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Fracture Behaviour Study on the Cross-ply Composite Laminate with a Circular Hole Subjected to Thermo-Mechanical Loading with Temperature Fall

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Abstract:

The development and the usage of many innovative composite structures is on the rise due their inherent characteristics which offer several advantages in comparison with those of the conventional monolithic materials. The main limitations in the applications of these materials occurs due to the lack of knowledge about their fracture behaviors. So, there is need for establishing extensive data. So, conducting research in this path is still very much significant. In this paper, a composite laminate with a cross ply stacking sequence has been considered with a circular crack located at the center. The composite was modelled and then subjected to simple temperature loading and then thermo-mechanical (combined temperature + pressure) loading conditions. The temperature in both of the cases was considered to be falling and the in the case of the thermo-mechanical loading, the mechanical load was assumed to be constant. Strain Energy Release Rate (SERR) was calculated using the technique of Virtual Crack Closure Technique (VCCT) were used for studying the fracture propagation in the composite laminate that was considered. The effect of different parameters such as the temperature fall and combined loading with temperature fall on the SERR value in the 3 different modes of fracture with a circular crack located at the center of the composite laminate was studied and the influence was discussed in this paper.

1. INTRODUCTION:

Different properties such as light weight, higher stiffness to weight ratio, high strength to weight ratios, are some of the best characteristics exhibited by the advanced composites which lead to the rise in the use of materials for structural purposes in the 20th century. This rise in the usage of composite materials, is one of the crucial factors that has sparked interest in the research community and lead for works that intend for predicting the behavior of the composite laminated materials. Then coming to other reasons, for undertaking the research on this topic is that the fracture failures occur more often in composite laminates than expected. To avoid the catastrophic failure of the composite materials we should be able to predict the facture behavior of the laminate subjected to different loading conditions is crucial. A lot of understanding is required on the crack propagation in different modes and mixed modes due to the application of the temperature loading and combined (Thermo-mechanical) loading especially when the temperature is rising as these two conditions are most often are cause of failure of the composite laminates in operation in addition other factors.

Different researchers have put efforts to predict the fracture behavior of various functionally graded materials, composite laminates…etc., Jin et. al. [1] modelled an edge crack present in a multi-layered functionally graded materials subjected to transient thermal loading. The material behavior of the material was considered to be thermally non-homogenous material and they calculated thermal stress intensity factors (TSIF) of TiC/SiC FGM for various volume fractions. It was observed that the TSIF was reduced or increased with respect to the FGM strip used Tic, SiC respectively. Rolfes et. al. [2] had established 2D elements for studying both steady state and transient problems. These elements will be explicitly used for modelling laminated plates and cylindrical shells, with reduced order of shape function. Different thermal lamination theories were used to verify these elements. Matsunaga. [3] had presented a 2-D global higher order deformation theory for thermal buckling analysis of angle-ply laminated composite and sandwich plates. Virtual energy theory was used for deriving the governing equations which takes the shear and normal stresses in to consideration. The variation the displacement continuity functions for the 3-D layer wise theory and global higher order theories were applied for thermal buckling of the angle ply and sandwich panels were described. Tsang et. al. [4] studied crack propagation thermo-elastic problems using the 2-D fractal elements. In order to check the thermal stress intensity factors different transformation functions were analytically established with respect to thermal loading. Kerezsi et.al. [5] has exposed the specimen for continuous 1-D thermal shocks, so to find out how the growth of crack develops through experimental investigation and to determine the method for analyzing the behavior. For predicting accurate results, they developed a two-stage crack growth model which also includes the effect of environment on the crack growth where the model was just true for carbon steel at below operating temperatures of creep range. Herrmann et.al. [6] considered an interfacial crack with a contact zone with thermal problem as a Dirichlet-Riemann boundary value problem and resolved it. To determine the real contact zone length, they have derived analytical formulations. They observed that the real contact zone length and its corresponding stress intensity factors depends on normal shear loading and heat flux. Panda et.al. [7] assumed linear elasticity for mechanical loading which super imposed the thermal stresses where they observed that the cause for mixed mode of interlinear fracture at delamination front was due to the anisotropy and heterogeneity nature of the composite. Gardin et.al. [8] modelled the crack shape analytically for a thermal cyclic loading induced with a thermal gradient in the specimen's thickness using stress intensity factors, weight functions and Paris law. The influence of thermal gradient on crack dissemination was understood by comparing their analytical solution with FEM and experimental results. Shahani et.al. [9] derived the steady state solution to thermo-elastic problem analytically and then used a weighted function method to know the stress intensity factors and to determine from where semi elliptical crack initiates. Pradhan et.al.[10] discussed the manufacturing defects that causes inter laminar elliptical delamination's to forego crack growth influenced by ply angle and thermo-elastic loading. Bhalla et.al.[11] described about the energy consumed for the crack to grow and about the material damage. For analyzing the crack growth due to the thermal load, they used infrared cameras by calculating the energy flux, crack growth can be studied. Tang [12] considered an infinite plate and studied a crack line subjected to thermo-mechanical loading. A Complex function method was used to formulate the solution for the problem, by integrating with thermo-elastic theory. Only mode I stress intensity factor was found to be effective and the heat flux along the vertical direction to the crack line has no effect on the thermal stress intensity factor. To calculate the failure stresses, strain energy density factor theory had been effectively used. It was observed that the direction of the heat flow had an influence on the crack growth whether it may be positive or negative. Many other references regarding the general matter regarding the design and analysis of composite materials, facture and FEM analysis of composite material as have been referenced from [13-28].

