MECH3900 Coursework 2 - Composites

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January 2024

Group 16

Contents

UNIVERSITY OF LEEDS

Executive Summary

This report aims to determine what the best material for the R22 horizontal helicopter stabilizer is, carbon fibre epoxy is compared to the aluminium material initially used. The main aim while determining the most suitable material is to reduce the weight of the stabiliser while still maintaining a deformation similar to or less than that of the aluminium stabiliser as well as maintaining safety. Tests were carried out to observe the effect of altering the number of plies and orientation of angles on the deflection and stress and a failure analysis was subsequently carried out. This study recommends 10 plies, oriented at 90-120-150-90-90-90-150-120-90, to be the optimal design with a 32.3% reduction in weight.

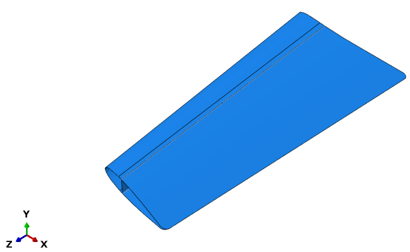
1 Introduction

The horizontal stabiliser of the R22 for the Robinson Helicopter Company is currently made of aviation aluminium. The report compares whether a composite material could replace the current aluminium to provide other advantages to the aircraft design/performance and the Robinson Company, such as a lighter weight and higher strength-to-weight ratios. It may also be more cost-effective to use this material due to a longer life span. Another advantage which will not be explored in this report is having greater design flexibility due to the complex shapes that composites can be moulded to, allowing for more optimised helicopter stabiliser designs. The objective of this analysis is to substantially reduce the weight of the stabiliser, whilst maintaining a deformation no more than that of the aluminium stabiliser. At the same time evaluate the risk of failure with the new material. The report follows a similar structure to this method analysis, starting by describing the methods and geometry used to represent the stabiliser. This is followed by the tests being performed on the model and the results of these tests. Finally, the analysis of the results and a recommendation for the best composite to use out of all of the ones that have been tested.

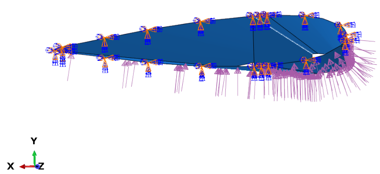
2 Method

2.1 Geometry, Boundary Conditions and Loads

The stabiliser that the geometry represents is the R22 helicopter stabiliser. The geometry has been approximated using a plate model part in the Abaqus 2019 Software. The thickness is added to the correct sections to mimic the thickness of the metal and create a 3D part, without having to mesh over this 3D section. Using a plate model is advantageous as the mesh of the model can be much more accurate using smaller element sizes as there is no geometric thickness resulting in significantly fewer elements. Also, the computational time is much faster when performing the analysis due to fewer elements. However, it is recognised that using the plate model will cause a loss in accuracy to the model as further geometry like rivets becomes very difficult to implement following the same methodology. For this means of examination, the model has been simplified not to include the reinforcing plates as the joins between the material cannot be accurately represented in this type of model and will create stress rises that may not occur in practice. These points can also introduce potential points of failure within the model and stress singularities into the model. Therefore, as they have a small impact on the deflection of the geometry and the model still accurately represents the physical stabiliser, the new model can be seen in Figure 1a.



(a) Isometric View of the stabiliser.



(b) Boundary Conditions and the area where the loading is applied to the stabiliser.

Figure 1: The different views of the geometry representing the stabiliser in the Abaqus Software.

Missing from the geometry still are the rivets and brackets that link all the metal plates together. To counteract this missing feature the geometries are all combined as if they are fused as one piece of metal giving a similar effect as being joined by rivets. The rivets also created some deformation in the model which has not been incorporated as without dimensions this is complex to judge. Having the rivets in the model will create stress risers and as they are not included some accuracy will be omitted from the model however, as a local stress directly related to the rivets is not being measured the missing rivets effect will be negligible.

