Technical University of Munich
Computational Mechanics Program
Software Lab 18/19

Software Lab Progress Report-1

Project Title:

Development of The Failure Criteria for Composites

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Abstract:

This report illustrates the progress made on the software lab project titled: "Development of the Failure Criteria for Composites". First, the research problem is addressed explaining the need for more advanced material models to cover complex aspects of composite materials behavior. Then, a summary of literature done in this filed is presented outlining multiple developed failure criteria for composites which are incorporated in most finite element commercial codes, these models are then compared to evaluate the strengths and limitations of each model. Based on this comparison, single approach is then recommended to be the most applicable for predicting failure pattern of composites. The previous knowledge is then applied to a simple tensile test modelled in ABAQUS to simulate the mechanical behavior of composites using different types of elements, loading conditions and fibers orientation within the composite layers. Finally, a future timeline plan is proposed for the project which includes the major activities to be done in order to achieve the research objective of the project and fulfill the deadlines of the software lab course.

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1.Introduction

1.1 Overview and Problem Statement:

Composite materials have proven their potential for use in high performance engineering applications over the last fifty years. High mass, specific stiffness, strength and energy absorption, high functionality (e.g. through tailored anisotropy), and optimized structural concepts (e.g. due to high levels of design integration) are the main reasons for specifying composites. Hence, composites offer product manufacturers several advantages in terms of weight and performance. Today, the benefits of components designed and produced in composite materials instead of metals are well recognized by many industries. However, composite materials also come with several challenges during product design when compared to normal materials such as metals. Delamination, micro-cracking leading to eventual failure, and other mechanisms, that are not factors in designing with metals, are very important for composites. In this context having comprehensive failure criteria for composites become an important point of concern, because these criteria should establish when the failure takes place and predict the post-failure behavior. The analysis and simulation of the failure of composite laminated structures are quite cumbersome tasks, due to the complex anisotropic behavior and differences in tensile and compressive strengths, the failure mechanisms are very different from those of traditional metallic structures where brittle and ductile failure modes are observed under different loading conditions. The current major finite elements software packages such as (ABAQUS, ANSYS, LS-DYNA) include some basic failure models for composites, such models are based on stress quadratic functionals (e.g. Tsai & Wu,1971) and imply failure once the maximum stress/strain limits of the material are exceeded. These models however are only capable of covering simple aspects of the complex materials in 3D, more advanced material models are therefore required to extend the basic models for more complex scenarios. In finite element analysis context, this can be achieved by utilizing the user programmable subroutines supported by software packages such as ABAQUS, LS-DYNA. The user material routine (UMAT) for example allows for the creation of user-defined materials with their own constitutive equations and failure criteria. As a result, this programming feature makes it an ideal tool for the development of composite materials failure models.

1.2. Aims and Objectives:

The aim of this project is to develop user defined material models within FEM framework that can capture more complex aspects of composite materials behavior and failure modes, this is achieved through the following suggested steps:

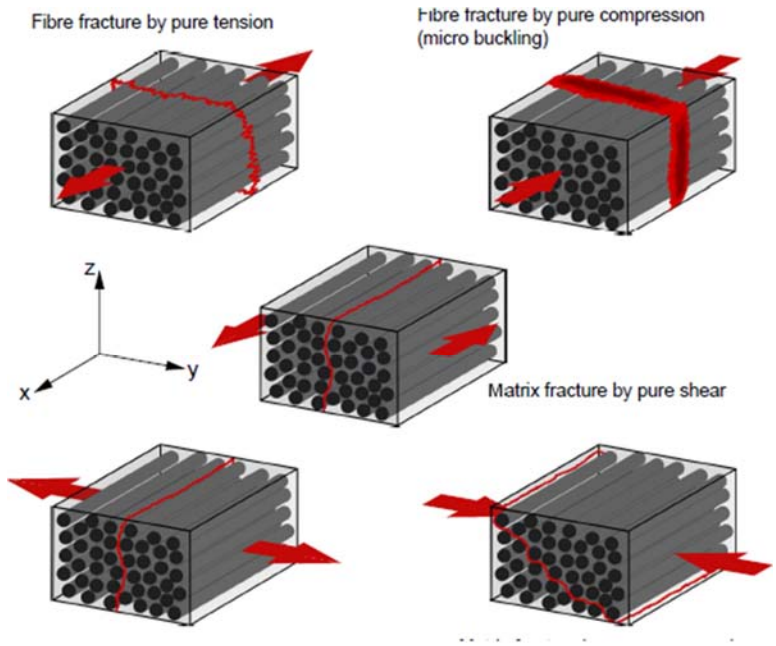
- Outline the current available failure theories for composites in literature.
- Comparing the most commonly used failure models for composites, illustrating the strengths and shortcomings of each approach.
- Extending an existing anisotropic material model for the failure behavior of composite using FORTRAN programming interface linked to ABAQUS.

