

DAMAGE ASSESSMENT OF COMPOSITE MAIN ROTOR BLADE BY FINITE ELEMENT SIMULATION AND EXPERIMENT

KR. Prashanth¹

C. Venkatesan²

¹Chief Manager-Design, PhD Student
Rotary Wing R &D Center,
Hindustan Aeronautics Limited
Bangalore-560017, India
rotor.rwrdc@hal-india.com

²HAL Chair Professor
Department of Aerospace Engineering,
Indian Institute of Technology
Kanpur-208016, India
cven@iitk.ac.in

Abstract

Rotor blades are constructed with composite materials. The root section of the rotor blade, which is made of thick composite layers, undergoes large dynamic loads. Due to this loading, thick composite section is amenable to various types of damages. This paper addresses a method for the analysis of damage prediction in root section of the rotor blade. Finite element model of root section of a composite main rotor blade is analysed in two stages. In the first step, rotor blade root is modeled with coarse mesh using continuum shell and solid elements. In this phase, damage initiation and evolution criteria for fibre and matrix are assessed using Hashin criteria. In the second stage, ply-by-ply FE sub-models are prepared and cohesive elements are introduced in the area of interest to study the tendency for delamination. Experimental study on rotor blade root section has been carried out for both static and fatigue loading cases. The results of FE analysis and experimentation are compared for the static case for stresses and displacements. The zone of damage initiation from FE static analysis is in agreement with the location of damage in experimentation under fatigue loading.

1. INTRODUCTION

Composite materials are widely used in aerospace applications due to their unique properties, such as strength to weight ratio, corrosion resistance, reliability due to less number of components, possibility of manufacturing intricate contours. Main rotor blade, tail boom, empennage, structures, doors, control surfaces of helicopters are a few examples which are made of fibre reinforced composites. Root end of helicopter main rotor blade is generally made with multiple layers of composite lamina and they are configured to meet the requirements of strength, and stiffness. During operation the rotor blades undergo complex loading conditions generated by aerodynamics, and dynamics. The

oscillatory loads experienced by main rotor blade are generally predicted using aeroelastic computational codes, however, the service loads are uncertain in reality. These loads induce various failure modes in the composite rotor blade such as delamination, fibre failure such as fibre breakage, matrix failure like matrix cracking. In fact, the failures not only depend on the fabrication process but also by environmental factors. Since rotor blade is a critical component and a primary structure of a helicopter, it has to be tested and validated for its structural integrity, fatigue capability, assessment of modes of failures and to define safe life of operation on helicopter. These tests will provide information about various parameters like residual stiffness, residual strength and also an insight into the modes of failure which

are important to determine safe life or dormant state of failure after some cycles of loading. In the present study, as part of certification and qualification of main rotor blade, experiments are carried out with loads obtained from aeroelastic load program and flight test data. These experimentation results are compared with results obtained from finite element analysis. In the finite element simulation studies, stress analysis of the thick composite structure is carried out using ABAQUS finite element software, progressive damage modeling is incorporated by using Hashin failure criteria and delamination analysis is performed using Cohesive Zone Modeling.

2. DESCRIPTION OF FINITE ELEMENT MODELING APPROACH

2.1 Rotor Blade Root End

Main rotor blade root end is a monolith composite made of fibre reinforced glass, carbon epoxy unidirectional and fabric layers. The structure is designed to withstand flap, lead-lag, torsional and axial loads. The blade root is rectangular in cross section with spoon type hollow region at the blade root at the hub attachment area. This root is fixed with rotor hub using four bolts through elastomeric bearings and blade forks.

2.2 Finite Element Model of Blade Root End

Finite element meshing is carried out using HYPERMESH software and then exported to ABAQUS software. FE model consists of beam, three dimensional continuum elements and continuum shell elements [1]. To reduce the computational efforts, FE meshing is carried out judiciously and the model is analysed in two phases.

In first phase, coarse FE model is prepared using beam, continuum, continuum shell elements. Composite layup manager available in ABAQUS is used for defining the layers in the finite element model with appropriate orientations and properties. Multiple layers are defined in a single element and the coarse model is subjected to quasi static analysis. Stress, displacement and Hashin damage criteria are analysed in this phase.

In the second phase, refined FE model is generated with selected zones in the blade root region and ply-by-ply model is prepared. In this model, Hashin damage criteria and cohesive elements(COH3D8) from ABAQUS element library are introduced locally at the ply level and at the interface layers respectively to analyse the damage initiation and evolution in detail. Linear elastic material model is used with orthotropic material for the composite layers. This model is analysed quasi statically. The results of coarse model is transferred to submodel zonewise. Interpolation of the solution from an initial, global model to appropriate parts of the boundary of the submodel is carried out. Totally six such zones and sub models are generated. Submodels are analysed to obtain accurate and detailed distribution of stress in the local region.

The composite material data used for the finite element analysis is generated by ASTM standard tests and evolved by the approach provided as guidelines in CMH-[2]. The loads used for experimentation and finite element analysis are derived from the in house aeroelastic analysis codes and compared with aeroelastic loads analysis codes developed by Laxman et al.[3] and Rohin et al. [4] which estimate blade loads and hub loads for various maneuvering flight. The calculated flap, lead-lag, centrifugal loads and torsional moment are applied at the collar tip. Blade is constrained at the root end region for all the

three displacements. The rotor blade root end is shown in Figure-1.

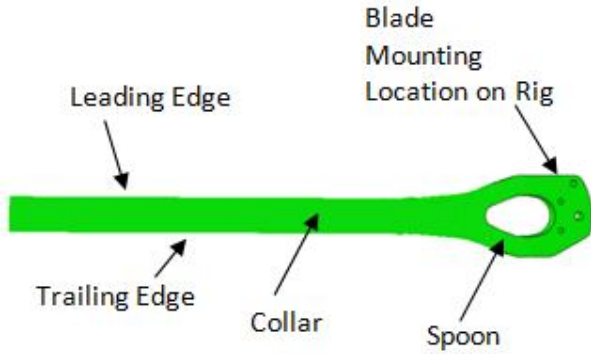


Figure-1 Rotor Blade Root End

3. DAMAGE CRITERIA AND COHESIVE ZONE MODELING

Commonly used failure criteria for fibre reinforced composite structures are strength based. For planar state of stress ($\sigma_3 = 0$, where σ_3 is stress out of plane) there exist a number of failure criteria. Generally used criteria are explained by Barbero [5]. Study of various theories for its key features and predictive capabilities of these theories for initial and final failures are compared by Soden et al. [6]. For 3D finite element analysis with prediction of matrix failure, reliable failure theories are required. Puck et al.[7-8] developed a theory for matrix cracking in a fracture plane with influence of transverse compression which increases the matrix shear strength. Puck's approach requires material data that are to be quantified by experiment such as internal material frictional coefficients. Davila et. al.,[9] developed a failure criteria for fibre reinforced composites based on phenomenological model. This approach can predict matrix and fibre failure accurately without curve fitting. They predict fracture plane by using Mohr-Coulomb effective stresses[10]. There are also other continuum based failure criteria proposed by Sun et al.,[11] and Hashin and Rotem[12-13] which predict failure by calculating the stresses and comparing with

the fibre and matrix strength and thereby determining the onset of failure.

