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Numerical Analysis of In-Plane Shear Strength on GFRP Composites under Adverse Thermal Ageing Condition

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Abstract*— Glass reinforced polymers are used in a wide variety of engineering applications and this occurrence continues. The exposure of composite structures to adverse environmental conditions during their service life period leads to degradation, which affects its material properties. The main objective of this paper is to determine the in-plane shear properties of uni-directional Glass/epoxy laminates when subjected to the various thermal conditions (Ambient, 253k, 343k). The in-plane shear properties of GFRP were studied by Iosipescu model, where the models were designed in various orientations (0°, 90°, 0/90°).The Iosipescu model has been designed as per the specifications prescribed in the ASTM 5379. The design and analysis of a three dimensional finite element model were carried out using ABAQUS/CAE. Crack initiation and propagation has been achieved by eXtended Finite Element Method (XFEM). In plane shear failures for [0], [90] and [0/90] were observed. Graphs have been plotted for in-plane shear stresses and shear strains to interpret the behavior of material under various thermal ageing conditions. Among all the other material orientations, cross ply laminates at room temperature possess higher in-plane shear strength, exhibits significant variations on both thermal ageing conditions than 0° and 90° orientations. The failure mechanism of thermally exposed FEA model has done by the C3D8R stress distribution model.

***Index Terms*—In-plane shear, Iosipescu shear test, Thermal Ageing, GFRP, ABACUS/CAE, (0°,90°,0/90°) orientation.**

I. INTRODUCTION

Glass reinforced plastics are widely used for aircraft wing fillets, fairings, control systems, wing tips, cabin floors, etc. In recent years, researchers intend to figure out the sensitivity of FRP composites that leads to damage. Delaminations and notches are the two main initial damages that play vital role in aerospace structural analysis. Researchers have shown special interest towards the experimental and analytical evaluation of in-plane shear test methods has been performed to determine the in-plane shear properties [1, 2]. Since the original Iosipescu shear test fixture provides a very small region of uniform shear stress and normal strains to the specimen, a modified Iosipescu shear test fixture was introduced [3]. It was believed that modified fixture consists of larger contact between the specimen and fixture, thus the uniform shear stress region increases while normal strains still exist in the specimen test section [4]. Influence of shear responses have been studied by various numerical approaches.

The authors in [5] applied concentrated forces to the specimen as per the original Iosipescu method in which it was clear that deformations found numerically is irrelevant to the experimental results, whereas the authors in [6] applied uniformly distributed load to the specimen test section as per modified shear test method in which the convergence of both numerical and experimental results were observed. It was found that the finite element modeling was not affected by the material properties but is influenced by the elastic stiffness due to different fiber orientation producing different deformations of the specimen in the fixture [7]. In some research works, continuum damage mechanics (CDM) have been developed which was effective to analyze macro structures with micro cracks. In CDM approach, the consequences of cracks are considered by degrading the material properties using some appropriate assumed damage variables [8]. An experimental investigation of unidirectional carbon-fiber/epoxy composites were done by means of 10 off-axis and 0 Iosipescu specimens subjected to shear. Complete non-linear finite element computations of these two tests were conducted using ANSYS. Later, the tests were compared in terms of stresses and strains at failure [9]. The influence of long-term moisture on the mechanical properties of Kevlar FRP has been reported, in which the tensile strength reduces while the longitudinal modulus remained constant [10]. The effects of moisture absorption on the mechanical properties of FRP composites were carried out by several other researchers [11, 12]. The moisture absorption of carbon reinforced epoxy composite laminates have been studied, in which all the possible mechanism for the failure is discussed. During the exposure period, the longitudinal tensile strength dropped by 25-30% in first month and latter remained constant; transverse tensile strength decreased; longitudinal tensile modulus decreased in first two months while transverse tensile modulus, in-plane shear modulus, poisson's ratio remained constant [13]. eXtended Finite Element Method (XFEM) is one of the methods that has been used to determine the crack initiation and propagation. XFEM uses partition of unity technique to extend the FEM by introduction of special displacement function which produces local enrichment to the nodes close to the crack [14]. In recent years, numerous attempts were done for the better understanding of shear responses on FRP composite materials. In the present study, specimens are modeled as prescribed in the ASTM standard [15] using a finite element software ABAQUS/CAE. The GFRP composites are then analyzed to determine the in-plane shear properties and the crack path in laminates with fiber orientation [0°, 90° and 0/90°]. In addition, the models are subjected to thermal ageing environment. The respective analysis for aged model is also carried out.