2.Literature Review

2.1 Mechanical behavior of composites and failure modes:

Generally, composite materials can be derived by combining two or more materials to use the benefit of the characteristics of each material and especially their interaction. Thus, the properties of a composite are normally better than those of its individual constituents. Considering fiber reinforced plastics, the following distribution of the individual tasks can be given: the fiber provides the strength and stiffness, whereas the matrix gives rigidity and environmental resistance.

Separating the main mechanical functions of the fibers and the matrix in a composite structure provides the following functionalities. The fibers carry the main load while the matrix binds the fibers and transfers the load between the fibers. In addition, the matrix isolates the fibers, so that individual fibers can act separately which slows or even stops crack propagation Furthermore, the failure is strongly affected by the type of the used material, the fiber distribution and the applied load. Since a composite material can consist of multiple layers, failure may occur within a single ply (intralaminar fracture) or between two plies (interlaminar fracture). The latter is also known as delamination of the bonded plies. Furthermore, a fracture oriented transversely to a ply is called translaminar fracture



Fracture modes in single unidirectional composite layer

The main failure modes of laminated fiber-reinforced composites are the following:

- Delamination: the process through which composite materials made of different plies stacked together tend to delaminate. The bending stiffness of delaminated panels can be significantly reduced, even when no visual defect is visible on the surface or the free edges. The physics of delamination is quite understood, and one of the best numerical tools to predict the propagation of delamination consists in the use of Decohesion Elements. These elements have been developed and implemented in commercial Finite Element (FE) codes, like ABAQUS.
- Matrix compression failure: what is commonly considered as matrix compression failure is shear matrix failure. Indeed, the failure occurs at an angle with the loading direction, which is the evidence of the shear nature of the failure process.
- Matrix tensile failure: the fracture on the surface resulting from this failure mode is typically normal to the loading direction. Some fiber splitting at the fracture surface usually can be observed.
- Fiber compression failure: this failure mode is largely affected by the resin shear behavior and imperfections such as the initial fiber misalignment of the angle and voids. Typically, kinking bands can be observed on a smaller scale, and they are the result of the fiber micro-buckling, matrix shear failure or fiber failure.

- Fiber tensile failure: this failure mode is explosive. It releases large amounts of energy. In structures that cannot redistribute the load, it typically causes catastrophic failure.

2.2 Failure theories for composites:

Many different failure criteria have been formulated in order to predict failure loads for general stress states. In this text is proposed the following classification, in which they could be grouped in two main groups firstly:

1. Failure criteria neglecting interactions between different stress components.

2. Failure criteria considering interactions between different stress components.

Criteria belonging to the first group are the simplest ones and they usually propose one inequality for each one of the three in-plane stresses (or strain) components.

In the remaining criteria, the failure in one direction may be sensitive to loads along other directions (including shear).

This last group can be divided into the following two subgroups.

a. Criteria proposing one single inequality to define the failure envelope.

b. Criteria proposing a combination of interactive and non-interactive conditions.

In general, one more Failure Indexes (FI) corresponds to each failure criteria. A FI exceeding the unitary value means that failure occurs, according to the applied criterion.

Some useful definitions are reported to a better understanding of the following concepts:

- Failure indices: represent a phenomenological failure criterion in that only an occurrence of a failure is indicated and not the mode of failure.
- Strength ratio: is a more direct indicator of failure than the failure index since it demonstrates the percentage of applied load to the failure criteria. Strength ratio is defined as: Strength Ratio (SR) = Allowable Stress / Calculated Stress.