In the present study, onset of damage is determined by the criteria proposed by Hashin and Rotem [12-13]. Hashin criteria is defined for fibre tension and matrix tension failures. Further, these two criteria were related to the fibre tension and compression and matrix tension and compression. Anisotropic damage model with emphasis on damage of material and effective elastic properties for stress analysis is based on the work of Matzenmiller et.al.[14]. The damage evolution is energy based. The material is linearly elastic before initiation of the damage. Evolution of damage is also assumed to be linear. The damage is analysed for the four failure modes, namely, fibre failure in tension, fibre failure in compression, matrix failure in tension and matrix failure in compression.

Considering a orthotropic material with in-plane stresses as the significant stresses, for planar state of stress, one can make the assumption that $\sigma_3 = 0$ and remaining stress components are non zero. The damage initiation criterion is having the following general form for failures of fibre and matrix in tension and compression states for a given value of effective stress component.

Fibre Tension Mode

$$(1) \quad \sigma_{11} \geq 0$$

$$F_f^t = \left(\frac{\sigma_{11}}{X^T} \right)^2 + \alpha \left(\frac{\tau_{12}}{S^L} \right)^2$$

Fibre Compression Mode

$$(2) \quad \sigma_{11} < 0$$

$$F_f^c = \left(\frac{\sigma_{11}}{X^C} \right)^2$$

Matrix Tension Mode

$$\sigma_{22} \geq 0$$

$$(3) \quad F_m^t = \left(\frac{\sigma_{22}}{Y^T} \right)^2 + \left(\frac{\tau_{12}}{S^L} \right)^2$$

Matrix Compression Mode

$$\sigma_{22} < 0$$

$$(4) \quad F_m^t = \left(\frac{\sigma_{22}}{2S^T} \right)^2 + \left[\left(\frac{Y_{22}}{2S^T} \right)^2 - 1 \right] \frac{\sigma_{22}}{Y^C} + \left(\frac{\tau_{12}}{S^L} \right)^2$$

Where,

X^T -Longitudinal tensile strength

X^C -Longitudinal compressive strength

Y^T - Transverse tensile strength

Y^C - Transverse compressive strength

S^L - Longitudinal shear strength

S^T - Transverse shear strength

α -Coefficient that determines the contribution of the shear stress to the fibre tensile initiation criterion as given in (1).

$\sigma_{11}, \sigma_{22}, \tau_{12}$ - Components of effective stress tensor $[\sigma]$ used to evaluate the initiation criteria.

$$(5) \quad \sigma = M \hat{\sigma}$$

Where $\hat{\sigma}$ is the true stress and M is the damage operator. M will have value 1 before damage initiation and evolution.

$$(6) \quad M = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 \\ 0 & \frac{1}{(1-d_m)} & 0 \\ 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix}$$

d_f, d_m, d_s are internal damage variables that are derived from damage variables $d_f^t, d_f^c, d_m^t, d_m^c$ corresponding to four modes

$$(7) \quad d_f = d_f^t \quad \text{if } \sigma_{11} \geq 0$$

$$(8) \quad d_f = d_f^c \quad \text{if } \sigma_{11} < 0$$

$$(9) \quad d_m = d_m^t \quad \text{if } \sigma_{22} \geq 0$$

$$(10) \quad d_m = d_m^c \quad \text{if } \sigma_{22} < 0$$

$$(11) \quad d_s = 1 - (1-d_f^t)(1-d_f^c)(1-d_m^t)(1-d_m^c)$$

Prior to damage initiation the material is linearly elastic with stiffness of a plane stress orthotropic material. Post-damage initiation, the constitutive relation of the material will be in the form

$$(12) \quad \sigma = C_d \varepsilon$$

Where ε is the strain and C_d is the damaged elasticity matrix reflecting damages due to fibre, matrix and shear.

$$(13) \quad C_d = \frac{1}{D} \begin{bmatrix} (1-d_f)E_1 & (1-d_f)(1-d_m)\nu_{21}E_1 & 0 \\ (1-d_f)(1-d_m)\nu_{12}E_2 & (1-d_m)E_2 & 0 \\ 0 & 0 & (1-d_s)GD \end{bmatrix}$$

Where D is

$$(14) \quad D = 1 - (1-d_f)(1-d_m)\nu_{12}\nu_{21}$$

E_1 is Young's modulus in fibre direction and E_2 is Young's modulus in direction perpendicular to the fibres, G is the shear modulus, and ν_{12}, ν_{21} are Poisson's ratios.

The damage progression is based on the energy dissipated during the process which is related to the work done by external loads. $G_{ft}^c, G_{fc}^c, G_{mt}^c$ and G_{mc}^c represent the energy dissipated for the failure modes of fibre tension, fibre compression, matrix tension and matrix compression. For all the

four failure modes, the linear damage evolution is represented in bi-linear stress-displacement form as shown in Figure-2.