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II.THEORETICAL BACKGROUND

The Iosipescu shear test endeavours to attain a state of pure shear stress at the mid-length of the model by applying two counteracting force couples. A state of constant shear loading exists in the middle section of the model and hence the bending moment equals zero at the mid-length of the model. The Iosipescu model was tested using Iosipescu test fixture. The loading scheme is illustrated in the Fig.1 for better perception. In this test, the models with two symmetric V-shaped notches through height were used.

The average shear stress applied through the notched section and shear strength of the model are given by

$$\tau = \frac{P}{L.t} \qquad S = \frac{Pu}{L.t}$$

Where, τ = applied shear stress, N/mm^2
S = ultimate shear strength, N/mm^2
P = load applied to the model, N
P_u = ultimate load of the model, N
L =height of the model at notch location, mm
t = thickness of the model, mm

The shear strain is given as $\gamma_{xy} = 2\,|\epsilon_{45}|$. The shear strain can be evaluated from the measured normal strain that has been located at the centre of the notched section at 45° along the loading direction. Thus, the shear stress-shear strain data can be determined and the corresponding strength and modulus can be found from the resulting stress-strain curve.

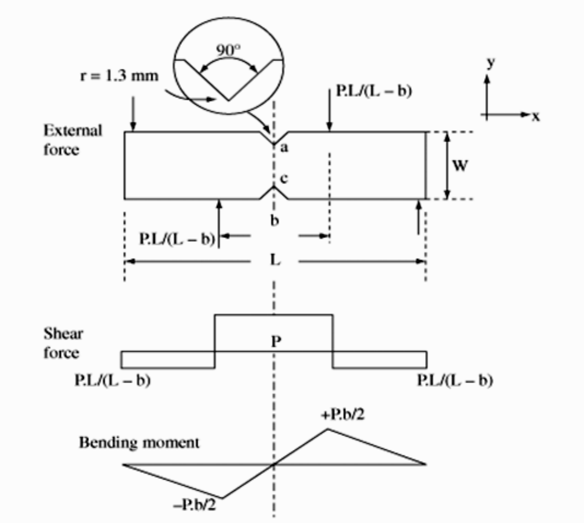

Fig 1.Shear force and bending moment diagram for the Iosipescu model.

Based on the above loading scheme, the numerical models are made to carry out in-plane shear variable fibre orientation and thermal ageing conditions (Ambient, -20°C and 70°C).

III. XFEM CRACK GROWTH

XFEM was first introduced by Belytschko and Black in 1999 which was an extension of the conventional finite element method based on the concept of partition of unity by Melenk and Babuska in 1996, which provides local enrichment to the nodes closer to the crack. As per [16], the extended finite element method (XFEM) enables to model discontinuities such as cracks, along an arbitrary, solution-dependant path during an analysis. Generally, XFEM is used to study the initiation and propagation of a crack. In order to perform fracture analysis, displacement jump across the crack surfaces are depicted by the discontinuous function and idiosyncrasy around the crack tip are imprisoned by the enrichment function.

Modeling of crack tip singularity becomes difficult since the constant tracking of moving crack is required. Therefore, asymptotic singularity functions are limited to stationary cracks whereas moving cracks are replicated by displacement jump across the cracked elements. The outcome shows that the crack will cut through an entire element at a time to avoid the difficulty in modeling crack tip singularity.

Based on traction separation cohesive law integrated within the framework of XFEM, used as a failure criterion to simulate crack initiation and propagation based on the concept of phantom nodes. Phantom nodes was superposed over the original nodes and used to replicate the discontinuity in the cracked element. Phantom nodes were tied together when the element was undamaged. When the element was cut by a crack, it splits into two parts whereas each part is the combination of original and phantom nodes based on the orientation of the crack. Thus each phantom node and its respective original node are no longer tied together and move apart.

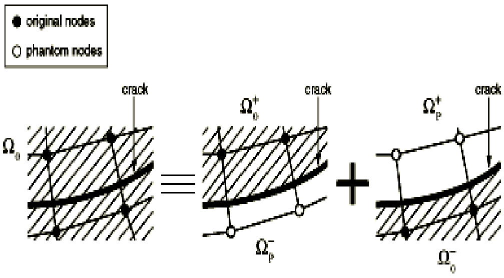

Fig 2.Representation of phantom and original nodes

IV. FINITE ELEMENT MODEL DESCRIPTION

A 3D finite element model has been developed to analyze the crack growth and in-plane shear properties using ABAQUS/CAE. The finite element model consists of 8 node solid model, which is of 76mm wide and 20mm long with symmetrical centrally located v-notches. The thickness of the model is 3mm that was partitioned into 10 sections to constitute a composite plate. Discretizations of thickness were demonstrated in fig.3 and Fig4.