2. FEA WORK

2.1 Problem Description:

A cross ply composite laminate plate with a circular hole and a virtual crack located at the center of the plate was taken. The behavior of the crack propagation with respect to the fall in the temperature that is applied was studied. The Effect of temperature fall on the crack propagation present in the composite laminate with circular hole was studied in the first case. In the second case, an additional pressure load was applied in conjunction to the temperature loading and the effect of combined thermo-mechanical loading (temp fall + pressure) on the crack propagation was studied. Conclusions were presented from the results obtained by conducting this work, and were presented in this paper.

2.2 Geometry:

The dimensions of the geometry of the composite laminate plate were taken as 100 X 100 X 5 mm in length, width and thickness dimensions. The total laminate was divided into 4 laminas, each of 1.25mm in thickness, which combinedly make up a laminate of 5 mm thickness. A layup sequences of [0, 90, 90, 0] was considered for modelling the fiber angles of the laminate. A circular hole of 40mm diameter is modelled at the midpoint of the composite laminate plate and a virtual circular crack of 0.22mm diameter was modelled at exact mid plane of the composite laminate thickness. The geometry of the composite laminate is shown in the fig.1 and the geometry of the edge crack is shown in the fig.2.

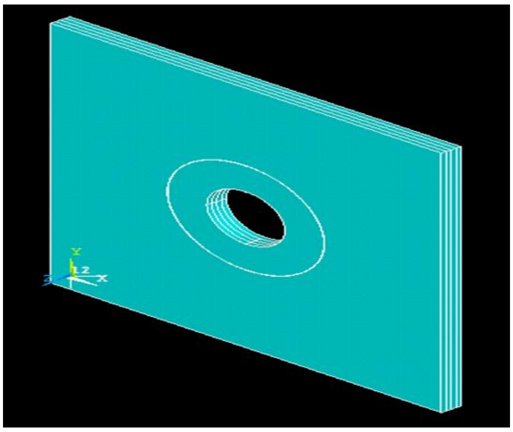

Fig.1: Geometry of the Composite Laminate

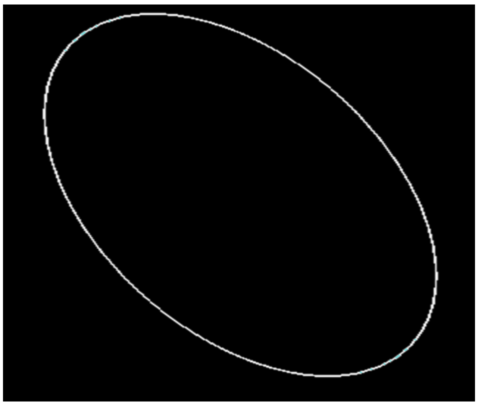

Fig.2: Geometry of the Virtual Crack

2.3 Material Properties

The properties of the As4 carbon fiber placed inside the 3501-6 epoxy matrix was the material that was considered for the lamina. Using these lamina mechanical properties shown in the below table no.1, the composite laminate with 4 layers was modelled. The material properties were taken from the textbook of I.M.Daniel& Ori ish [28]. Once the material properties of the lamina with 0^o fiber angle were taken from the reference, these properties of the lamina were used to find out the properties of the 90^o lamina using a simple MATLAB code. Table.1 shows the properties of the AS4/3501-6 Carbon/Epoxy lamina.