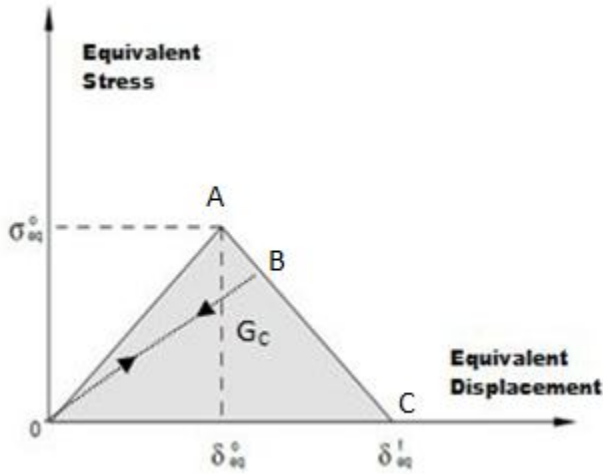


Figure-2: Linear Damage Evolution

The damage initiation is represented by the linear positive slope and evolution by negative slope. δ_{eq}^0 is the initial equivalent displacement at which the initiation criterion for that mode is met and δ_{eq}^f is the displacement at which the material is completely damaged in this failure mode. σ_{eq}^0 is the peak equivalent stress at which initiation criterion is met. G_C is the energy dissipated, for each failure mode this is defined, which is equivalent to the area of triangle OAC in Figure-2. B is partially damaged state from which unloading or loading is carried out.

In the next phase, the inter-laminar failure (delamination) is assessed using cohesive zone modelling (CZM). Based on the results obtained in the global FE model, submodel with refined ply-by-ply mesh is generated and the ply interfaces are modelled with cohesive elements (COH3D8) available in ABAQUS library. The cohesion is defined by linear elastic traction separation law and mixed mode decohesion is based on the Comanho et al., [15] and Benzeggagh et al., [16].

The material is assumed to be linear before damage. Material degradation starts as

soon as the criterion is satisfied. The traction separation response is given in Figure-3. Positive slope indicates the contact stress delamination initiation and δ^0 represents the peak value of contact separation. The symbols t_n , t_s , t_t represent the peak values of the contact stress when the separation is either purely normal to the interface or purely in the first or the second shear direction. Symbols δ_n^0 , δ_s^0 , δ_t^0 represent the peak values of the contact separation, when the separation is either purely along the contact normal or purely in the first or the second shear direction, respectively.

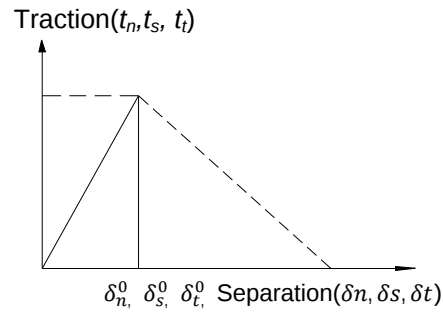


Figure-3: Traction – Separation Response

Quadratic nominal stress criterion is used for the initiation which is given as

$$(15) \quad \left\{ \frac{\langle t_n \rangle}{t_n^0} \right\}^2 + \left\{ \frac{\langle t_s \rangle}{t_s^0} \right\}^2 + \left\{ \frac{\langle t_t \rangle}{t_t^0} \right\}^2 = 1$$

Damage is assumed to be initiated if the condition in Eq. 15 is satisfied.

For damage evolution, scalar damage variable D_1 representing combined effect of all damage is considered. It will have a value of zero before damage and reaches 1 for damage. Stress or traction is affected by the variable D_1 as given below.

$$(16) \quad \begin{aligned} t_n &= \{(1 - D_1) \bar{t}_n, \bar{t}_n \geq 0 \\ \bar{t}_n, & \text{ Otherwise (No damage to compressive stiffness)} \end{aligned}$$

$$(17) \quad t_s = (1 - D_1) \bar{t}_s$$

$$(18) \quad t_t = (1 - D_1) \bar{t}_t$$

$\bar{t}_n$, $\bar{t}_t$, $\bar{t}_s$ are stress components without damage in normal, tangential and shear directions.

Damage evolution due to combination of normal and shear separation at interface is represented by effective displacement[15]

$$(19) \quad \delta_m = \sqrt{\langle \delta_n \rangle^2 + \delta_s^2 + \delta_t^2}$$

The damage evolution assessment can be carried out by either energy based method or traction based method. Both the methods have mixed mode definition for deformation. In this study mode mix ratio, available in ABAQUS, based on traction is implemented.

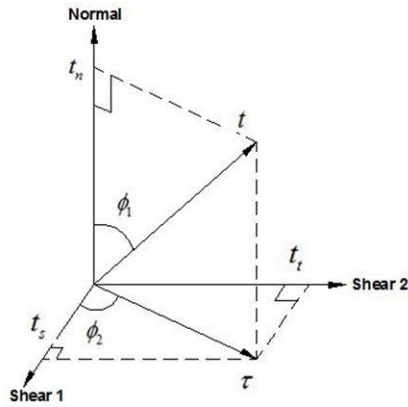


Figure-4: Mode Mix Based on Traction

Based on tractions as shown in Figure-4, effective shear traction in mixed mode is given by

$$(20) \quad \tau = \sqrt{t_s^2 + t_t^2}$$

and the angular measurements from the above traction vectors are given as,

$$(21) \quad \phi_1 = (2 / \pi) \tan^{-1} \left(\frac{\tau}{\langle t_n \rangle} \right)$$

$$(22) \quad \phi_2 = (2 / \pi) \tan^{-1} \left(\frac{t_t}{t_s} \right)$$

4. TESTING OF COMPOSITE BLADE

The composite main rotor blade root is tested by applying flap, lead-lag, torsion and axial loads. A special structural test rig is made for mounting the main rotor blade root end. The test set up is shown in Figure-5. Hydraulic actuators are used for applying predetermined loads. The blade root end is instrumented using multi-channel strain gauge and servo controllers are used for controlling the hydraulic actuators.

Calibration is performed by application of loads in steps and measuring the corresponding deflections and strains. Static loading of the root end is carried out using hydraulic actuators in flap, lead lag, torsion and axial directions. The output of the tests such as moments, strains, deflection and jack loads are measured through instrumentation.



Figure-5: Main rotor root end test

Fatigue tests are performed on the same root end specimen at lower load levels based on the aeroelastic load estimates till the blade root undergoes fatigue failure.

This test is carried out at a frequency of 0.2Hz. During the fatigue tests, the blade root specimen is subjected to visual inspection, non-destructive tests such as A Scan and CT scan to record the failure zone and magnitude of failure.

The experimental results show that during static tests the initiation of failure of the fibre or matrix is not noticed visually or during the ultrasound scanning. However, during experimenting on the blade root end for fatigue tests the failure is noticed on the vertical face of hollow spoon region and also on the outer face. Further, delamination and cracks are noticed in the spoon outer region also. The damaged blade root end is inspected visually and by A scan and CT scan. The scan and visual cracks are shown in the figures given in Appendix. The delamination is noticed after several tens of thousand cycles at various zones in the spoon. During this period, the delamination propagated in parallel planes. Later, continuation of cyclic loading has created the vertical cracks in the spoon region and propagated in vertical (stack up) direction. The fatigue tests indicated that the loss of stiffness at the end of tests is negligible at around 3 percent from the initiation of the fatigue test.