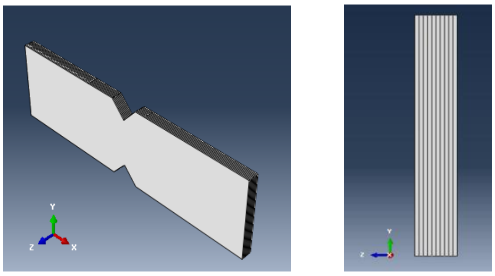

Fig.3 and Fig.4.Representation of 3D model and its layers

The finite element analysis of in-plane shear failure was studied by C3D8R, which is an 8 node linear brick, reduced integration, hourglass control. The hexagonal element is used for meshing and the model comprises of 69470 elements and 78606 nodes. Three different orientations of the model, such as [0], [90], [0/90] has been considered for the study and are represented in fig.5.

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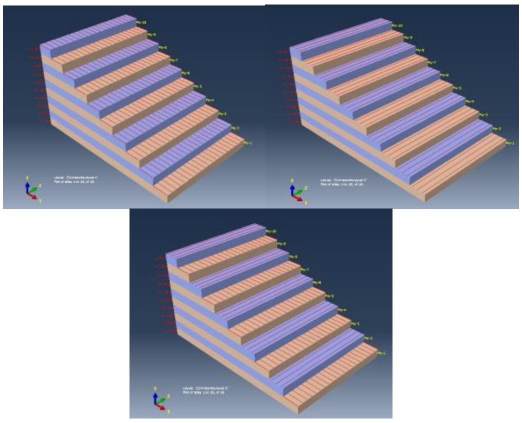

Fig.5. Ply stack configuration for $[0]_{10}$, $[90]_{10}$ and $[0/90]_{10}$

The 3D model requires maximum principal stress value to determine the crack path. In addition, the damage evolution has to be specified. The composite layup was formed using solid element type. As per the recommendation of ASTM 5379, the model is fixed in the y and z translational degree of freedom on the left side whereas the load is applied on the right side. An illustration of boundary conditions and load distributions were represented in fig.6.

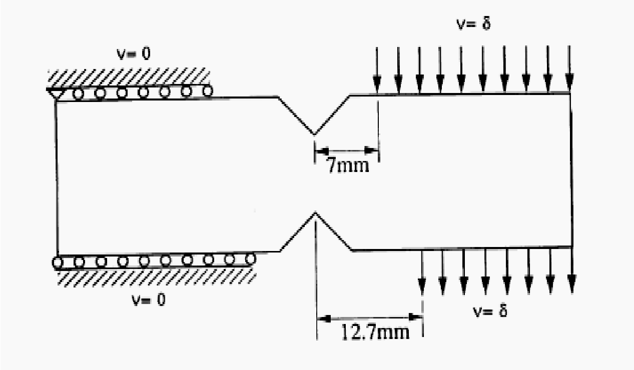

Fig.6. Loading scheme and boundary condition

V. RESULTS AND DISCUSSION

A total of three conditions have been considered for carrying out an XFEM crack analysis, in which the in-plane shear stresses and strains are determined. A 3D finite element model with material orientation 0°, 90° and 0/90 ply are analyzed with and without exposure to thermal environment. A 3D model was loaded with a magnitude of 10kN as shown in fig.6.

A. *Laminate with 0° Ply*

Three different orientations of the model were constructed as [0°,90°,0/90°] for studying the in-plane shear performance of GFRP and are represented in fig:5.

