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Study of the Fracture Behavior under the Effect of Cross-ply and Angle-ply Arrangement of FRP Composite Laminate Subjected to Central Circular Cut-out with Mechanical and Thermal Loading Conditions

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ABSTRACT

In advance composite material the propagation of crack is a regular failure problem in various engineering applications especially in aircrafts body. The aircraft body components are subjected to various thermal and mechanical loading conditions. It is very difficult, time-consuming and costly process of testing the aircrafts components failure due to various thermal and mechanical conditions. Strain energy release rate (SERR) is the significant parameter for the composite materials and quality of composite materials depends on SERR values.The present investigation is based on ANSYS analysis for finding the strain energy release rate (SERR) value using Virtual Crack Closure Technique (VCCT) to understand the fracture behavior of the composite lamina. The circular crack present in the middle of the composite plate and subjected to pressure and temperature loading for different angle (cross-ply and angle-ply) composite structure laminas. The angle-ply shows less SERR in mode I & II while cross-ply shows less SERR in mode III under the constant pressure loading conditions. Mode II shows the maximum SERR in cross-ply compared to mode I and III for temperatures 30ºC, , 130 ºC and 180ºC. SERR for mixed-mode was found by considering the total mode of fracture and validation based on published literature for SERR due to the thermal load of mode I (G_I) for different fiber layup configurations of the circular cut-out.

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1. INTRODUCTION

Composite materials play an essential role in various Engineering applications because of their beauty related to their material properties. Composites have properties like low coefficient of thermal expansion and density, higher strength, good resistance to fatigue, corrosion, wear and creep. The properties of composite do not only depend on its materials properties; they widely vary with composite construction. The Automotive and Aerospace Industries fiber-reinforced composite (FRP) is used to develop the structural and nonstructural components [1-3]. Reasreschers are used biopolymer and natural fibers [1], natural fiber reinforced polymer composites (NFRPCs) [2], carbon nanotube-reinforced polymer composite [3], and wood and another composite [4] for various application armor structure system and electrical transmission system application [5]. For structural applications, the fracture toughness of composite materials plays an important role. Many researchers tried to improve the fracture toughness, creep, energy absorption characteristics, creep, and other mechanical properties by changing the use of materials for developing the composite and adopting various changes with construction methods like sandwich [6] and various orientations of the composite materials. Also, the researchers work on the various loading (mechanical, thermal, and thermo-mechanical) conditions and their effect on fracture behaviors of composite materials.

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Wang et al. [7] studied the effect of course loading on the graphite-epoxy cross-ply laminates and their various cracking events. They observed 0.3% lower strains induced at the transverse crack at 90º ply. The crack increased continuously with continuously increasing applied tension. Also, they observed matrix dominant cracking modes are emerging before breaking of fiber at 0º ply. Bae et al. [8] used aluminum, polymetheyl-methacrylate samples used to investigate the effect of thermo-mechanical loads on the samples interfacial cracks with mismatches in thermal and mechanical loading. They observed the propagation path of cracks to be occurred due to the effect of temperature. It could be the measure of crack tip stresses that occurred while loading. Aiello et al. [9] proposed the analytical model for finding the temperature rise (ΔT) to initiate the cracking phenomenon to complete concrete failure. They found the FRP reinforced concrete elements under Thermal loads. The nonmetallic rebars were presented with high transverse coefficients of thermal expansion, which increased the temperature of concrete when tensile stresses act. Camanho and Catalanotti [10] studied the fracture toughness of a multidirectional carbon–epoxy composite with 0º ply angle. The model developed was the combination of lamination theory and linear-elastic fracture mechanics. Fracture toughness of any material would play an important role in offering considerable resistance to cracks. Shi et al. [11] developed a method to predict the compressive strength and failure of the silica fiber-reinforced phenolic composites under thermo-mechanical loading. They got results with good agreement between the experimental measured strength values and curve obtained by calculated values. Shi et al. [12] proposed a model for predicting FRP composite degradation behavior supporting static compressive loading under high temperatures. They found that the proposed model can be good for predicting FRP composite properties based on the temperature.