The following failure theories are briefly described below:

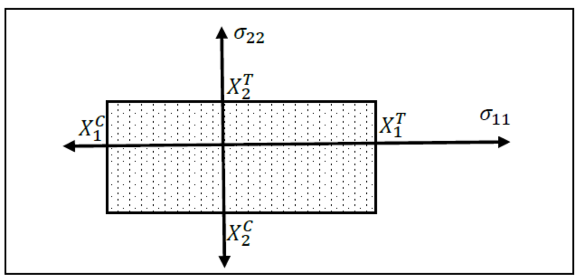
- Maximum Stress Criterion:

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

This approach considers stress components separately and assumes that the failure would occur when any of the stress components reach the allowable strength in a corresponding direction. This criterion proposes following inequalities to examine failure.

$$\sigma_{11} \geq X_1^T \ , \qquad \sigma_{11} \leq -X_1^C \ , \qquad \sigma_{22} \geq X_2^T$$
$$\sigma_{22} \leq -X_2^C \ , \qquad \sigma_{12} \geq S \ , \qquad \sigma_{12} \leq \ -S$$

Where X is the allowable stress and subscripts 1, 2 corresponds to fiber and transverse directions, while superscripts T, C stands for tension and compression, respectively; and S is the shear allowable. According to the criteria, if any of these inequalities is satisfied, the failure would occur. This failure envelop is graphically represented below



- Maximum Strain Criterion

This theory is based on the maximum normal strain theory by St. Venant and the maximum shear stress theory by Tresca as applied to isotropic materials. The strains applied to a lamina are resolved to strains in the local axes. Failure is predicted in a lamina, if any of the normal or shearing strains in the local axes of a lamina equal or exceed the corresponding ultimate strains of the unidirectional lamina. Similar to the maximum stress approach, allowable strains are utilized in this criterion. Failure criteria is given in terms of inequalities as follows:

$$\epsilon_{11} \geq e_1^T \ , \qquad \epsilon_{11} \leq -e_1^C \ , \qquad \epsilon_{22} \geq e_2^T$$
$$\epsilon_{22} \leq -e_2^C \ , \qquad \epsilon_{12} \geq e_{12} \ , \qquad \epsilon_{12} \leq \ -e_{12}$$

Where e is the allowable strain in the corresponding direction.

➢ Tsai-Hill Criterion:

This theory is based on the distortion energy failure theory of Von-Mises distortional energy yield criterion for isotropic materials as applied to anisotropic materials by Hill. Distortion energy is a part of the total strain energy in a body. The strain energy in a body consists of two parts; one due to a change in volume and is called the dilation energy and the second is due to a change in shape and is called the distortion energy. It is assumed that failure in the material takes place only when the distortion energy is greater than the failure distortion energy of the material. Then, Tsai adapted it to a unidirectional lamina. The criterion was simplified by assuming plane stress conditions (e.g. out of plane stresses are neglected). Tsai also claimed that material properties are equal in the direction transverse to the fibers, with these simplifications, failure criterion takes the following form:

$$\frac{1}{X^2}\sigma_1^2 - (\frac{1}{X^2})\sigma_1\sigma_2 + \frac{1}{Y^2}\sigma_2^2 + \frac{1}{S^2}\tau_{12}^2 = 1$$

The Tsai–Hill failure theory is a unified theory and thus does not give the mode of failure like the maximum stress and maximum strain failure theories do. The Tsai–Hill failure theory does not also distinguish between the compressive and tensile strengths in its equations. However, unlike the maximum strain and maximum stress failure theories, the Tsai–Hill failure theory considers the interaction among the three unidirectional lamina strength parameters.

➢ Tsai-Wu Criterion:

This failure theory is based on the total strain energy failure theory of Beltrami. Tsai-Wu applied the failure theory to a lamina in plane stress. This failure theory is more general than the Tsai–Hill failure theory because it distinguishes between the compressive and tensile strengths of a lamina. A lamina is considered to be failed if:

$$F_1\sigma_1 + F_2\sigma_2 + F_{11}\sigma_1^2 + F_{22}\sigma_2^2 + F_{66}\sigma_6^2 + 2F_{12}\sigma_1\sigma_2 = 1$$

$F1$ and $F11$ are obtained by tensile and compressive tests in longitudinal direction; on the other hand, $F2$ and $F22$ are obtained from tests in transverse direction. $F66$ can be obtained by calculating shear strength in shear test. As a result, the constants are:

$$F_1 = \frac{1}{X_1^T} - \frac{1}{X_1^C} \qquad F_{11} = \frac{1}{X_1^T X_1^C}$$

$$F_2 = \frac{1}{X_2^T} - \frac{1}{X_2^C} \qquad F_{22} = \frac{1}{X_2^T X_2^C}$$

$$F_{66} = \frac{1}{S^2}$$

The remaining constant, $F12$, must be evaluated by the biaxial test; however, it is a complicated test to conduct. As an alternative, Tsai and Hahn proposed that, $F12 = -0.5\sqrt{F11F22}$, can be used.