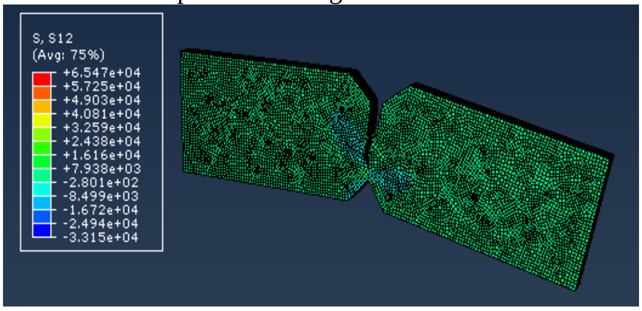

Fig.6. In-plane shear stress of 0° ply under ambient temperature

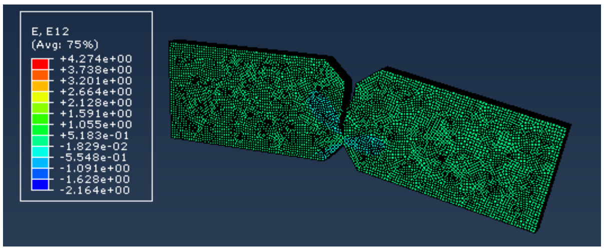

Fig.7. In-plane shear strain of 0° ply under ambient temperature

From fig. 6 & 7, it is observed that maximum in-plane stress and strain takes place at node 67789 which is at the end of crack path. A maximum in-plane stress of 65.467GPa and a maximum in-plane strain of 4.274 were formed.

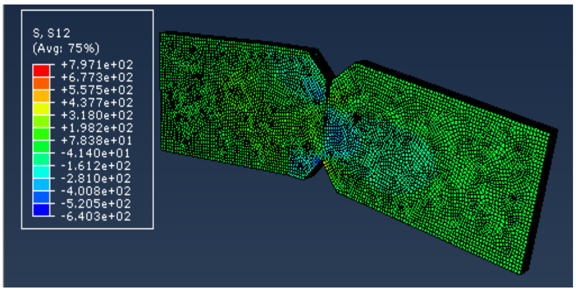

Fig.8. In-plane shear stress of 0° ply under -20°C

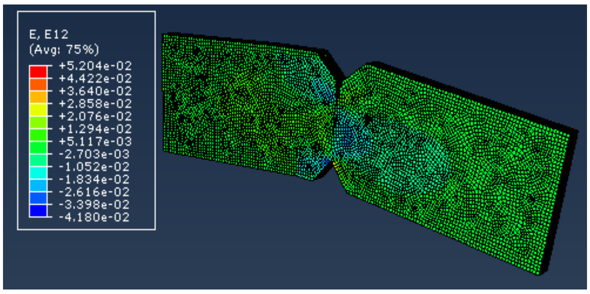

Fig.9. In-plane shear strain of 0° ply under -20°C

From fig.8 & 9, the model was exposed to a low temperature of -20°C at about 86400 seconds. A significant amount of degradation takes place for a low temperature treated model. A maximum in-plane stresses and strains occur at the center of bottom V-notch is observed as 797.1MPa and 0.05204 respectively.

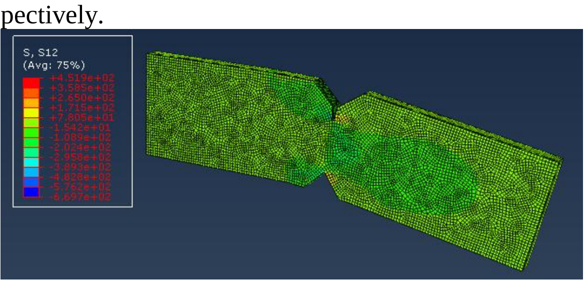

Fig.10. In-plane shear stress of 0° ply under 70°C

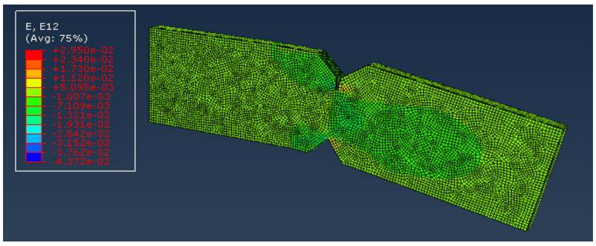

Fig.11. In-plane shear strain of 0° ply under 70°C

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Fig 10 & 11 represents the model exposed to a high temperature of 70°C at about 86400 seconds. A maximum in-plane shear stresses and strains were obtained at the crack path is 451.9MPa and 0.0295 respectively.