Table 1: Material Properties Taken for FEA

As4/3501-6 Epoxy carbon Composite Properties								
E_{11}(Gpa)	E_{22}(Gpa)	E_{33}(Gpa)	G_{12}(Gpa)	G_{23}(Gpa)	G_{13}(Gpa)	ν_{12}	ν_{23}	ν_{13}
147	10.3	10.3	7.0	3.48	7.0	0.27	0.51	0.27

α1 (10^{-6}/ºC)	**α2 = α3 (10^{-6}/ºC)**
-0.9	27

2.4 FE Model

The above-mentioned geometrical model was converted in to FEM model by using the process of meshing. For this purpose, the solid 20 node 186 element was used for the process of meshing. Suitable refinement and mesh settings were also used in the process of meshing the geometry. Both homogeneous solids and also layered solids can be effectively modelled using this particular element. In the present work, the element was used to mesh a layered solid. Fig.3 shows the FEM element used for meshing the composite geometry.

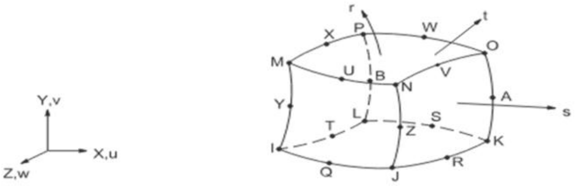

Fig.3: 20 Node 186 Solid Element used for Meshing

2.5 Boundary & Loading conditions:

Simply supported boundary conditions were used to constrain the four edges of the lamina using the displacement constraints present in the Ansys Software. In the first case where, pure thermal loading was considered, different temperature starting from -30 ºC to -180 ºC with a step size of -50 ºC were applied on the composite laminate. In the second case where, combined loading was considered a pressure load of 5 MPa was applied to the top face of the laminate in the downward direction in addition to the earlier stated thermal loading. Fig.4 shows the boundary conditions and loading conditions considered for the present work.

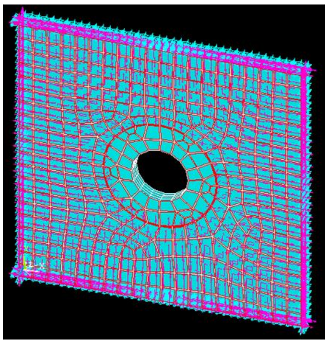

Fig.4: Boundary Conditions applied for the composite laminate

2.6 Validation of FE Model:

Validation of the FE model was conducted using the results taken from V.V. Venumadhav et al. [13]. SERR values were obtained for different crack lengths were taken from our FE model, which were validated against the taken reference. Table.2 shows the results obtained from validating the FE model.

Table 2: SERR due to Pressure load for different values of Virtual Crack

Virtual Crack Length (mm)	SERR (KJ/m^2)
5	12.35
3	11.22
2	10.64
1	10.05
0.5	9.94

From the results obtained from the Table.2, it can be stated that the percentage of error between the FEM values and the reference values is very low. From this we can say that our FEM model has been verified.

3. RESULTS

3.1 Effect of Pure Thermal Loading:

The change in the SERR values for different fracture modes for the circular hole with a crack that is located at the middle of the composite laminate due to the application of the temperature (fall) loading for a cross-ply composite laminate are shown in the fig. 5,6,7.

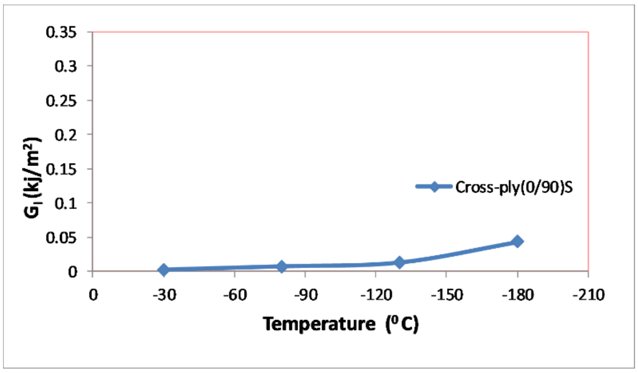

Fig.5: SERR vs Temperature for a cross-ply composite in Fracture Mode-I

From the figure 5, it can be observed that as the temperature is falling, the SERR value is increasing for a cross-ply composite laminate. So, there is an evident effect of the temperature falling on the SERR value in fracture mode -I (G_I), especially at lower temperatures for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to temperature (fall) loading.