5. RESULTS AND DISCUSSION

The finite element model of the blade root segment is shown in Figure-6(a). Classification of zones for carrying out submodeling is shown in Figure-6(b). The results from submodel zone 5 and 6 are considered to be insignificant for the detailed analysis as the delamination was not very predominant in this zone during the fatigue testing experiments. The results obtained from the global FE model for progressive failure analysis and the stresses in the blade root are shown in Figures-7(a) to 9(c). Failure criteria in these zones match to the test results. Cohesive

zone modeling and analysis were carried out in the submodel level and the results are shown in Figures-10(a) to 10(c). The delamination indicated by failure of cohesive element in the submodel zones-1, 4 and 5 are in good correlation with the fatigue test results. Hashin failure criteria results from the analysis of submodling are given in Figures-11(a) to 11(d) which indicates that the matrix failure in tension and compression and fibre failure in tension are more likely. The ply-by-ply stress analysis results for the submodel is presented in Figures-12(a) to 12(d). It is clear that shear stresses are very high in the delaminated region. High transverse stress shows the interlaminar bond failure in correlation to tests.

Results obtained from the experimental tests are shown in the Figures-13(a) and 13(b). These correpond to the fatigue tests results; and the delamination and matrix cracking/matrix dominated failures are noticed in the leading edge side of the blade root after many cycles. Figure-13(c) indicates the matrix cracking at the bottom surface of the fatigue test specimen. Figure-13(d) indicates the delamination after a few tens of thousand cycles during fatigue tests. Figure-13(e) shows the CT scan image of the blade root end which indicates the delamination. The tests indicate that the failure is matrix dominated.

Longitudinal (S11), lateral (S22), transverse (S33) and in plane shear (S12) stresses are obtained from the FE results of submodels. The results are taken at the edges of the sub model and also at regions where damage is predominant. The variation of stresses in the plies are plotted in the stackwise (thickness) direction. Stress distribution are shown in the Figures-14(a) to15(c) for submodel zone-1 and it indicates that longitudinal stresses are higher in this location. In the submodel zone-2 towards the inboard location stress magnitudes are less which are as shown in Figures-16(a)

to16(c). In the submodel zone-3 and zone-4 the longitudinal and lateral stress magnitude are high which shows the possibility for fibre damage and matrix damage. Compared to the other zones these two zones show a higher in-plane shear stress values as shown in Figures-17(a) to17(c) for submodel zone-3, and Figures-18(a) to18(c) for submodel zone-4. Delamination due to shear stress is possible in these two zones.

6. CONCLUDING REMARKS

In this work, a detailed FE analysis with damage detection/identification criteria has been carried out for the root end of a composite rotor blade. The blade root end was tested by applying suitable cyclic loads in flap, lag, axial and torsion directions. The computational result of FE analysis clearly predicts the locations of damage initiation and progression, as observed in experimental tests. This good correlation between FE analysis and experimental tests has given a positive direction to undertake further studies on the life prediction of composite rotor blade structure.

7. ACKNOWLEDGMENTS

The first author wishes to acknowledge Rotary Wing Research & Design Centre, HAL and IIT Kanpur for providing all the necessary facilities in pursuing this research.

8. REFERENCES

- [1] Abaqus Analysis User Manual, Simulia, 2016.
- [2] MIL Composite Material Handbook, Volume 1: Polymer matrix composites guidelines for characterisation of structural materials, CMH-17-1G, March 2012.
- [3] Laxman, V. and Venkatesan, C., "Influence of Dynamic Stall and Dynamic Wake Effects on Helicopter Trim and Rotor Loads", Journal of the American Helicopter Society, Vol. 54, No. 3, July 2009.
- [4] Rohin K, M., Venkatesan, C., "Rotorcraft Aeroelastic Analysis using Dynamic Wake/Dynamic Stall Models and its Validation," Journal of Aeroelasticity and Structural Dynamics, Vol. 3, No. 1, 2014.
- [5] Barbero, E. J., "Introduction to Composite Materials Design", Taylor & Francis, 1998.
- [6] Soden P, D., Hinton, M, J., and Kaddour, A.S., "A Comparison of the Predictive Capabilities of Current Failure Theories for Composite Laminates", Composites Science and Technology, Vol.58, 1998, pp. 1225-1254.
- [7] Puck, A., and Schurmann, H., "Failure Analysis of FRP Laminates by Means of Physically Based Phenomenological Models", Composites Science and Technology, Vol.58, 1998, pp. 1045-1067.
- [8] Puck, A., and Schurmann, H., "Failure Analysis of FRP Laminates by Means of Physically Based Phenomenological Models", Composites Science and Technology, Vol.62, 2002, pp. 1633–1662.
- [9] Davilla, C, G., Camanho, P, P., and Rose, C, A., "Failure Criteria for FRP Laminates,"Journal of Composite Materials, Vol.39, 2005, pp.323-345.
- [10] Salencon, J., "Handbook of Continuum Mechanics: General Concepts,

Thermoelasticity," Springer, New York, 2001

- [11] Sun, C.T., Quinn, B.J., and Oplinger, D.W., "Comparative Evaluation of Failure Analysis Methods for Composite Laminates", DOT/FAA/AR-95/109, 1996.
- [12] Hashin, Z., and Rotem, A., "A Fatigue Failure Criterion for Fiber-Reinforced Materials," Journal of Composite Materials, Vol. 7, 1973, pp. 448-464.
- [13] Hashin, Z., "Failure Criteria for Unidirectional Fiber Composites," ASME Journal of Applied Mechanics", Vol. 47, 1980, pp. 329-334.
- [14] Matzenmiller, A., J. Lubliner, and R. L. Taylor, "A Constitutive Model for Anisotropic Damage in Fiber-Composites," Mechanics of Materials, vol. 20, pp. 125–152, 1995.
- [15] Camanho, P. P., and C. G. Davila, "Mixed-Mode Decohesion Finite Elements for the Simulation of Delamination in Composite Materials," NASA/TM-2002–211737, pp. 1–37, 2002.
- [16] Benzeggagh, M. L., and M. Kenane, "Measurement of Mixed-Mode Delamination Fracture Toughness of Unidirectional Glass/Epoxy Composites with Mixed-Mode Bending Apparatus," Composites Science and Technology, vol. 56, pp. 439–449, 1996.