B. Laminate with 90° Ply

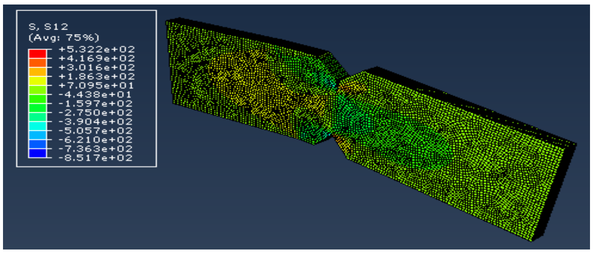

Fig.12. In-plane shear stress of 90° ply under ambient temperature

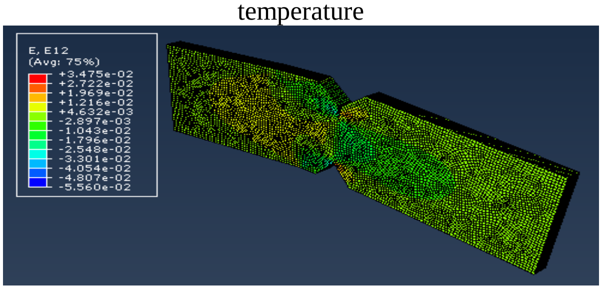

Fig.13. In-plane shear strain of 90° ply under ambient temperature

Fig.12 & 13 shows that the maximum values of in-plane stress and strain arises at the bottom tip of V-notch which contributes 532.2MPa and 0.03475 respectively.

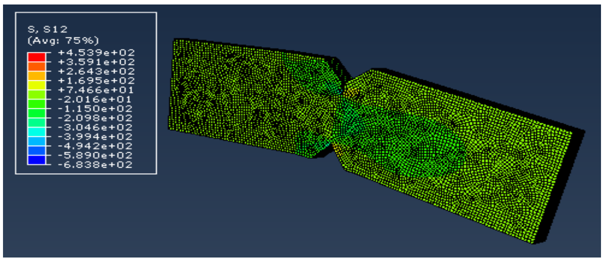

Fig.14.In-plane shear stress of 90° ply under -20°C

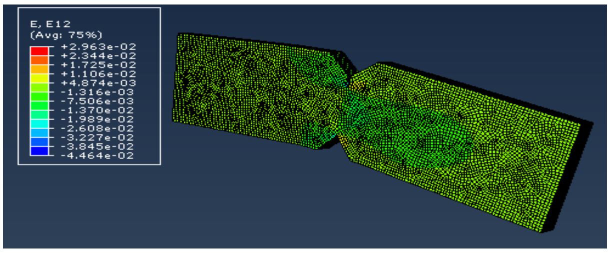

Fig.15. In-plane shear strain of 90° ply under -20°C

From fig.14 & 15, the maximum in-plane stress and strain values occur in the crack path with a magnitude 453.9MPa and 0.02963 correspondingly.

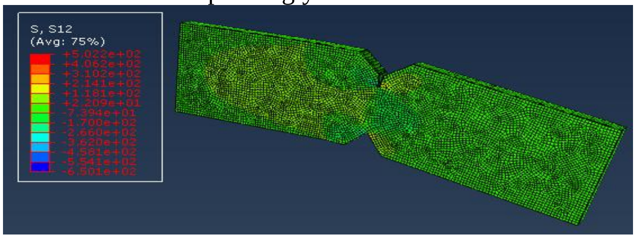

Fig.16. In-plane shear stress of 90° ply under 70°C

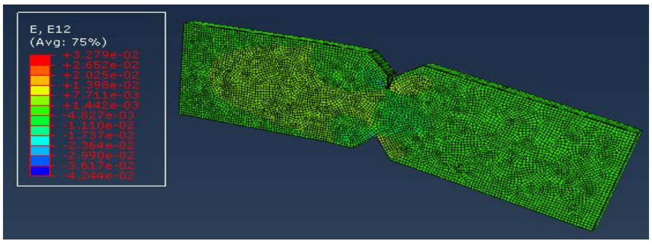

Fig.17. In-plane shear strain of 90° ply under 70°C

From fig.16 & 17, it has been noted that the maximum values occurs at the crack path which accords to 502.2MPa and 0.0327 subsequently.

C. Laminate with Cross-Ply [0/90°]

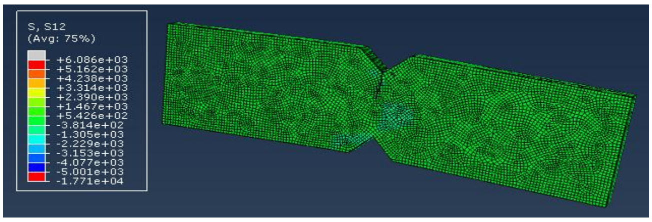

Fig.18. In-plane shear stress of 0/90° ply under ambient temperature

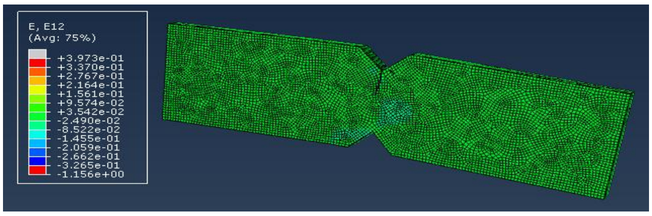

Fig.19. In-plane shear strain of 0/90° ply under ambient temperature

From fig.18 & 19, due to different material orientations, the crack propagates but the separation has not formed to a large extend 608.6GPa and 0.3973 are the maximum in-plane shear stress and strain obtained respectively.