- Hoffman Criterion:

The Hoffman criterion is an extension of Tsai-Hill theory, this theory takes into account the difference in tensile and compressive allowable stresses by using linear terms in the equation. The resulting failure index in Hoffman's theory for an orthotropic lamina in a general state of plane stress (2D) with unequal tensile and compressive strengths is given by:

$$FI_{Hoffaman2D} = \left(\frac{1}{X_t} - \frac{1}{X_c}\right)\sigma_1 + \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right)\sigma_2 + \frac{\sigma_1^2}{X_t X_c} + \frac{\sigma_2^2}{Y_t Y_c} + \frac{\sigma_{12}^2}{S^2} - \frac{\sigma_1 \sigma_2}{X_t X_c},$$

To calculate the strength ratio and then the margin of safety, the following terms are defined:

Hoffman's failure index (2D) coefficients	
$\boldsymbol{F_1 = \frac{1}{X_t} - \frac{1}{X_c}}$	$F_{22} = \frac{1}{Y_t Y_c}$
$\boldsymbol{F_2 = \frac{1}{Y_t} - \frac{1}{Y_c}}$	$F_{66} = \frac{1}{S^2}$
$\boldsymbol{F_{11} = \frac{1}{X_t X_c}}$	

In case of composites modelled using solid elements, so for a 3D mesh and stress state, the relation of failure index becomes:

$$FI_{Hoff3D} = C_1(\sigma_2 - \sigma_3)^2 + C_2(\sigma_3 - \sigma_1)^2 + C_3(\sigma_1 - \sigma_2)^2 + C_4\sigma_1 + C_5\sigma_2 + C_6\sigma_3 + C_7\tau_{23}^2 + C_8\tau_{13}^2 + C_9\tau_{12}^2,$$

With the following failure index coefficients in 3D:

Hoffman's failure index (3D) coefficients	
$C_1 = \frac{1}{2}\left(\frac{1}{Z_tZ_c} + \frac{1}{Y_tY_c} - \frac{1}{X_tX_c}\right)$	$C_6 = \left(\frac{1}{Z_t} - \frac{1}{Z_c}\right)$
$C_2 = \frac{1}{2}\left(\frac{1}{X_tX_c} + \frac{1}{Z_tZ_c} - \frac{1}{Y_tY_c}\right)$	$C_7 = \frac{1}{S_{23}^2}$
$C_3 = \frac{1}{2}\left(\frac{1}{X_tX_c} + \frac{1}{Y_tY_c} - \frac{1}{Z_tZ_c}\right)$	$C_8 = \frac{1}{S_{13}^2}$
$C_4 = \left(\frac{1}{X_t} - \frac{1}{X_c}\right)$	$C_9 = \frac{1}{S_{12}^2}$
$C_5 = \left(\frac{1}{Y_t} - \frac{1}{Y_c}\right)$	

In each case, the following material data are required:

-Xt,Xc are the maximum allowable stresses in the 1-direction in tension and compression;

- Yt,Yc are the maximum allowable stresses in the 2-direction in tension and compression;

-Zt,Zc are the maximum allowable stresses in the 3-direction in tension and compression;

-$S12$ is the maximum allowable in-plane shear stress;

-$S23$ is the maximum allowable 23 shear stress;

-$S13$ is the maximum allowable 13 shear stress.

- Hashin Criterion:

In 1980, Hashin [11] made further studies on Tsai-Wu Criterion. He implies that Tsai-Wu Criterion had improvements over previous ones and it provided good fit with test data. However, Hashin also proposed that different failure modes can occur, and a single quadratic function may not predict all of failure modes. On the other hand, proposing a failure criterion with higher than a quadratic degree would make things more complicated. As different from previous studies, Hashin examined fiber and matrix failure separately. By that way, instead of continuous failure surface a piece-wise continuous failure one is obtained. The Hashin criterion proposes a combination of four interactive and non-interactive conditions in order to distinguish between matrix or fiber failure caused by tension or compression. The conditions for failure being given by the following inequalities:

a) Matrix Failure for compression ($\sigma 22 \geq 0$)

$$\left(\frac{\sigma_{22}}{Y^T}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \geq 1$$

b) Matrix failure for tension (σ22<0)

$$\left(\frac{\sigma_{22}}{2S^T}\right)^2 + \frac{\left[\left(\frac{Y^C}{2S^T}\right)^2 - 1\right]\sigma_{22}}{Y^C} + \left(\frac{\tau_{12}}{S^L}\right)^2 \geq 1$$

c) Fiber failure for tension (σ11≥0)

$$\left(\frac{\sigma_{11}}{X^T}\right)^2 + \left(\frac{\tau_{12}}{S^L}\right)^2 \geq 1$$