APPENDIX

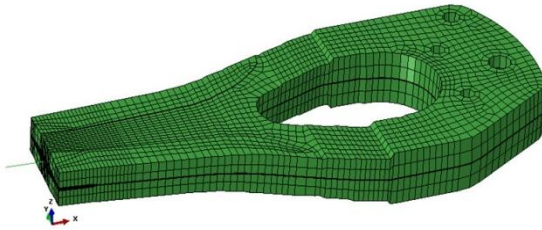


Figure-6(a): FE model of the blade root end

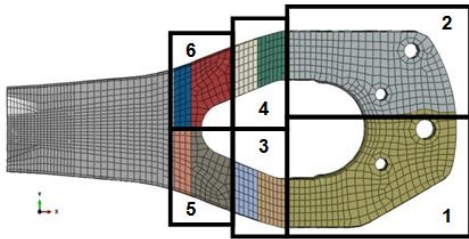


Figure-6(b): Regions of refined FE Submodel

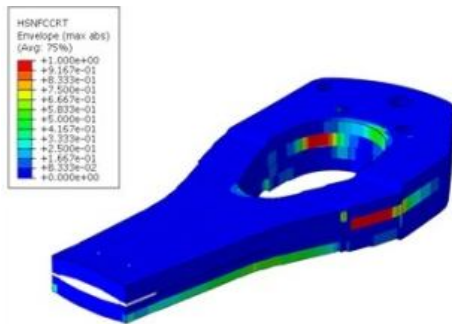


Figure-7(a): Hashin Fibre Compression Criteria

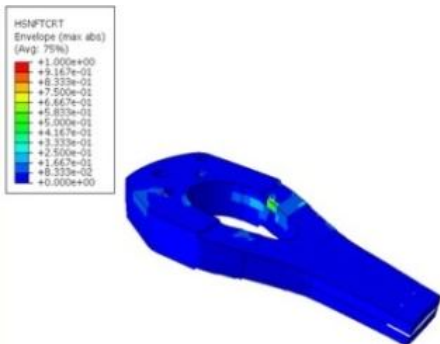


Figure-7(b): Hashin Fiber Tension Criteria

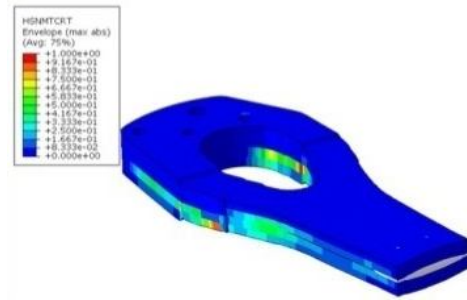


Figure-7(c) : Hashin Matrix Tension

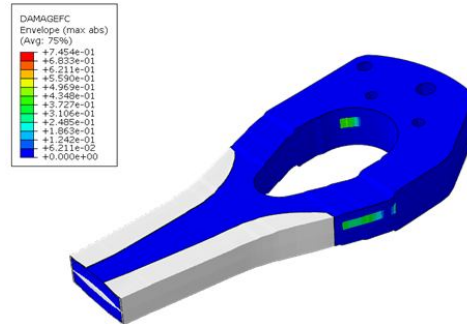


Figure-8(a) : Damage criteria(Fibre Compression)

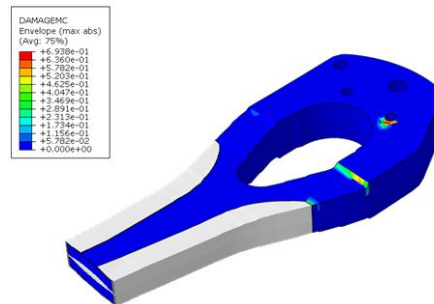


Figure-8(b): Damage criteria(Matrix Compression)

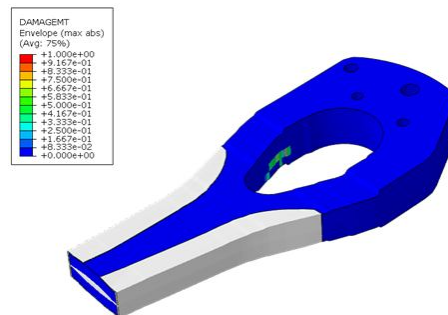


Figure-8(c): Damage criteria(Matrix Tension)

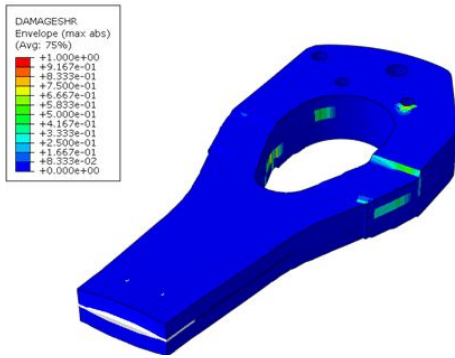


Figure-8(d) :Damage criteria(Shear)

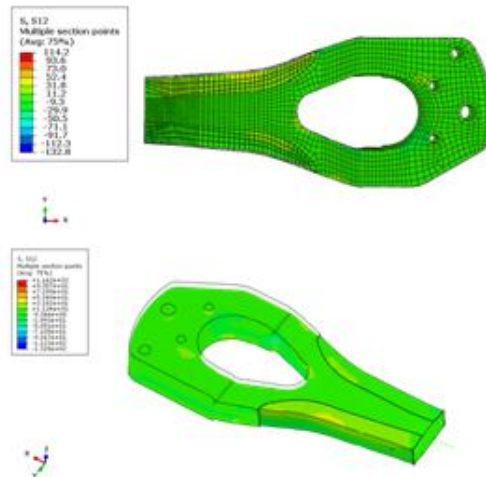


Figure-9(c): Stress in Shear Plane 12

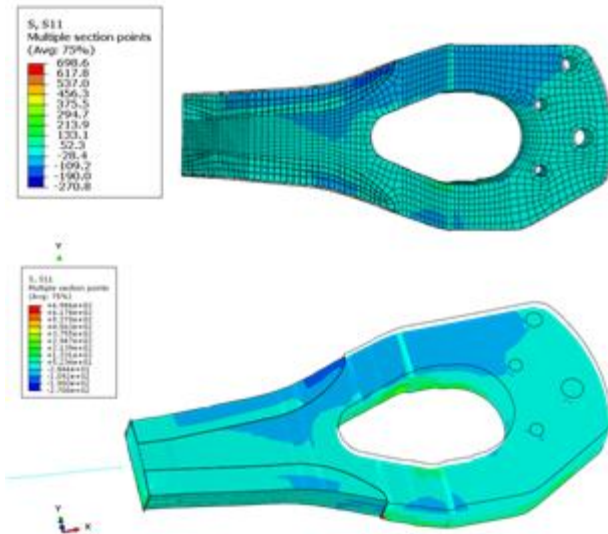


Figure-9(a):Stress in Longitudinal Direction(S11)