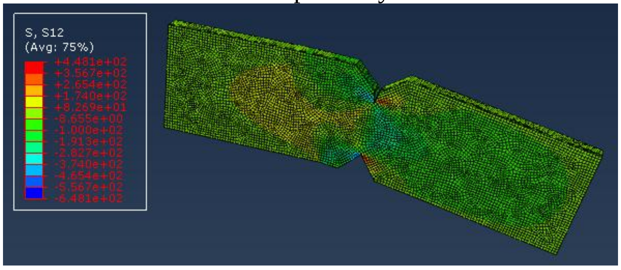

Fig.20. In-plane shear stress of 0/90° ply under -20°C

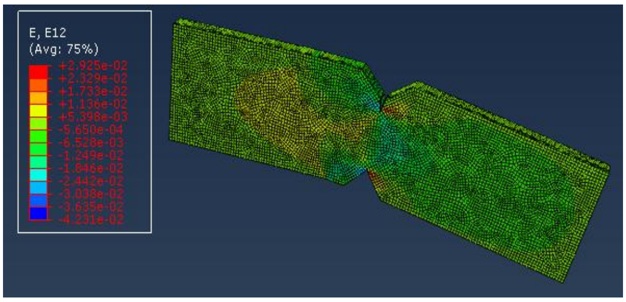

Fig.21. In-plane shear strain of 0/90° ply under -20°C

Fig.20 & 21 subjected to a low temperature exhibits a maximum in-plane shear stress and strain values of 448.1MPa and 0.02925 appropriately.

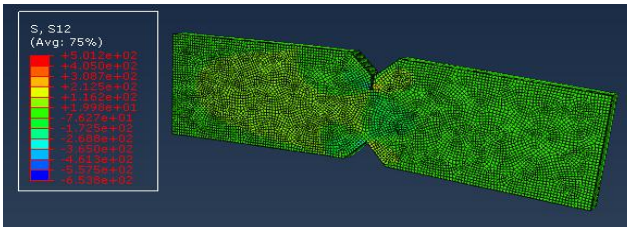

Fig.22. In-plane shear stress of 0/90° ply under 70°C

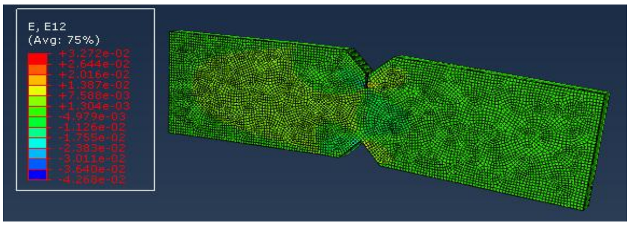

Fig.23. In-plane shear strain of 0/90° ply under 70°C

In fig.22 & 23, both the maximum values of stress and strain exist at the end of crack path which is 501.2MPa and 0.03272 correspondingly.

VI. CORRELATION

Conditions	Orientation in degree	Exposure interval in seconds	Maximum shear stress (MPa)	Comparison of strength (%)
Room temp	0	0	50.47	100
-20°C	0	86400	53.2098	94.85
70°C	0	86400	55.942	90.21
Room temp	90	0	99.0142	100
-20°C	90	86400	91.9374	92.85
70°C	90	86400	85.5475	86.39
Room temp	0/90	0	102.39	100
-20°C	0/90	86400	93.3486	91.1
70°C	0/90	86400	94.7351	92.52

Table.1.Comparison of the percentage reduction in shear strength

The above table correlated the FEA model of In-plane shear strength of material with different orientations under various thermal conditions with different intervals of exposure . From this table, the maximum in-plane shear stress value was compared .

From the fig.24, it can be inferred that the percentage of in-plane shear strength decreases with increase in time under thermal environment. A greater decrease in shear strength occurred in the laminate with 90° ply under exposure to 70°C which is approximately 14% with respect to the other thermal environment.