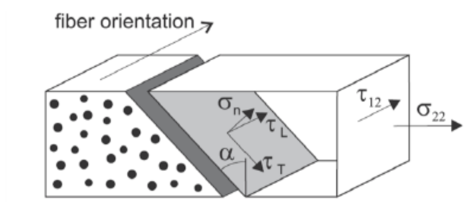
d) Fiber failure for compression (σ11<0)

$$-\frac{\sigma_{11}}{X^C} \geq 1$$

In formula *b)* the term ST is the transverse shear strengths which is very difficult to measure experimentally. An analytic relation is suggested:

$$S^T = Y^C \cos(\alpha)\,(\sin(\alpha) + \frac{\cos(\alpha)}{\tan(2\alpha)}$$

where α is the angle of fracture plane as graphically depicted in the figure below:

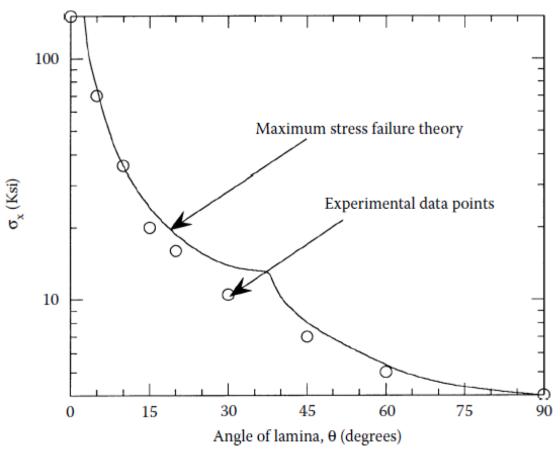


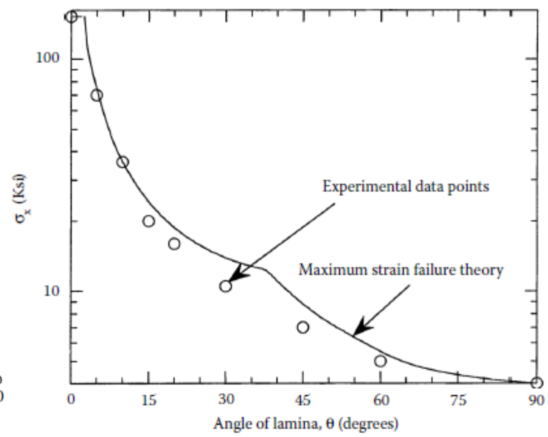
Angle of fracture plane of an unidirectional lamina subjected to transverse compression and in-plane shear

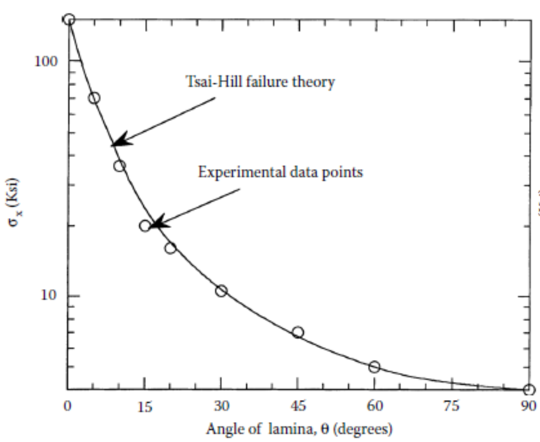
2.3 Comparison with experimental results:

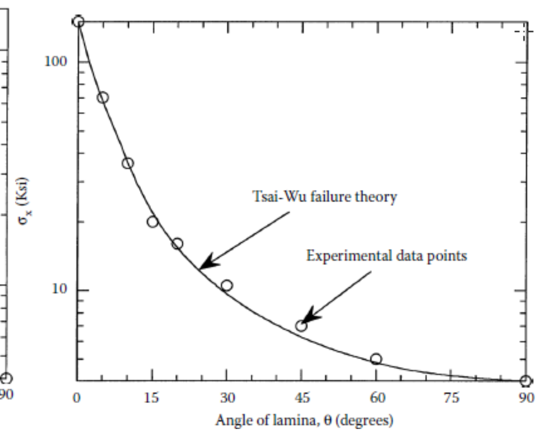
Tsai compared the results from various failure theories to some experimental results. He considered an angle lamina subjected to a uniaxial load in the x-direction, σx, as shown below, the failure stresses were obtained experimentally for tensile and compressive stresses for various angles of the lamina

