.
- The load carrying capacity of the single lamina got reduced 25% for minor defect. 25% for major defect and 26% of severe defect.
- High stress concentrations are developed near the vicinity of the defect, the stresses are increased from 115 ksi to 154 ksi at an application of fixed load 800 lb/in on the three laminas,
- The Strength ratio of the lamina got reduced from 1.43 (no defect) to 1.07(severe defect) at an applied load of 800 lb/in.

Kevlar /Epoxy

- The effect of major, minor, and severe fiber waviness and the resin rich area were analyzed in a lamina made with Kevlar/Epoxy
- The load carrying capacity of the single lamina got reduced 14% for minor defect. 15% for major defect and 26% of severe defect.
- High stress concentrations are developed near the vicinity of the defect, the stresses are increased from 136ksi to 184ksi at an application of fixed load 1000ksi on the three laminas,
- The strength ratio of the lamina got reduced from 1.51(no Defect) to 1.11(severe Defect) at an applied load of 1000 lb/in.
- Strain values got increased to 41 % as the severity of the defect increases at the failure loads of the lamina

$[0/90]_S$ LAMINATE

- The three defective laminas are modeled and assembled together as a laminate.
- The load carrying capacity of the single lamina got reduced 5% for minor defect 6% for major defect and 7% for severe defect.
- High stress concentrations are developed near the vicinity of the defect, the stresses are increased from 63 ksi to 68 ksi at an application of fixed load 1000ksi on the three laminates,
- The Strength ratio of the lamina got reduced from 5.24(no defect) to 4.89(severe defect) at an applied load of 1000lb/in.

- Strain values got increased to 19 % as the severity of the defect increases at the failure loads of the laminate

[0/90/45/-45]s Laminate

- The three defective laminas are modeled and assembled on the surface of the laminate
- The load carrying capacity of the single lamina got reduced 5% for minor defect 5% for Major defect and 7% for severe defect.
- High stress concentrations are developed near the vicinity of the defect, the stresses are increased from 127 ksi to 137 ksi at an application of fixed load on the three laminas.
- The strength ratio of the lamina got reduced from 2.60(no defect) to 2.41(severe defect) at a First ply failure load of 2184lb/in.

7.2 RECOMMENDATIONS

Based on the knowledge gained in studing the in-plane fiber waviness and resin rich pockets the following areas can be researched upon:

- The effect of fiber waviness can be studied on a laminate for bending and twisting loads to study the delaminations.
- The laminate can be manufactured and tested to analyze the values obtain using FE predictions.
- Out of plane waviness can be studied using Finite element analysis.
- Effect of different patterns of resin rich areas can be studied.
- Multiple defects like fiber waviness and resin rich areas on a single lamina can be studied.

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APPENDIX

Modelling Of Defective Lamina in Abaqus

Create Part	Model – Create Part – 3D- Deformable Solid- Extrusion- Approximate Size (Depends)
Solid Extrusion (tow)	Sketch the section for the solid extrusion
Solid Extrusion (wavy tow)	Use spline or arc option to create a wavy pattern as shown in below figure (a) and (b)