From the figure 6, it can be stated that as the temperature is falling, the SERR value is increasing. So, there is an increased effect of temperature fall on the SERR value in fracture mode -2 (G_{II}), for the cross-ply laminate with a circular hole & crack at the middle of the laminate subjected to temperature (fall) loading.

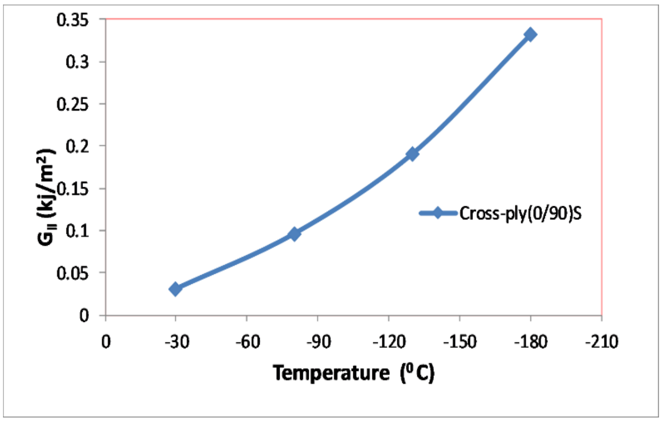

Fig.6: SERR vs Temperature for a cross-ply composite in Fracture Mode-II

From the figure 7, it can be observed that as the temperature are falling, there is very negligible change that was observed in the SERR value. So, there is no profound effect of the temperature fall on SERR value in fracture mode -3 (G_{III}), for the cross -ply laminate with the circular hole & crack at the middle of the laminate subjected to temperature (fall) loading.

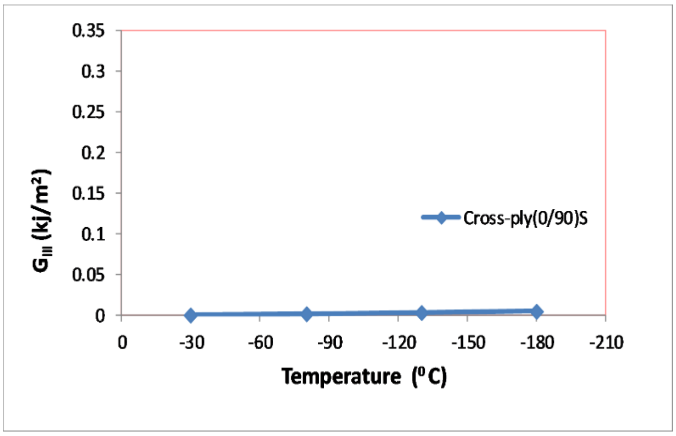

Fig.7: SERR vs Temperature for a cross-ply composite in Fracture Mode-III

The variation on the SERR values for different mixed fracture modes for the circular hole & crack that is located at the middle of the cross-ply composite laminate due to the application of the temperature (fall) loading are shown in the fig. 8,9.10.

From the figure 8, it can be observed that as the temperature is decreasing, there is a very minimal change that was observed in the SERR value initially but at very low temperatures the SERR value is increasing. So, there is no evident effect of temperature fall on SERR value in mixed fracture mode -1 (G_I/G_T), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to temperature (fall) loading.

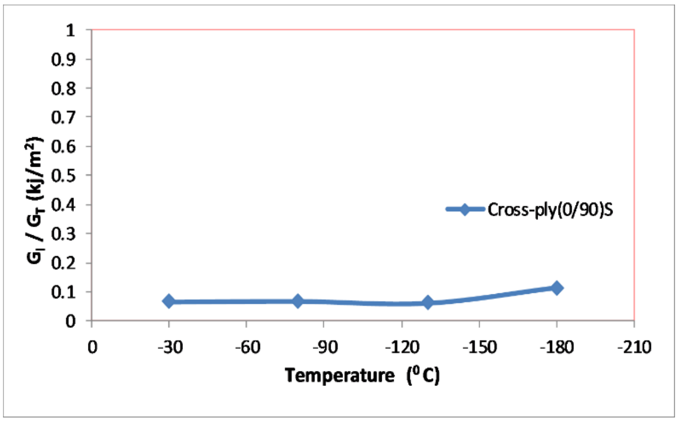

Fig.8: SERR vs Temperature for a cross-ply composite in mixed fracture Mode-I

From the figure 9, it can be observed that as the temperature is decreasing, there is a very minimal change that was observed in the SERR value initially but at very low temperatures the SERR value is decreasing. So, there is no profound effect of temperature fall on SERR value is observed in mixed fracture mode -II (G_{II}/G_T), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to temperature (fall) loading.