The comparison for the four failure theories is shown in the figures below:









Observations from the figures are:

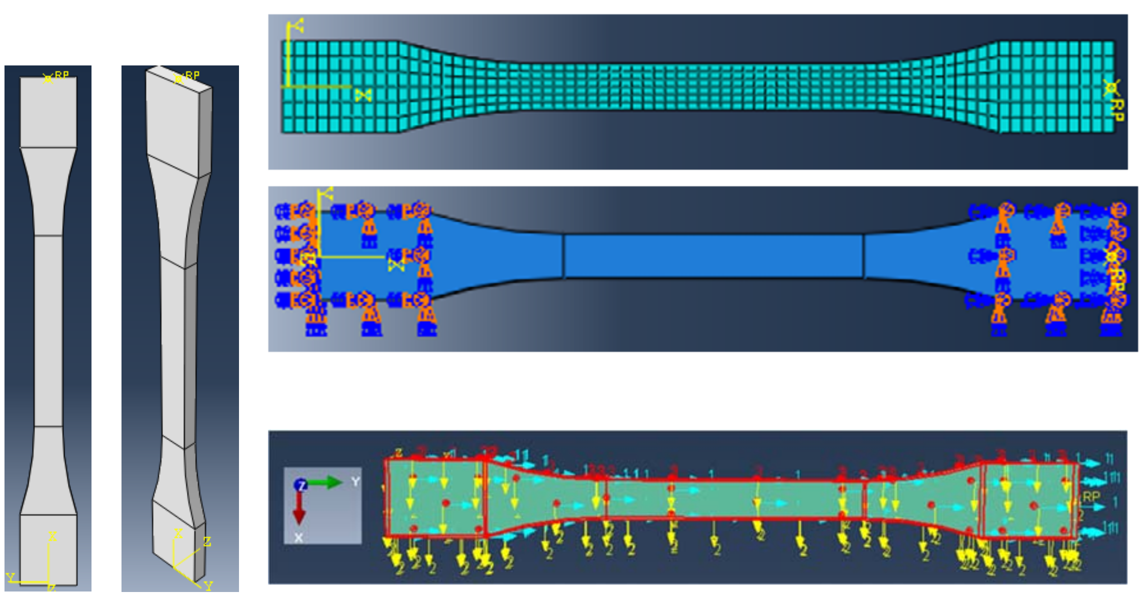
-The difference between the maximum stress and maximum strain failure theories and the experimental results is quite pronounced.

- Tsai–Hill and Tsai–Wu failure theories' results are in good agreement with experimentally obtained results.

-The variation of the strength of the angle lamina as a function of angle is smooth in the Tsai–Hill and Tsai–Wu failure theories but has cusps in the maximum stress and maximum strain failure theories. The cusps correspond to the change in failure modes in the maximum stress and maximum strain failure theories.