The load has been applied to the underside of the wing at the three panels shown just as in the previous test to ensure comparability of the results. A pressure load has been used to mimic the effect of the stabiliser subjected to the loads of a real-life flight situation. Loads of 0.00306MPa, 0.00368Mpa and 0.000903MPa have been used for the three seconds. Similarly, the boundary conditions have been left as encastre at the root of the wing tip. These can be seen in Figure 1b

2.2 Materials

The material being used in this model is a carbon epoxy composite. The material properties of this composite are shown in Table 1. In the comparison model created from aviation aluminium, the material

Table 1: Table of properties of the carbon-epoxy composite.

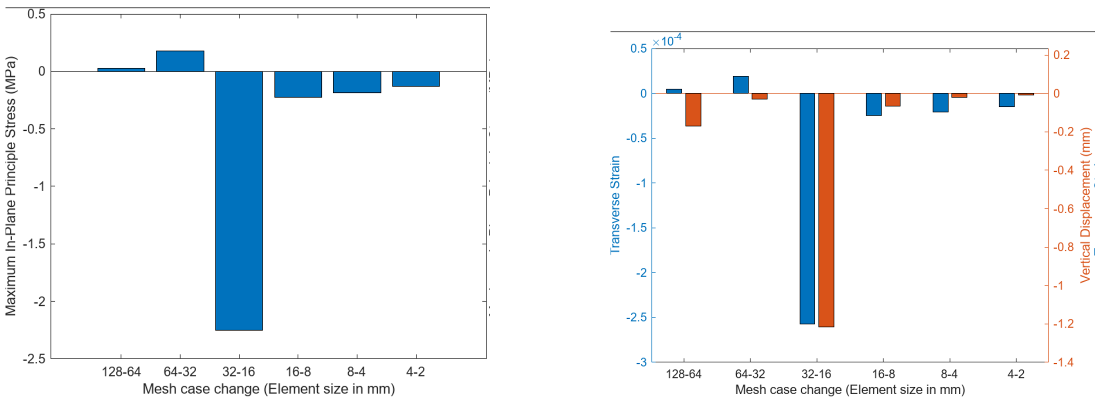
Property	Units	Carbon-epoxy
Nominal cured ply thickness	mm (inch)	0.130 (0.0051)
Nominal fibre volume	%	58
Nominal laminate density	g/cm^3 (lb/in^3)	1.57 (0.057)
Longitudinal modulus E_1	GPa (Msi)	131 (19.1)
Transverse modulus E_2	GPa (Msi)	8.8 (1.27)
In-plane shear modulus G_{12}	GPa (Msi)	5.0 (0.73)
Major Poisson's ratio V_{12}		0.27

is set up as a linear elastic material with a Young's Modulus of 69 GPa and a Poisson's ratio of 0.3. This is applied to all sections of the model, with only the thickness of each section changing.

To create the lamina composite a reference direction from the aerofoil tip to the root was used throughout each test. With a global coordinate system to align the fibres. The composite layup feature on Abaqus was used to represent the composite used within the model. This was verified as a valid model for a composite through the technique shown in Appendix 2.

2.3 Elements and Mesh

The geometry is modelled as a 3D shell feature so an element type to best represent the model is the S4R shell element. To determine the element size and therefore mesh density that should be used to represent the model, a mesh convergence test was performed. The results of this test can be seen in Figure 2. The geometry in Figure 1 is used to perform this sensitivity test and contains a single lamina with an orientation of 0° from the reference direction and a section thickness of 1mm. To ensure that this test is valid for the rest of the analysis the vertical deflection (U2), maximum in-plane stress and transverse strain (E22) have been examined. As the highest stresses and strains are located towards the root of the stabiliser the values have been measured at the node below the stabiliser has been used to determine these values. For the deflection which is maximum at the other end of the beam, the values have been obtained from the point on the lower surface of the wing under the spar at the tip.



(a) Maximum In-Plane Stress.