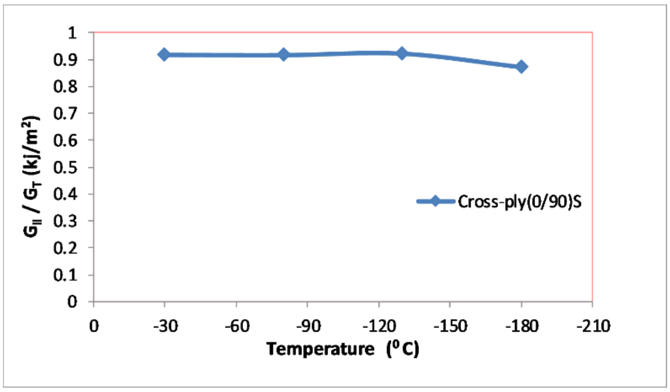

Fig.9: SERR vs Temperature for a cross-ply composite in mixed fracture Mode-II

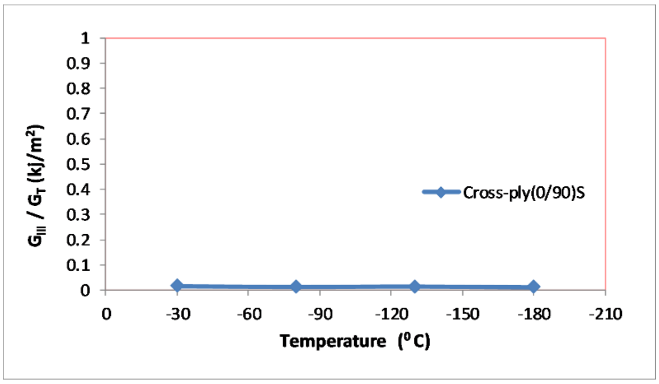

Fig.10: SERR vs Temperature for a cross-ply composite in mixed fracture Mode-III

From the figure 10, it can be observed that as the temperature is decreasing, there is no obvious change that was observed in the SERR value. So, there is no evident effect of temperature fall on SERR value is observed in mixed fracture mode -III (G_{III}/G_T), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to temperature (fall) loading.

3.2 Effect of Combined (Thermal + Mechanical) Loading:

The variation on the SERR values for different fracture modes for the circular hole & crack that is located at the middle of the cross-ply composite laminate due to the application of the combined loading are shown in the fig. 11,12,13.

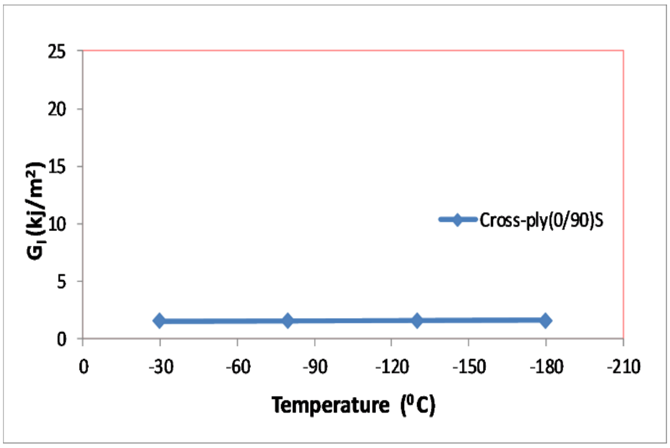

Fig.11: SERR vs Temperature (combined) for a cross-ply composite in Fracture Mode-I

From the figure11, it can be observed that as the temperature is falling and the pressure load remaining the same, there is no evident change that was observed in the SERR value. So, there is no evident effect of temperature fall on SERR value is observed in fracture mode -I (G_I), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to combined (temp fall + pressure) loading.