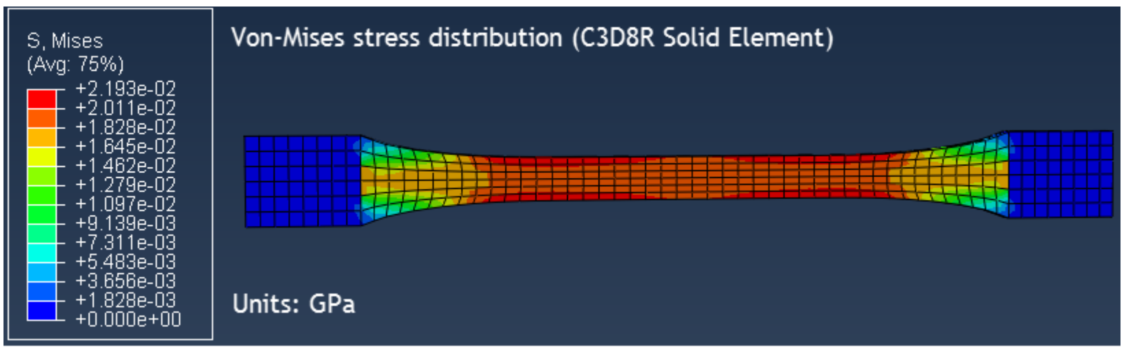
3. Research Methodology

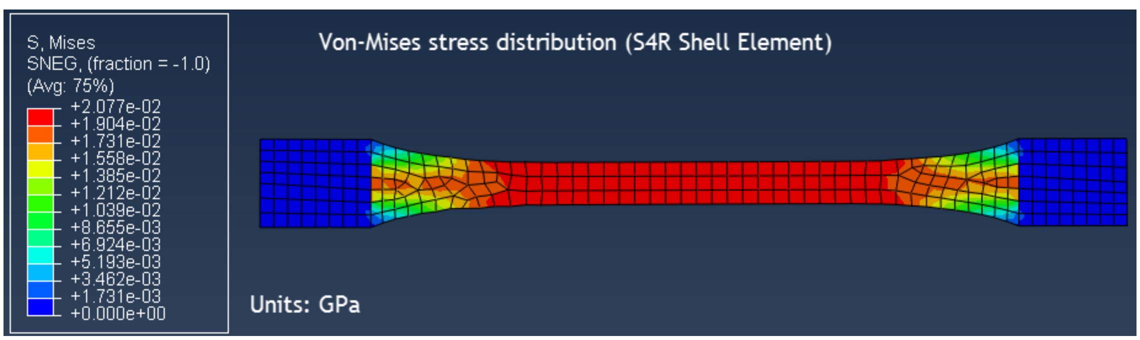
In order to visualize the behavior of an anisotropic material in context of finite element analysis, a simple tensile test is simulated in ABAQUS, first the specimen geometry is modelled in the drawing board interface, the specimen is modelled using three type of elements (solid, shell and membrane elements), the specimen is also portioned into multiple parts to allow for application of loads and boundary conditions as per the test setup. A standard elastic anisotropic material is then defined and assigned to the specimen, the material parameters entered include Young's Modulus, Shear Modulus and Poisson ration for the three principal directions, it should be noted also that since anisotropic material model is defined, the material ordination axes need to be defined with respect to the global coordinates of the model (e.g. longitudinal/transverse fiber directions).With respect to loading and boundary conditions, a concentrated longitudinal force of 1 kN is applied to a predefined reference point acting as the master node for one end of the specimen, the load is applied in a tabular format, the specimen is fixed for all six DOF on one end while only the longitudinal DOF is released on the other end, linear elastic analysis is performed for this model. The following figures preview the major steps done for the preparation of the FE model

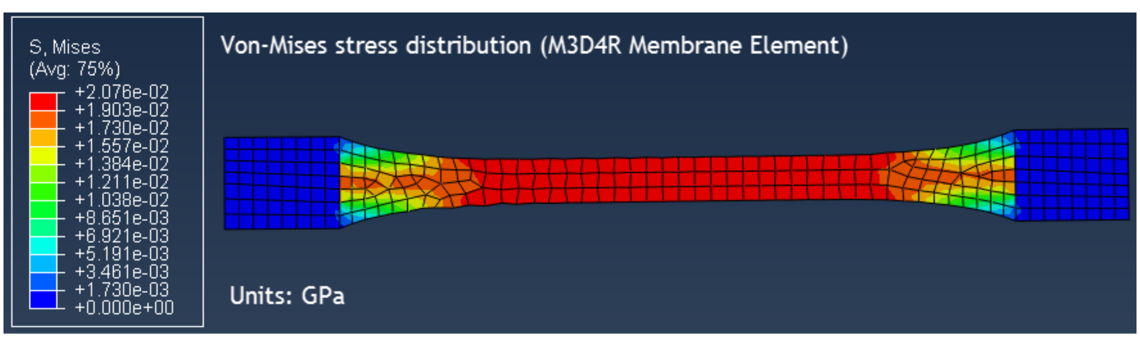


4. Initial Results and Findings

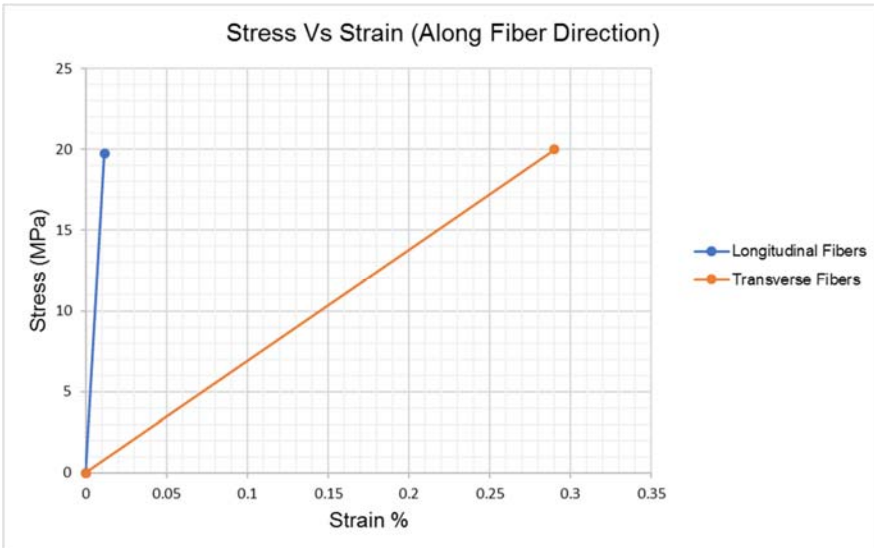
The figures below show the distribution of equivalent stresses as per Von-Mises theory under the applied tensile loading using three different FE formulations. it can be inferred from the contour results that the difference of maximum von mises stresses values between the three models is relatively small, only 2.8% between solid and shell elements while shell and membrane element stresses are almost identical. Considering the close numerical values between the three models, the specimen geometry and the loading direction (in-plane). Dimensional reduction of the model can be applied here to a plane stress problem.