(b) Longitudinal Strain and Vertical Displacement.

Figure 2: Mesh Convergence test for the Longitudinal Strain and the Vertical Displacement measured consistently at the same point for each of the different mesh size cases.

The results of this test show that a constant element length of 8mm provides a very good approximation of the values for the three parameters, with a clear convergence pattern for each of the parameters. A mesh error for the vertical deflection of 0.0959mm has been calculated.

2.4 Tests and Outputs

To determine the ply orientations to take forward in testing a standard single-ply 1mm thick lamina was used along with different fibre orientations to determine which orientations gave the smallest deflection

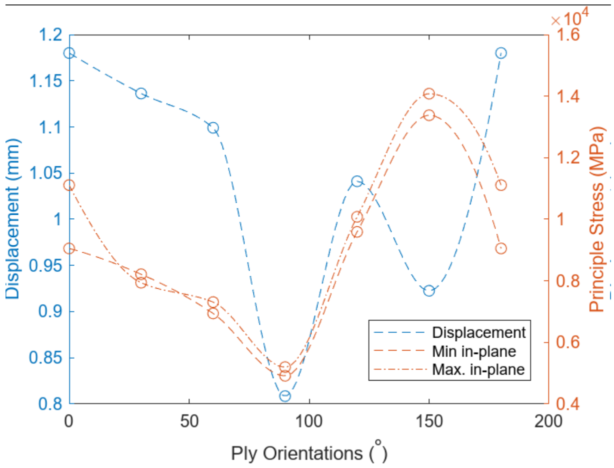


Figure 3: The effect of different fibre orientations on a single-ply composite on the deflection of the stabiliser tip under the spar.

and experienced the lowest stress. The results of this test are shown in Figure 3 narrowed down the test cases to use 90°, 120°and 150°angles. The angle giving the lowest displacement is 90°.

With the angles now known, considering the company's requirement, the weight of the stabiliser should decrease. The limiting factor of the number of plies is the weight of the stabiliser. The weight of the stabiliser made from aviation aluminium is 622g so the new weight with the composite material should be lower than this. With the weight of each layer being 47g the design is limited to a maximum of 13 plies, ensuring a weight decrease. To ensure a significant weight decrease and due to the time length of the tests, the maximum number of plies has been decided as 10.

The next company requirement is that the deflection is no greater than the deflection of the aluminium stabiliser. So to determine the minimum number of plies, the orientation with the lowest deflection (90°) was used for each layer and the minimum number of layers was found when the deflection of the composite stabiliser was less than the aluminium stabiliser (0.205266mm). This test limited the tests to a minimum of 8 plies. Resulting in test cases of 8,9 and 10 layers to be compared.

With the time limitations of this analysis, symmetry is used for each of the composites. This limited the test cases that could be performed making it easier to determine the most interesting cases to take forward. Symmetric components are also widely used in the Aeronautical industry already [1]. This symmetry also means that the weight distribution of the plies will maintain a similar centre of gravity so the aerodynamics of the stabiliser do not need to be considered as much.

The outputs being measured were closely considered with the parameters for the test. The displacement of the tip is being measured as the criteria states that the displacement should not increase. With this in mind, the original ply orientation cases were reduced to some of the more feasible cases. Deflection values are obtained at the tip of the stabiliser at both the underside of the spar and on the bottom surface behind the spar. Due to different ply orientations based on a global coordinate system and applied the same way to all sections, the different orientations will have different effects on the different directions of the geometry. Therefore, it is necessary to consider the deflection under the spar and behind the spar to find the fibre orientation that is best for both geometries. It is possible that a tiny deflection under the spar could have a rather large deflection for the rest of the geometry due to the fibre orientation being strong in the spar and weak along the stabiliser shell. As the model has been simplified for this analysis the deflections behind the spar will likely be amplified as there are no reinforcing plates on the wing tip. This meant that the primary consideration was with the deflection under the spar and as a secondary consideration, the deflection behind the spar was considered. The second consideration is the safety of the structure so to accurately represent this the maximum and minimum in-plane principle stress have been used, this gives a representation of which models are more likely to fail. This then gave 3 cases to take forward and conduct the final safety analysis and determine the best ply number and orientations. To do this the ultimate stresses and strains have been considered through each layer of the model.