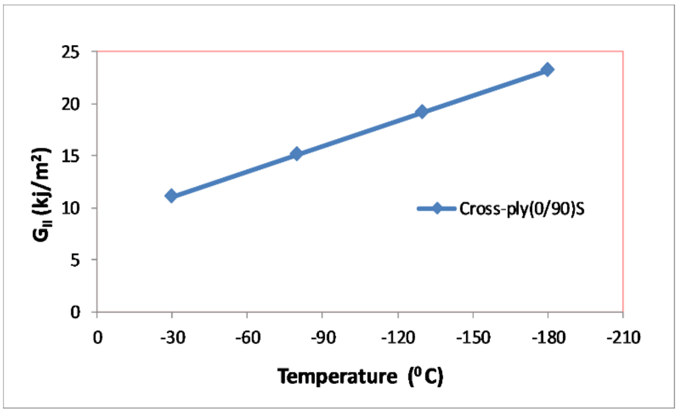

Fig.12: SERR vs Temperature (combined) for a cross-ply composite in Fracture Mode-II

From the figure 12, it can be observed that as the temperature is falling and the pressure load remaining the same, the SERR value is increasing. So, there is an evident effect of temperature fall on SERR value is observed in fracture mode -II (G_{II}), for the cross-ply laminate with the circular hole &crack at the middle of the laminate subjected to combined (temp fall + pressure) loading.

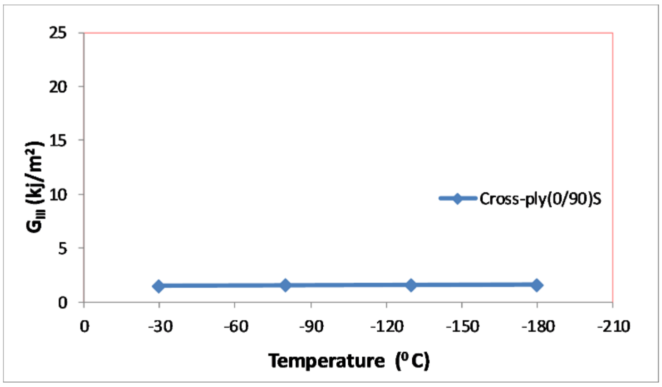

Fig.13: SERR vs Temperature (combined) for a cross-ply composite in Fracture Mode-III

From the figure 13, it can be observed that as the temperature is falling and the pressure load remaining the same, there is no evident change that was observed in the SERR value. So, there is no evident effect of temperature fall on SERR value is observed in fracture mode -III (G_{III}), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to combined (temp fall + pressure) loading.

The variation on the SERR values for different mixed fracture modes for the circular hole & crack that is located at the middle of the composite laminate due to the application of the combined loading for different fiber angles of the composite are shown in the fig. 14,15,16.

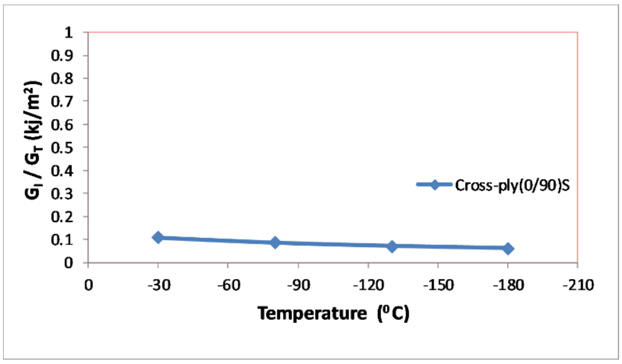

Fig.14: SERR vs Temperature (combined) for a cross-ply composite in mixed fracture Mode-I

From the figure 14, it can be observed that as the temperature is falling and the pressure load remaining the same, The SERR values were observed to be decreasing. So, there is evident effect of temperature fall on SERR value is observed in mixed fracture mode -I (G_I/G_T), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to combined (temp fall + pressure) loading.