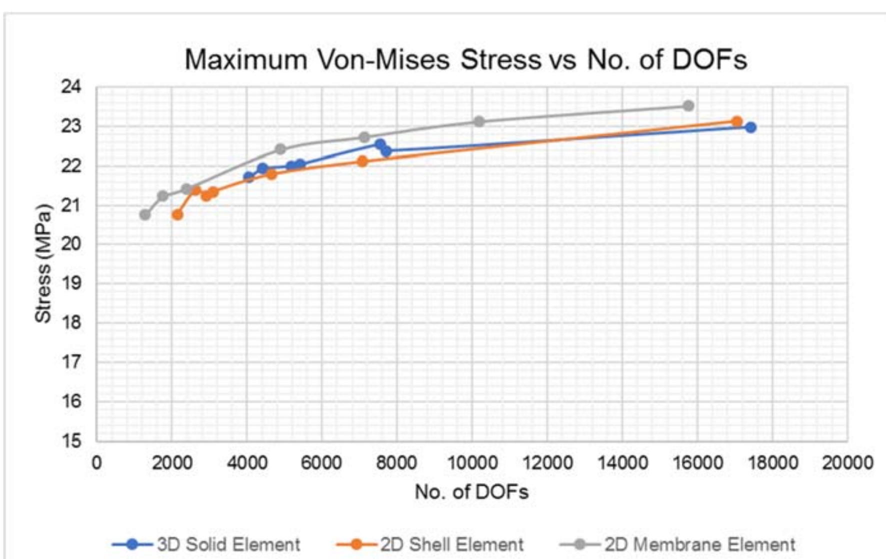




The chart below describes the elastic directional stress strain behavior for the defined anisotropic material in ABAQUS, with two different ordinations of the fibers, along and transverse the specimen longitudinal direction. It can be inferred form the chart, that the model acquires higher stiffness when the fibers are mounted longitudinally.



The chart below shows the variation of maximum von-mises stress captured in the model with respect to the mesh density represent by the total number of degree of freedoms to be solved for, the curves show an increase in the stress values with mesh refinement for the three element types discussed earlier. However, the average change in stress values is not significant (2% for solid elements, 4% for shell and 4.6% for membrane elements). It can be also noted that membrane and shell elements provide an adequate prediction of stress values with lesser number of variables to solve for.



5. Future Schedule of work

The following table shows the planned tasks during the summer semester period with the expected time required for finishing these tasks. It also highlights the deadlines for the review assessments and the fixed meeting dates with the project supervisors.

Task Name/Milestone	Duration (Days)	Date/Start Date	Expected Finish Date
Group Meeting #2	-	8-May-19	-
Submission of 1st progress report	1	10-May-19	-
Preparing presentation slides for 1st review	9	8-May-19	17-May-19
Submitting draft version of first presentation to supervisors	-	14-May-19	-
Submitting final presentation slides for 1st review	-	18-May-19	-
1st Review Presentation	-	21-May-19	-
Development for the provided anisotropic user-defined material model	24	18-May-19	11-Jun-19
Group Meeting #3	-	12-Jun-19	-
Submission of 2nd progress report	-	13-Jun-19	-
Adding enhanced features to the developed material model in Fortran	27	12-Jun-19	9-Jul-19
Group Meeting #4	-	10-Jul-19	-
Submission of 3rd progress report	-	11-Jul-19	-
Preparing presentation slides for 2nd review	12	10-Jul-19	22-Jul-19
2nd Review Presentation	-	23-Jul-19	-
End of lecture period for Summer Semester 19/20	-	27-Jul-19	-

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