3 Results

Using 8, 9 and 10 plies and testing different combinations of angle orientations of 90, 120 and 150, different test cases can be determined. The vertical deflection needs to be under 0.377908mm under the spar and

0.505638mm behind the spar at the stabiliser tip. All three-ply layups taken forward have a lower weight than the mass of the aluminium model. This changes with each added ply layer of the model. The mass ranges from 376g, 423g and 470g for the 8, 9 and 10 plies respectively. The temperature was also assumed to be constant as changes in temperature can cause disturbances in localized areas of expansion and contraction, which would create stresses and even lead to damage to the composite.

Table 2: The values measured for each of the parameters considered in the initial analysis for the different number of plies and orientations used. The grey rows show the cases taken forward into the final analysis. Deflection 1 is measured under the Spar and Deflection 2 behind the spar

Number of Plies	**Angle orientations (degrees)**	**Deflection 1 (mm)**	**Deflection 2 (mm)**	**Max. In-Plane Principle Stress (MPa)**	**Min. In-Plane Principle Stress (MPa)**
8	90-120-120-120//	0.501424	1.0786		
8	120-90-90-90//	0.263934	0.824861	8.855	-28.51
8	150-90-90-90//	0.319417	0.528054	11.40	-24.47
8	90-120-150-90//	0.337367	0.738581		
8	150-120-90-150//	0.54191	0.747595		
9	90-120-120-120-150//	0.455703	0.865528		
9	150-90-90-90-120//	0.285871	0.441637	10.04	-19.93
9	150-120-90-90-90//	0.305391	0.463142	10.10	-18.39
9	90-90-120-150-120//	0.310289	0.397383	8.809	-13.11
9	120-120-90-90-150//	0.317365	0.711706		
10	90-120-150-90-90//	0.256483	0.45528	8.001	-10.90
10	150-120-90-150-120//	0.462871			
10	150-150-150-120-90//	0.511608	0.621972		
10	150-120-90-90-90//	0.266357	0.392443	9.440	-16.72
10	90-90-90-150-120//	0. 242398	0.536294		

Table 3: Compares the different ultimate values for the stresses and strains in each of the models taken forward.

Property	Units	Carbon Epoxy Material	9 Ply - 150-120-90-90-90//	9 Ply - 90-90-120-150-120//	10 Ply - 90-120-150-90-90//
Longitudinal tensile strength F_{1t}	MPa (ksi)	2280 (330)	11.18	16.81	11.96
Transverse tensile strength F_{2t}	MPa (ksi)	57 (8.3)	1.194	2.827	1.271
In-plane shear strength F_6	MPa (ksi)	71 (10.3)	0.9080	0.9715	0.7878
Ultimate longitudinal tensile strain ε_{1t}^{u}		0.015	0.00008524	0.0001275	0.00009077
Ultimate transverse tensile strain ε_{2t}^{u}		0.006	0.0001532	0.0003180	0.0001479
Longitudinal compressive strength F_{1c}	MPa (ksi)	1440 (209)	-20.14	-19.96	-18.19
Transverse compressive strength F_{2c}	MPa (ksi)	228 (33)	-0.8767	-2.966	-1.548

From the results in Table 2, the max in-plane and min-plane principle stress values are determined for the plies and orientations with the lowest overall deflections. The 8-ply model was not taken forward as its deflection is deemed to be too great in comparison to the original model. Although the deflection below the spar was low enough the deflection away from the spar was significantly higher. The highlighted rows in Table 2 depict the plies with the lowest overall deflection and stress values and were therefore taken forward for safety analysis, which is a crucial step due to the nature of the application of the product. The safety factors show considerable differences in stress and strain values in comparison to the data provided in the brief as shown in Table 3. Maximum values were obtained for stress and strain to ensure valid comparison. It is recognized that an increase in plies decreases the maximum longitudinal and transverse tensile and compressive stresses, with 10 plies having the lowest values.