Le and Gardin [13] studied the propagation of a surface crack due to the cyclic thermal loading over a stainless steel specimen. They introduce the analytical and numerical approach for kinematics of the crack and crack shape evolution. They found the results are in good agreement with the analytical approach and numerical approaches supported by experimental results. Barroso et al. [14] provided a general procedure for evaluating fracture toughness value with different experimentation techniques. The process, explained in their work, was apt to apply it for anti-symmetric models that possessed dual singularity of multi-material corners. Berto et al. [15] conducted more than 70 fracture tests on specimens with notches made of polymethyl-methacrylate at room temperature. The notch root radius varies from 0.1 to 7mm for semicircular notches, U-shaped and V-shaped notches to conduct the static test.

Pinto et al. [16] developed a method to measure inter-laminar cracks that occurred due to extreme temperatures. The double-edge notched (DEN) specimen is used to find the crack resistance curve. Li et al. [17] analyzed the dynamic nature of crack growth in elastic-plastic solids numerically when the local heating and temperatures raised the whole phase transition of crack-tip stress and deformation from elastic to plasticity by estimating the work done due to heat generation. Rolfes and Rohwer [18] estimated temperature distribution in the thickness direction. They developed suitable elements for numerical analysis and experimentally verified the same with the problems about both steady-state and transient cases. The researchers also tried to improve the flexural and shear strength of RC Beam Reinforced by Glass Fiber-Reinforced Polyurea (GFRPU) [19]. They observe significant improvement in resistive capacity and ductility for non reinforce beams over reinforced beams. Also, the change in design like blade edge and adding edged on the torsional bar helps improve mechanical properties of components used in various engineering applications [20].

From the literature survey, it is clear that most researchers are tried to investigate the fractural toughness of various composite materials. For the investigation, researchers are used numerical simulations and experimental methodologies depending on various conditions and applications. Researchers used some thermal, mechanical, and thermo-mechanical loading conditions and the different types of composite construction conditions. But there is still scope to introduce the effect of cross-ply and angle-ply composite laminated structures on thermal, mechanical, and thermo-mechanical loading combination in the single composition of composite materials. Therefore, the present investigation is based on the study of the fracture toughness of FRP composite effect on composite laminate (cross-ply and angle-ply) under the thermal, mechanical, and thermo-mechanical loading conditions finite element analysis methodology. FEA results validate with published literature.

2. FEA WORK

2. 1. Problem Configuration, Geometry and Fracture Mode A cross-ply and angle-ply composite laminate along a virtual crack and circular hole at its center was considered. Figure 1 shows the application of circular cut-out in a composite panel used in the Aircraft. For the present investigation, two types of cases i.e., pure thermal and structural loading was

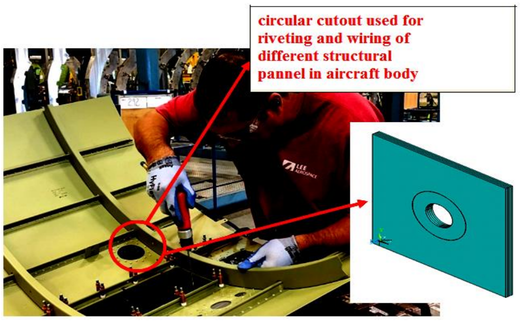

Figure 1. Circular Cut-out in a Composite panel used in the Aircraft

considered. The angle (+45º/-45º) and (0º/90º) is considered for the angle-ply and cross-ply, respectively. Figure 2 shows the angle-ply and cross-ply representation used in the development of composite lamina. A volume has been created with 100 mm X100 mm X5 mm of length, width, and thickness, and a circular cut-out of 20mm diameter is modeled at the geometrical center of the plate. Figure 3 shows the geometry of the composite laminate along with dimensional details and arrangements. A crack is modeled with 20 mm around the circular cut-out periphery-out with a virtual crack of a 0.22 mm diameter around it and between the second and third layers of the laminate. The thickness of the laminate 5mm is divided into four laminas i.e.5/4= 1.25 mm, with each layer having a thickness of 1.25 mm. In this 1.25 mm layer, the desired fiber angle is maintained.