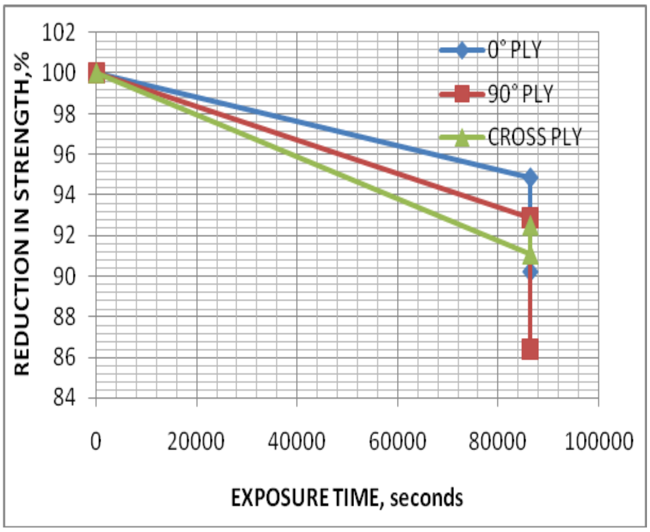

Fig.24 Reduction in strength Vs Exposure time

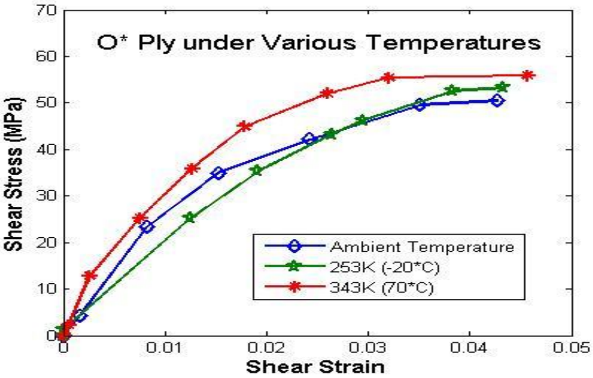

Fig.25. Shear stress Vs Shear strain for 0° ply

From the fig.25, it can be inferred that a maximum in-plane shear stress of 55.942MPa has been reached by the laminate subjected to 70°C, in comparison with the laminate subjected to room temperature and -20°C.

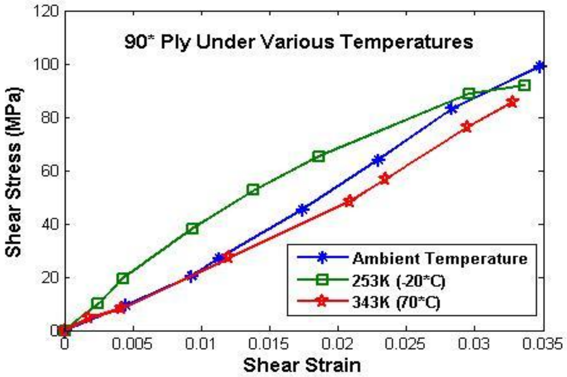

Fig.26 Shear stress Vs Shear strain for 90° ply

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Fig.26 represents that a maximal in-plane shear stress of 99.0142MPa has been outstretched by the laminate under room temperature.

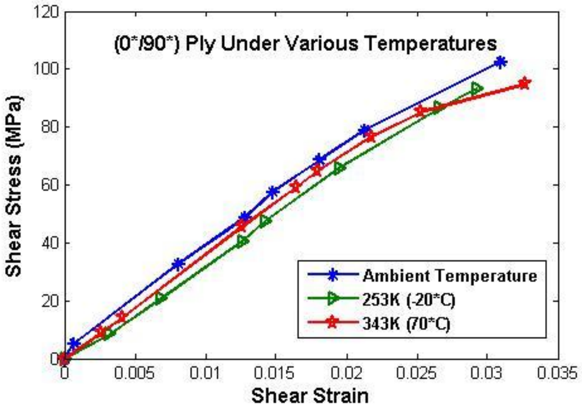

Fig.27 Shear stress Vs Shear strain for cross ply

From fig.27, it can be surmised that an extreme in-plane shear stress of 102.39MPa has been obtained by the laminate subjected to room temperature.