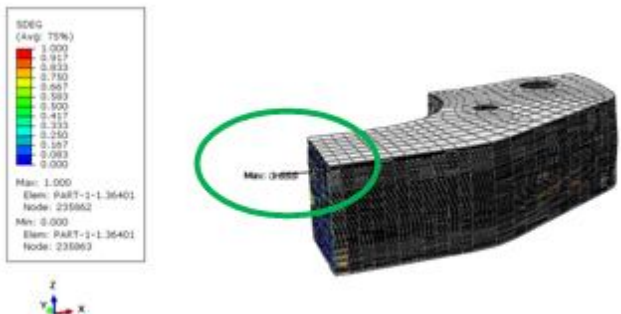


Figure-10(a): Cohesive Element Failing at Submodel Zone1

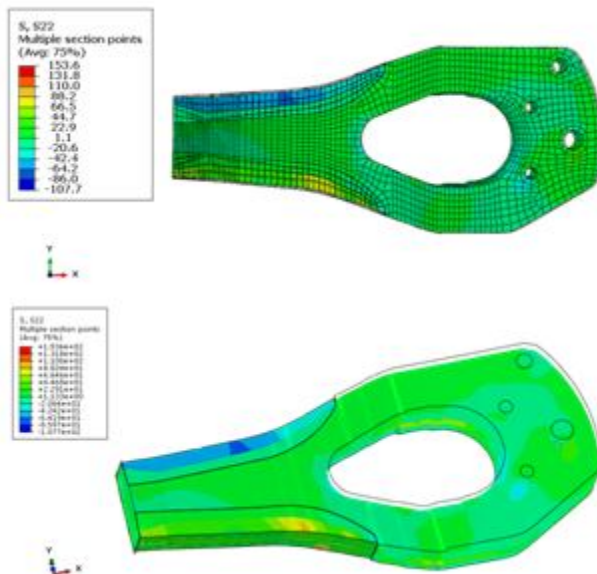


Figure-9(b):Stress in Lateral Direction(S22)

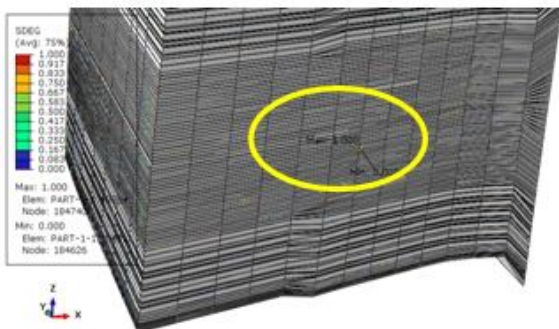


Figure-10(b): Cohesive Element Failing at Submodel Zone 5

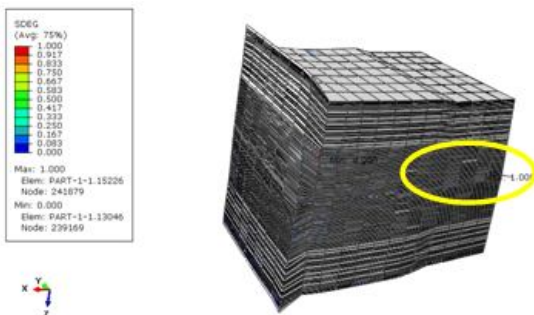


Figure-10(c): Cohesive Element Failing at Submodel Zone 4

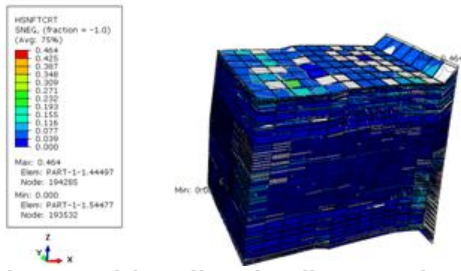


Figure-11(a): Failure in Fibre Tension

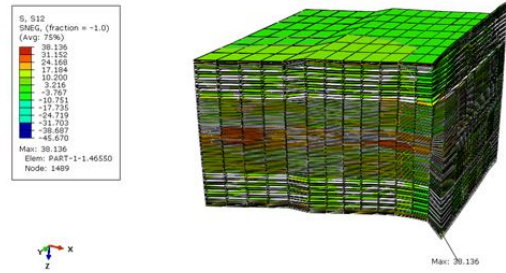


Figure-12(b): Shear stress in the plane(S12)

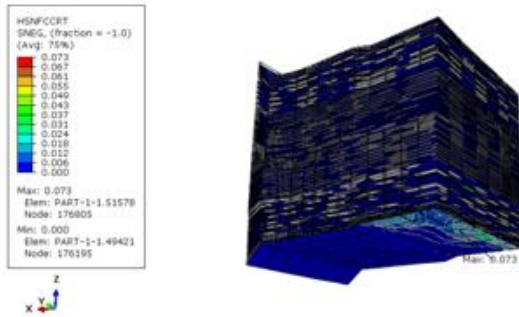


Figure-11(b): Failure in Fibre Compression

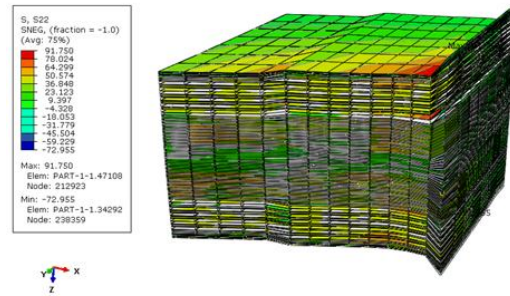


Figure-12(c): Stress in Lateral Direction(S22)