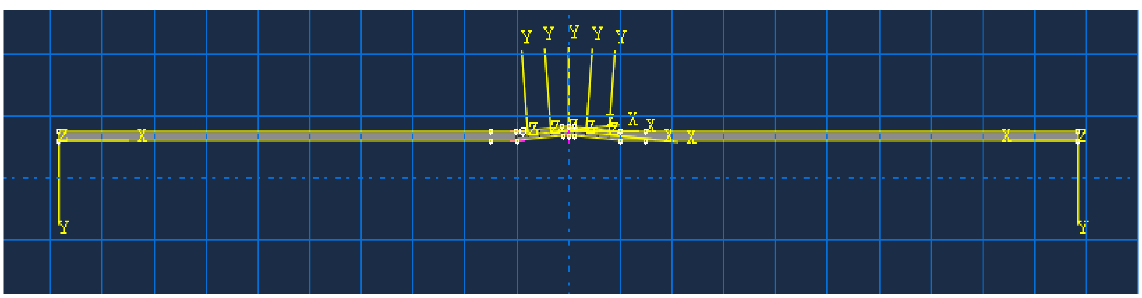

Figure (a) : Sketch of Wavy Tow

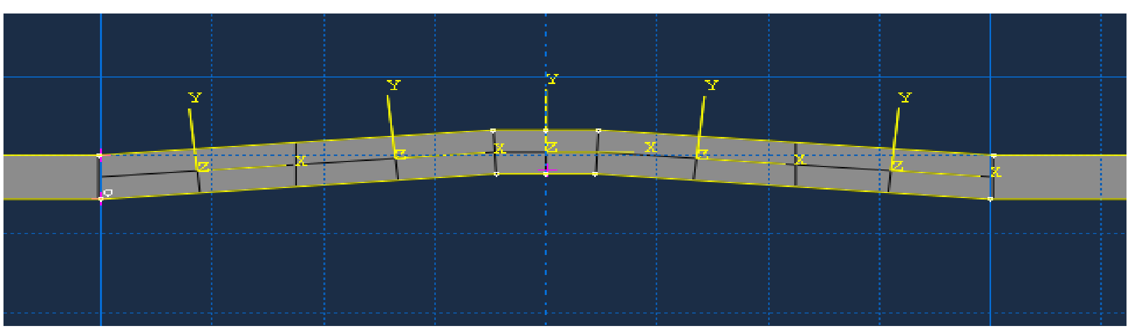

Figure (b) : Zoomed View

Since material orientation got misaligned partition done to specify local orientations of material	Tools- partition- face- Sketch-select face of the material to create partitions on the face and Select cell-extrude/sweep edges to extrude the partition as shown in figure (c) No. of partitions depends on the severity of the wave.
Material orientations	Create the path through the center of the face to assign the material orientation
Create datum Co-ordinate System	Module : Part – 2 line datum co-ordinate system –Rectangular- Select the lines which represents X and Y axis Repeate the process for all the partitions and weavy tows
Assigning Material Properties Creating Section Assigning the Section	Materials – Elasticity- Elatic- Engineering Constants – Enter Required Values. Select Section-Solid-Homogenous- ok Assign Sections Repeat this for all the parts

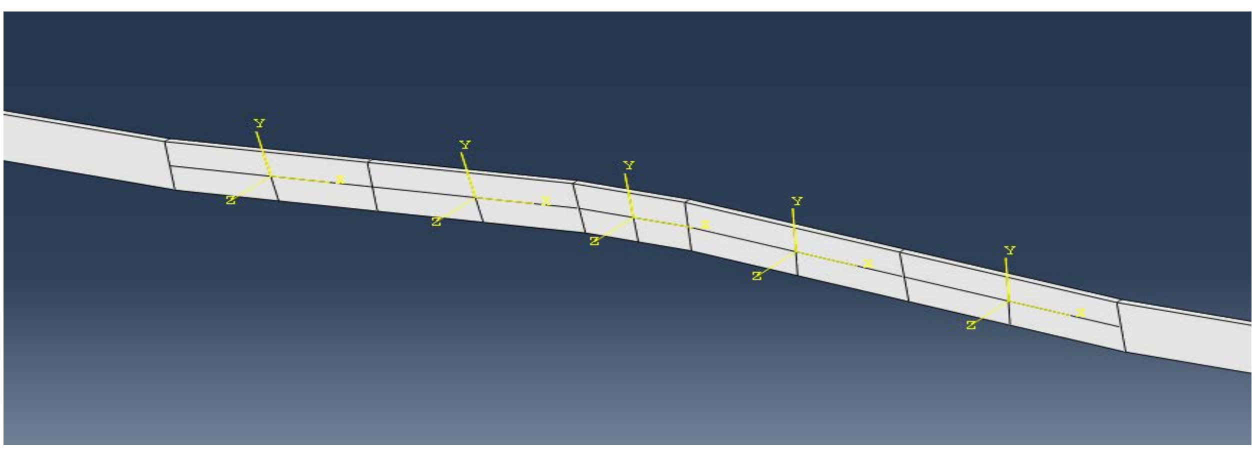

Figure: (c) Assigning Material Orientation and Datum Co-ordinate System

Creating Resin Rich Area	Copy the first Wavy tow model and Rename it considering resin rich packet, Trim all lines except bottom curvy line and join the two ends of curve by line to create closed section.
Assembly	Assemble all the tows together Instances-Select all the part and Translate Instances side by side.
Create Surfaces	Assembly- Surfaces-Select surfaces and name it orderly.
Tie Constraints	Consraints - Select Tie Constarints – Surface – Select Surfaces - Ok
Create Step	Initial – Static General – Continue – Ok
Create Boundary Conditions	Symmetry/ Anti- Symmetry / Encastre – OK – Encastre all DOF – Select One end surfaces of the Lamina.
Apply Loads	Load – Step-1 – Surface traction – Continue –Distribution = Uniform – Traction = General –Direction Vector (0,0,0) and (1,0,0)-Enter Magnitude(Example : 270000 lb/in^2)- ok
Submit Job	Run the Analysis and Post-Process