VII. CONCLUSION

In this study, the In-plane shear strength of GFRP laminate with different orientation is numerically observed with ABACUS /CAE under various thermal ageing conditions. The failure mechanism of thermally exposed FEA model has been studied from the stress distribution of the C3D8R model. The obtained results were tabulated and summarized below;

- In 0◦ ply, the in-plane shear strength of material which revealed the loss in strength about 10% at 70°C and 5% at -20◦C than ambient temperature. It emphasized that the in-plane shear strength which influence largely with direction of loading and its relative temperature. The mechanism of matrix failure is dominating at the temperature where the large reduction of strength was obtained nearer the glass transition temperature (70◦C) of materials over the other conditions.
- In 90◦ ply, the in-plane shear strength drastically decreases by 14% for 70°C while mere decrease of 8% takes place in -20°C conditions. The stress distribution over the model is relatively sensitive with orientation of fiber direction, which produces the fiber shrinkages through the thickness of model. The fiber shrinkage leads to drastic variation of strength at high temperature and moderately decreases in strength at low temperature.
- In cross ply laminate, there is less changes in strength between 20°C and 70°C conditions which constitutes 9% and 7.5% respectively. In the above, the material performance relatively high influence with matrix shrinkage and spontaneously interfacial failure between the fiber and matrix phase at low temperature and the same interfacial failure confined with 70◦C temperature. Hence, it has been concluded that, the in-plane shear strength of GFRP with 90◦ laminate shows abrupt decrease in strength at 70◦C where as the extended in strength was accomplished by 0◦ laminate under -20◦C. Altogether, the GFRP with three distinct orientations were subjected to three dissimilar environmental conditions, cross ply laminates at room temperature possess higher in-plane shear strength and exhibits significant variations on both thermal ageing conditions.

REFERENCES

[1] Pindera, M. J. and Herakovich, C. T., "Shear Characterization of Unidirectional Composites with the Off-Axis Tension Test," *Experimental Mechanics*, 26 (1): 103-112 (1986).
[2] Whitney, J. M., Stansbarger, D. L. and Howell, H. B., "Analysis of the Rail Shear Test-Application and *Limitations," Journal of Composite Materials*, 5:24-34 (1971).
[3] Adams, D. F. and Walrath, D. E.,"Further Development of the Iosipescu Shear Test Method,"Experimental *Mechanics* : 27 (2):113-119 (1987).
[4] Morton, J., Ho, H., Tsai, M.Y. and Farley, G.L., " An Evaluation of *the* Iosipescu Specimen for *Composite* Materials Shear Property Measurement," *Journal of Composite Materials,* 26 (5) :708-750 (1992).
[5] Sullivan, J. L., Kao, B.G. and Van Oene, H.,"Shear Properties and a Stress Analysis Obtained from Vinyl-ester Iosipescu Specimen," *Experimental Mechanics*, 24 (3):223-232 (1984).
[6] Walrath, D.E. and Adams, D. F., "Analysis of the Stress State in an Iosipescu Shear Test Specimen," Report UWME-DR-301-10I-1, Department of Mechanical Engineering, University of Wyoming, (June 1983).
[7] H. Ho, M.Y. Tsai, J. Morton and G, L. Farley," Numerical analysis of the Iosipescu specimen for Composite materials" Report NASA-CR-190658.
[8] Rabotnov YN. Creep rupture. In: Proceedings of the XII international congress applied mechanics. Stanford: Springer; 1968.
[9] G. Odegard, M. Kumosa, "Determination of shear strength of unidirectional composite materials with the Iosipescu and 10 off-axis shear tests", Composites Science and Technology 60 (2000) 2917±2943.
[10] S. Ravi, N.G.R. Iyengar, B.D. Agarwal, Inst. Eng. India: Aerosp. Eng. J. 76 (1995) 23.
[11] H.S. Choi, K.J. Ahn, J.-D. Nam, H.J. Chun, Compos. Part A Appl. Sci. Manuf. 75 (5) (2001) 709.
[12] P.J.C. Chou, D. Ding, J. Thermoplast. Compos. Mater. 13 (3) (2000) 207.
[13] S.B. Kumar∗, I. Sridhar, S. Sivashanker, "Influence of humid environment on the performance of high strength structural carbon fiber composites", Materials Science and Engineering A 498 (2008) 174–178.
[14] Moes, N.; Dolbow, J.; Belytschko, T. A finite element method for crack growth without remeshing. International Journal for Numerical Methods in Engineering, 1999; 46 (1): 131 -150.
[15]. ASTM D 5379, "Test Method for Shear Properties of Composite Materials by the V-Notched Beam Method," American Society for Testing and Materials, West Conshohocken, PA, 1993.
[16] ABAQUS Version 6.10 online documentation, SIMULIA Inc.