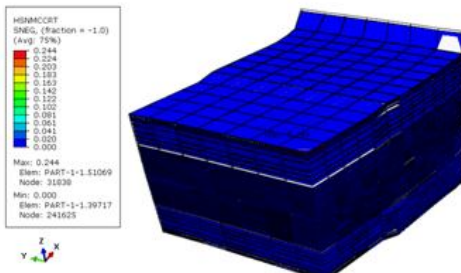


Figure-11(c): Failure in Matrix Compression

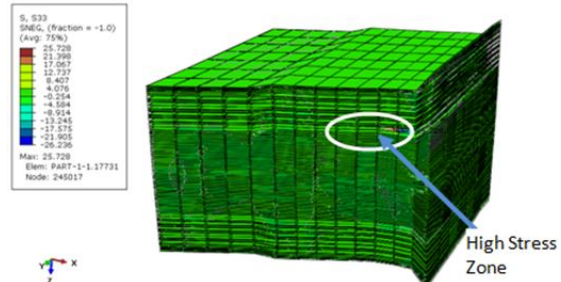


Figure-12(d): Transverse Stress(S33)

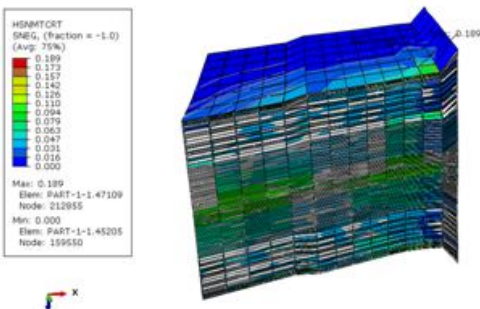


Figure-11(d): Failure in Matrix Tension

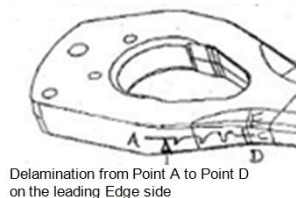


Figure-13(a): Delamination noticed at Blade Spoon

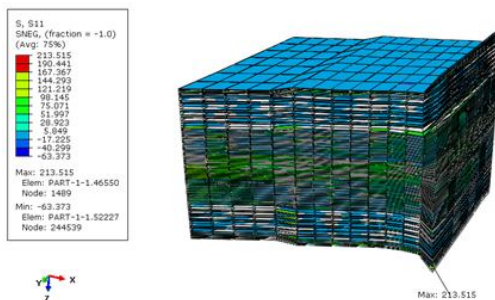


Figure-12(a): Stresses in Longitudinal Direction(S11)

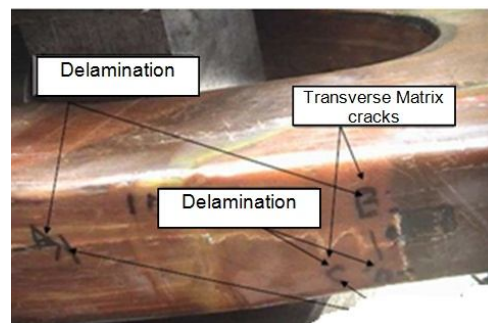


Figure-13(b): Delamination at Blade Spoon

Delamination Noticed after several thousands of cycles

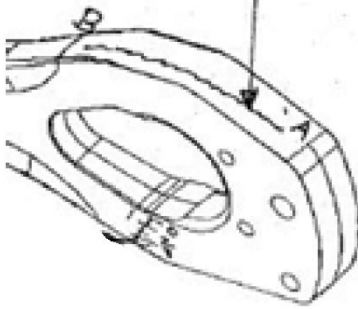


Figure-13(c): Delamination at bottom surface

Delamination after several thousands of cycles



Figure-13(d): Delamination in the inner surfaces

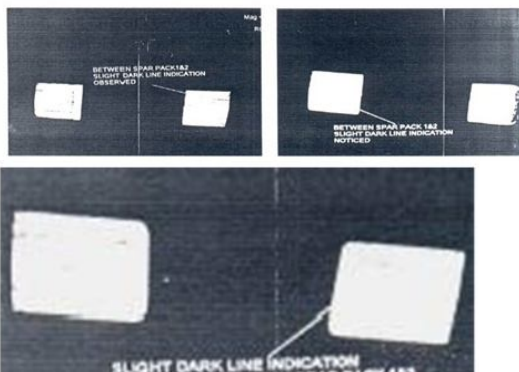


Figure-13(e): Delamination by CT Scan

Variation of Stresses- Logitudinal(S11), Lateral (S22) and Shear (S12) stresses along the blade root thickness(z direction) near the damage location in the blade root finite element model are shown in the following plots.

In Submodel Zone-1

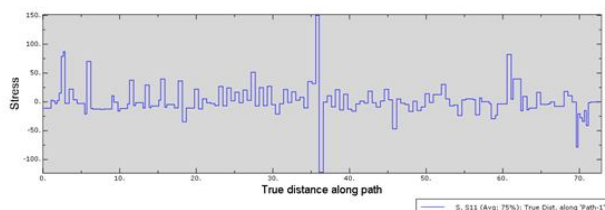


Figure-14(a): Longitudinal Stress(S11)

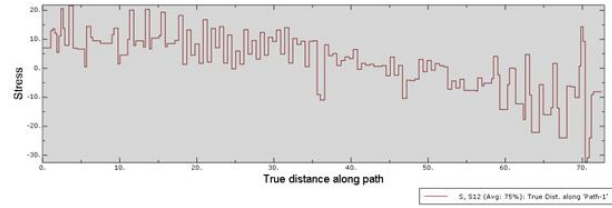


Figure-14(b): Shear Stress(S12)

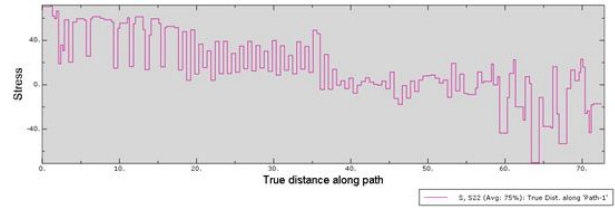


Figure-14(c): Lateral Stress(S22)