4 Conclusions

The analysis and tests carried out allow us to determine a more suitable material with the ideal number of plies and orientation. A single-ply lamina was initially used to determine the lowest deflection which was determined to be at 90°, 120°and 150°. The weight was limited to a maximum of 13 plies however to ensure a significant weight decrease and due to the duration of tests the maximum number of plies to be tested was decided to be 10. The minimum was decided to be 8 as at the orientation with the lowest deflection (90°) the deflection of the composite stabiliser was less than that of the aluminium stabiliser. Following this, the results were obtained for each of the different layers and compared against each other and the original aluminium model. To make the tests simpler some of the reinforcing plates were not included in the model so this could have brought it a degree of error. Especially with the deflection values measured at the tip behind the spar as these are likely to be smaller due to the extra support from the plate. Due to the use of the shell model, it is harder for Abaqus to accurately simulate the stresses between the joins of the spar and the stabiliser. This could have brought in potential error when considering the stresses at maximum and minimum points throughout the model.

The analysis and tests concluded result in the ideal ply was the 10-ply model with an orientation of 90-120-150-90-90//. This was chosen as the ideal solution as it had the lowest deflection measured at both the spar and away from the spar as well as the lowest overall maximum in-plane and minimum in-plane principal stress values. The safety factors measured also showed a significant decrease in stress and stain at 10 plies and the weight reduction was determined to be 32% less than that of aviation aluminium. Switching to Carbon fibre epoxy is highly recommended as it is an orthotropic material with a high-strength-to-weight ratio making it a more ideal material for a helicopter stabiliser than aluminium as well as because of the significant reduction in weight, deflection and stress observed. One thing to be cautious of with the safety analysis is that the mesh convergence test was for a different stress and in a different direction to the values used for the safety consideration. This could introduce potential error here, especially with the issues with the shell model mentioned before that could introduce a potentially exponential increase in stress with a more refined mesh. Depending on the importance of weight loss, if a more significant weight loss is required then each of the 9-ply models taken forward for safety testing could be used as another design. They both have deflections lower than the aluminium model and they have stresses and strains much lower than the ultimate tensile and compressive values shown in Table 3. Therefore, this would also be a valid choice in the final composite design used. Further analysis to be considered involves the use of asymmetrical material as it might produce a lower deflection with fewer plies as well as analysing different composite layups for different sections of the material, the consideration of temperature on the material could also be taken into account as it was assumed to be constant in this test and may have effects on the results. A classical lamination theory could also be analysed, whereby the mechanical properties of the model based on the number of plies, material orientation and stacking sequence can be predicted. Further study could also be conducted into the effect of having different composites for different sections of the wing. Such as one layup for the spar and one for the shell of the stabiliser. Another consideration would be to look at the deformation of the model, which could be done by measuring the differences in deflection between the top and bottom of the spar. Another consideration to take into account is the aerodynamics of the stabiliser. With the new design from the new composite, the centre of mass of the stabiliser should be considered as this would have a large effect on the performance of the helicopter. Also with such a significant weight loss it is important to consider what effect this change will have on the overall helicopter as this could cause the centre of gravity to shift which will also impact the flight.

References

[1] *Symmetry*. [Online; accessed 17. Mar. 2024]. Mar. 2024. URL: https://www.mdpi.com/journal/symmetry/special_issues/Symmetry_Asymmetry_Composite_Materials_Structures.

A Representing Composites in Abaqus

Problem: Model a single ply of carbon/epoxy under in-plane loading of 1 kN /mm. The ply is initially stretched along the fibre direction. The dimensions of the ply are 100 x 100 x 1 mm. The properties of the composite material are shown in Table 4 and the unit system used is shown in Table5.