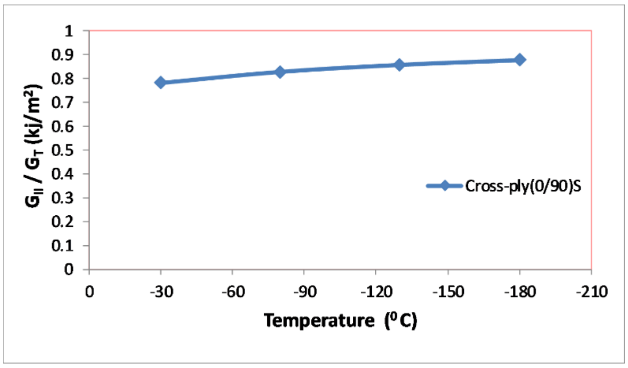

Fig.15: SERR vs Temperature (combined) for a cross-ply composite in mixed fracture Mode-II

From the figure 15, it can be observed that as the temperature is falling and the pressure load remaining the same, The SERR values were observed to be increasing. So, there is evident effect of temperature fall on SERR value is observed in mixed fracture mode -II (G_{II}/G_T), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to combined (temp fall + pressure) loading.

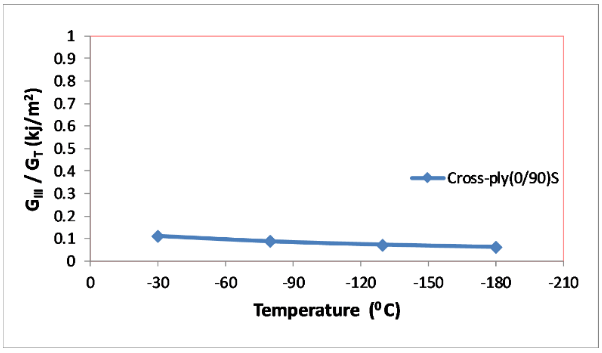

Fig.16: SERR vs Temperature (combined) for a cross-ply composite in mixed fracture Mode-III

From the figure 16, it can be observed that as the temperature is falling and the pressure load remaining the same, The SERR values were observed to be decreasing. So, there is evident effect of temperature fall on SERR value is observed in mixed fracture mode -III (G_{III}/G_T), for the cross-ply laminate with the circular hole & crack at the middle of the laminate subjected to combined (temp fall + pressure) loading.

4. CONCLUSION

Inter laminar fracture analysis of a cross-ply symmetric simply supported laminate with a circular hole and a crack at the center of the plate in middle interface was modelled and subjected to uniform transverse pressure and temperature fall. The crack propagation was studied using Virtual Crack Closure Technique using the process of finite element analysis. The SERRs in principal modes with respect to change in temperature(fall) loading were evaluated for pure thermal fall and thermo- mechanical cases and the trends were provided in this paper.

REFERENCES

[1] Z.H.Jin, Glaucioh Paulino, 2001, “Transient thermal stress analysis of an edge crack in functionally graded material”, International Journal of Fracture 107;73-98.

[2] R.Rolfes, K. Rohwer, 2000, “Integrated thermal and mechanical analysis of composite plates and shells”, Composite Science and Technology 60;2097-2106.

[3] Hiroyuki Matsunaga, 2006, “Thermal buckling of angle-ply laminated composite and sandwich plates according to a global higher-order deformation theory”, Composites Structures 72;177-192.

[4] D.K.L Tsang, S.O.Oyadiji, A.Y.T. Leung, 2007, “Two-dimensional fractal-like finite element method for thermoelastic crack analysis”, International Journal of Solids and Structures 44;7862-7876.

[5] B. Keresi, J.W.H Price, R. Ibrahim, 2003, “A two-stage model for predicting crack growth due to repeated thermal shock”, Engineering Fracture Mechanics 70;721-730.

[6] K.P.Herrmann, V.V. Loboda, I.V. Kharun, 2004, “Interface crack with contact one in an isotropic biomaterial under thermomechanical loading”, Theoretical and Applied Fracture Mechanics 42;335-348.

[7] S.K.Panda, B. Pradhan, 2007, “Mixed-mode analysis of superimposed thermo-elastic effects in fiber-reinforced composites with embedded interface delamination”, Composite Structures 77;570-580.

[8] Hoai Nam Le, C. Gardin, 2010, “Analytical prediction of crack propagation under thermal cyclic loading inducing a thermal gradient in the specimen thickness – comparison with experiments and numerical approach”, Engineering Fracture Mechanics 78;638-652.

[9] A.R. Shahani, S.M. Nabavi, 2006, “Closed form stress intensity factors for a semi-elliptical crack in a thick-walled cylinder under thermal stress”, International Journal of Fatigue 28, 926-933.