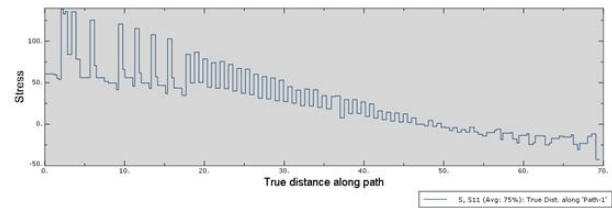


Figure-15(a): Longitudinal Stress(S11)

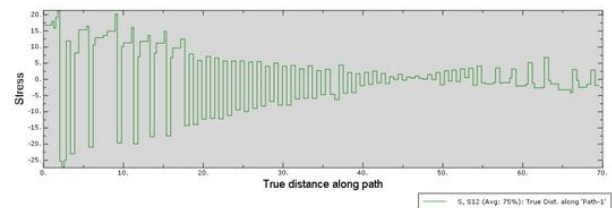


Figure-15(b): Shear Stress(S12)

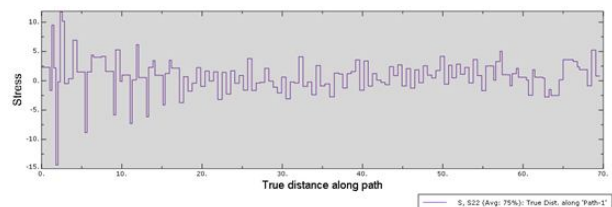


Figure-15(c): Lateral Stress(S22)

In Submodel Zone-2

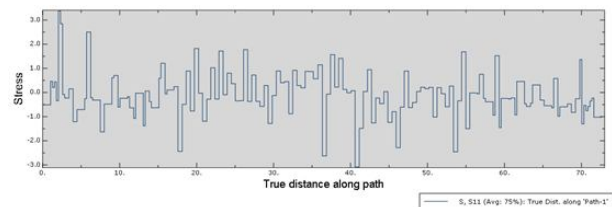


Figure-16(a): Longitudinal Stress(S11)

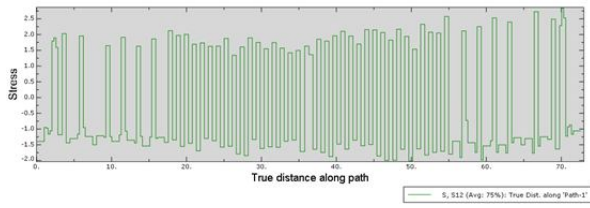


Figure-16(b): Shear stress(S12)

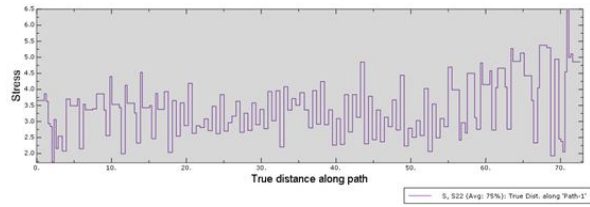


Figure-16(c): Lateral stress(S22)

In Submodel Zone-3

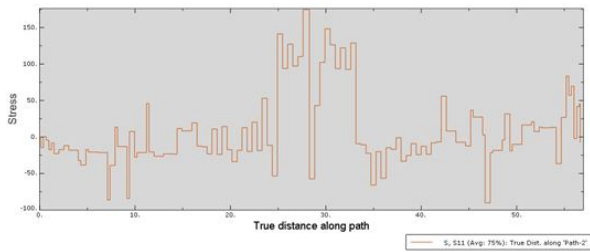


Figure-17(a): Longitudinal Stress(S11)

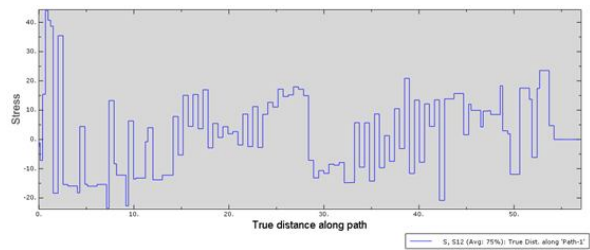


Figure-17(b): Shear Stress(S12)

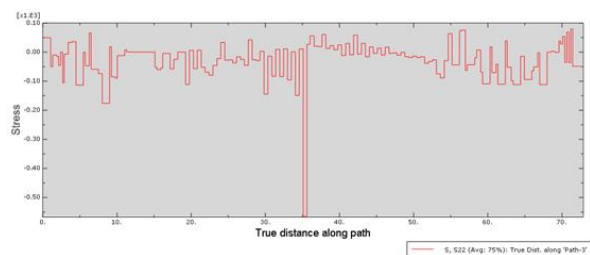


Figure-17(c): Lateral Stress(S22)

In Submodel Zone-4

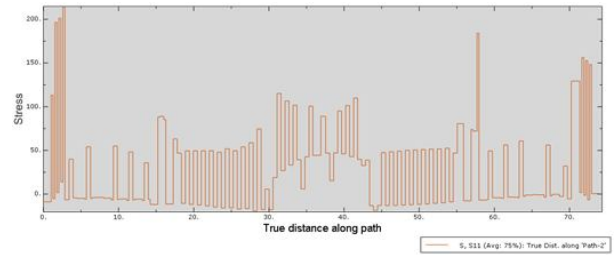


Figure-18(a): Longitudinal Stress(S11)

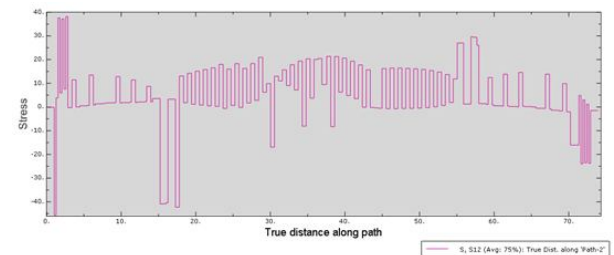


Figure-18(b): Shear Stress(S12)

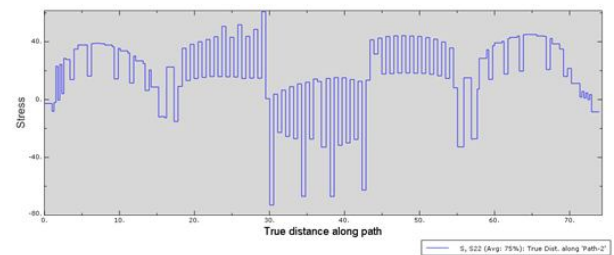


Figure-18(c): Lateral Stress(S22)