Table 4: Properties of a carbon-epoxy composite

Property	Value
E1 (GPa)	131
E2 (GPa)	8.8
G12 (GPa)	5.0
ν (GPa)	0.27

Table 5: The unit system used to create the Abaqus model.

Distance	Force	Pressure
m	N	Pa

G_{13} and G_{23} do not affect the model's outcome due to the direction in which the force is applied to the plate, therefore they can be just set to the value of G_{12} for Abaqus to complete the calculations. The deflections measured from this analysis are shown in Table 6

Table 6: Deflection values at either side of the plate model, in the same direction as the fibre orientation.

Position	Deflection (m)
Top Left Node	-0.00132756
Top Right Node	-0.000564199

The strain in the direction of loading is 0.007634 which matches correctly with the calculated value. These values change depending on where the initial model is positioned. The displacement between the two points always remains the same and the strain is always the same. The theoretical comparison calculation can be seen below.

Change in length: $-0.000564199 - (-0.00132756) = 0.000763m$

$$E = 131x10^9 Pa$$

$$Stress\sigma_{11} = 1GPa([Force/unitlength]/thickness)$$

$$Strain\varepsilon_{11} = \sigma_{11}/E = 1e9/131e9 = 0.00763$$

$$\Delta L = \varepsilon_{11} L = 0.0076x0.1 = 0.000763m$$

The theoretical values match correctly with the Abaqus values showing that this is a valid method of representing a composite in Abaqus. Knowing this the fibre orientation was changed to match the previous group number and the strain measured. For an angle of 225°the strain in the U1 or loading direction is 0.07929.

B Multi-Ply Composite

The same model specification as in Appendix 1, but with a loading of 0.1kN/mm applied. The material properties can be seen in Table 7

Table 7: Properties of a graphite-epoxy composite used for this verification test.

Property	Value
E1 (GPa)	181
E2 (GPa)	10.3
G12 (GPa)	7.17
ν (GPa)	0.28

Table 8: Displays the deflection data for each of the different stacks.

Stack	Top Left (m)	Top Right (m)	Difference (m)	Difference (mm)
90 0 0 90	-5.14917e-5	5.26844e-5	0.0001041761	0.1041761
0 0 0 0	-4.80287e-5	7.21988e-6	0.00005524858	0.05524858
90 90 90 90	-0.0014495	-0.000478626	0.000970874	0.970874

The first stack has a displacement in between the other two values which is expected as it has some fibres orientated in the U1 direction and some perpendicular to the U1 direction in the same plane. For the case that the fibres are orientated in the same direction as the loading i.e. with stack orientation of 0,0,0,0 for each of the layers, this can be assumed as 1 layer of 1mm thickness. This is the same as the case in Appendix 1, which means that the same calculations can be applied theoretically to compare the displacements. This calculation can be seen below.

$$E = 181x10^9 Pa$$

$$Stress\sigma_{11} = 0.1GPa([Force/unitlength]/thickness) = 0.1kN/mm/1mm$$

$$Strain\varepsilon_{11} = \sigma_{11}/E = 1e8/181e9 = 0.000552m$$

$$\Delta L = \varepsilon_{11}L = 0.000552x0.1 = 0.0000552m \equiv 0.0552mm$$

This value matches the value calculated by Abaqus, thus verifying the composite layup feature used in Abaqus to represent the model. To further verify this method Figure 4 can be used to compare the strain over a range of fibre orientations for calculated values and the values calculated by Abaqus. When the points received from Abaqus are plotted against the theoretical graphs produced they line up perfectly. This is expected as Abaqus uses the same technique as the Matlab code to calculate the strain values. Each orientation matches precisely with the Matlab calculation. This suggests that using the composite layup tool will be highly accurate.

Finally, Figure 5 shows the envelope feature that will be used later for the safety analysis. This feature enables the stress and strains throughout the composite for each layer to be found. For this model, the envelope has been plotted.