[10] B. Pradhan, S.K. Panda, 2006, “The influence of ply sequence and thermoelastic stress field on asymmetric delamination crack growth behaviour of embedded elliptical delaminations in laminated FRP composites”, Composites Science and Technology 66, 417-426.

[11] K.S. Bhalla, A.T. Zehnder, X.Han, 2003, “Thermomechanics of slow stable crack growth: closing the lop between experiments and computational modelling”, Engineering Fracture Mechanics 70,2439-2458.

[12] X.S.Tang, 2008, “Mechanical/thermal stress intensification for mode I crack tip: Fracture initiation behaviour of steel, aluminum and titanium alloys”, Theoritical and Applied Fracture Mechanics 50,92-104.

[13] V.V.VenuMadhav ,A.V.S.S.K.S. Gupta and V. Balakrishna Murthy, 2018, “Thermo-Elastic Fracture Analysis of Angle-ply laminates”, Materials Today: Proceedings 5; 6045–6052.

[14] Potluri Rakesh, “Mechanical Properties of Pineapple Leaf Fiber Reinforced Epoxy Infused with Silicon Carbide Micro Particles”. J. Nat. Fibers. 00, 1–15 (2017).

[15] Potluri Rakesh.,]K. Supriya, Vital, G.V.V.N.G, “Effect of Effect of boron carbide particles inclusion on the mechanical behaviour of S2-Glass fiber based polyester composites”, Mater. Today Proc. 5, 20257–20267 (2018).

[16] Potluri Rakesh., Dheeraj, R.S., Vital, G.V.V.N.G., “Effect of Stacking Sequence on the Mechanical & Thermal Properties of Hybrid Laminates”, Mater. Today Proc. 5, 5876–5885 (2018).

[17] Potluri Rakesh., Eswara, A., Raju, M.N., Prakash, K.R, “ Finite Element Analysis of Cellular Foam Core Sandwich Structures”, Mater. Today Proc. 4, 2501–2510 (2017).

[18] Potluri Rakesh., Eswara Kumar, A., Navuri, K., Nagaraju, M., Rao, “Buckling analysis of a ring stiffened hybrid composite cylinder”, IOP Conference Series: Materials Science and Engineering (2016).

[19] Potluri Rakesh., Diwakar, V., Venkatesh, K., Reddy, B.S, ” Analytical Model Application for Prediction of Mechanical Properties of Natural Fiber Reinforced Composites”, Mater. Today Proc. 5, 5809–5818 (2018).

[20] Potluri Rakesh., Rao, U.K, “Determination of Elastic Properties of Reverted Hexagonal Honeycomb Core : FEM Approach”, Mater. Today Proc. 4, 8645–8653 (2017).

[21] Potluri Rakesh., Paul, K.J., Babu, B.M. “ Effect of Silicon Carbide Particles Embedment on the properties of Kevlar Fiber Reinforced Polymer Composites”, Mater. Today Proc. 5, 6098–6108 (2018).

[22] Potluri Rakesh., K, J.P., Abdul, S., Prasanthi, P, “Mechanical Properties Characterization of Okra Fiber Based Green Composites & Hybrid Laminates”, Mater. Today Proc. 4, 2893–2902 (2017).

[23] Rakesh Potluri, (2018) "Mechanical properties evaluation of T800 carbon fiber reinforced hybrid composite embedded with silicon carbide microparticles: A micromechanical approach", Multidiscipline Modeling in Materials and Structures, Vol. 14 Issue: 3, pp.589-608.

[24] Potluri Rakesh., “Comparative Study of Pressure Vessels Made from Laminated Composite Material (COPV) with the Pressure Vessels Made with Sandwich Core Composite Material”, J. Mater. Sci. Mech. Eng. 2, 203–207 (2015).

[25] Potluri Rakesh., Ketha, K.K., “Comparison between GFRP and CFRP Composite Power Take-off Shaft in Helicopters for Prescribed Torque and Geometrical Constraints”, J. Mater. Sci. Mech. Eng. 2, 214–219 (2015).

[26] Potluri Rakesh, 2018, “Natural Fiber-Based Hybrid Bio-composites: Processing, Characterization, and Applications”, Green composites, 1-42, Springer Singapore.

[27] ANSYS Reference Manuals, (2016).

[28] I. M. Daniel & Ori Ishi, Engineering Mechanics of Composite Materials (2006).