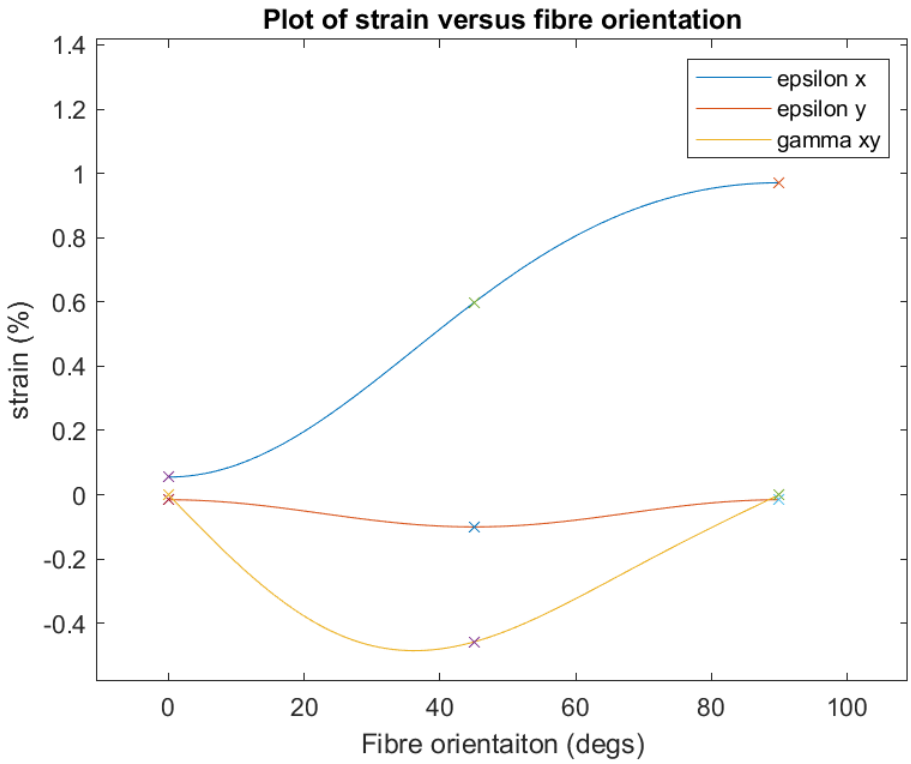


Figure 4: Comparison between the theoretical calculations shown by the lines on Matlab compared to the 'x' values which show the points of data from Abaqus.

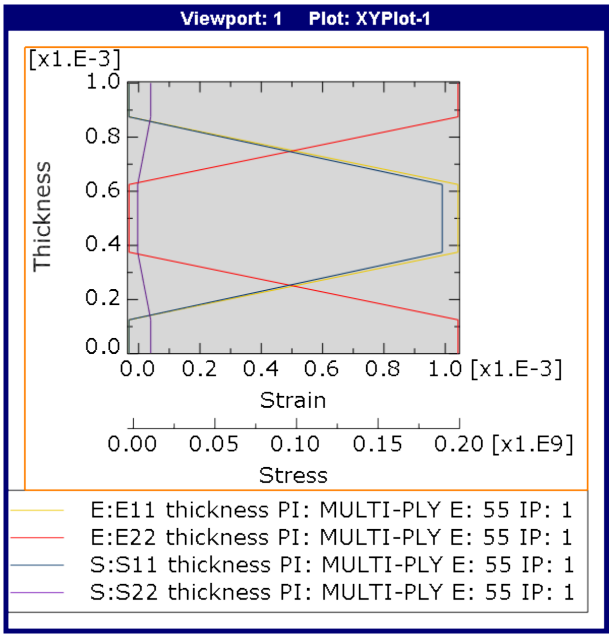


Figure 5: A plot of the stresses and strains throughout the layers of the ply model used in the Abaqus Model. Each layer is 0.25mm thick.