During the analysis the three different ways (Modes) fracture are considered of presenting a force to enable a crack to propagate. These ways are famously termed as modes of fracture as shown in Figure 4. Mode I fracture, where the tensile stress acts normal to the plane of crack. It is also termed as opening mode, as it creates an opening to the crack to propagate further. It is representing by G_I during the present investigation. Mode II fracture, where the shear stress is acting parallel to the plane of the crack and perpendicular to the crack front. It is represented by G_{II} during the present investigation. Mode III fracture, where a shear stress acting parallel to the plane of the crack and parallel to the crack front. It is represented by G_{III} during the present investigation. Mixed Mode fractures, in general structures are subjected to not only simple tension or compression loadings but also to shear as well as torsion loads. This combination of different type of loading patterns will lead to combination of three basic modes, known as mixed mode. Mixed modes can be a result of different types of interactions such as mixed mode I/II or mode II/III or mode I/III. The summation of all three modes i.e. total mode it is denoted by G_T.

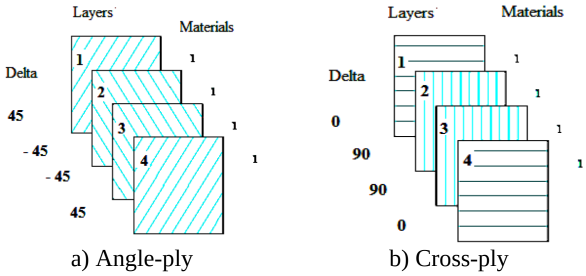

Figure 2. Angle-ply and Cross-ply representation[21]

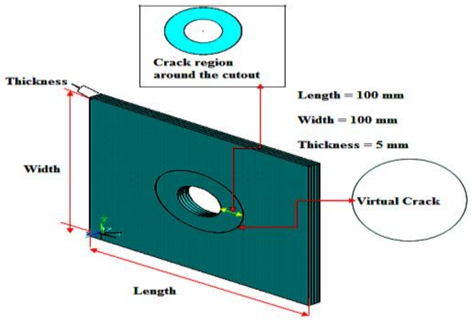

Figure 3. Circular cut-out composite laminate layup with the virtual crack

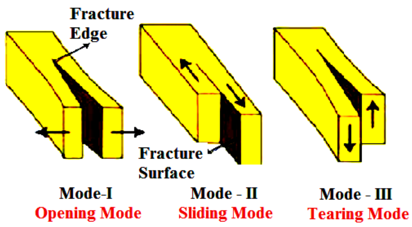

Figure 4. Fracture modes [21]

2. 2. FE Model Figure 5 shows the geometry of composite lamina and virtual crack which is considered for the analysis. The solid 20 node 186 elements are used for the present investigation along with refinement and suitable meshing.

2. 3. Material Properties The composite modeling was done using lamina material 3501-6 epoxy along AS4 carbon fiber inside surrounded. From I.

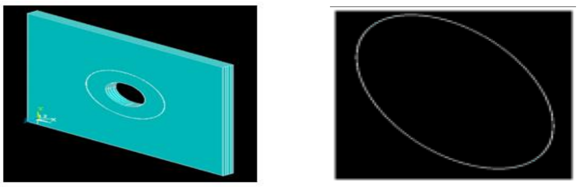

Figure 5. Geometry of the Composite Laminate and virtual crack

Daniel and Oriish [21] required material properties are used for the analysis. Initially composite lamina at 0° fiber angle are considered for the materials properties from reference, then material properties of composite lamina for 45° and 90° find using a simple MATLAB code. Table 1 shows the properties of the AS4/3501-6 Carbon/Epoxy lamina.

2. 4. Boundary and Loading Conditions

Figure 6 shows the composite lamina after applying meshing and boundary conditions. The ANSYS software is used for the meshing and applying the boundary conditions. The displacement constraints are applied on all four edges of the composite lamina by considering similar supported conditions. The two loading conditions are considered i.e., Thermal and Mechanical. Initially, in the first case, Mechanical loading is applying to geometry; for this loading, a pressure of 5 MPa is considered. The 5 MPa load pressure is applied on the top face of the composite lamina, and the direction of loading is downward. The thermal loading is considered in the second case of analysis. Thermal loading is applied on the geometry; for this loading 30˚C temperature is considered starting temperature, then temperature increases up to 180°C. Results are finding with the interval of 50°C temperature difference applied on the composite lamina.

3. RESULTS AND DISCUSSION

3. 1. Mechanical Load (Angle-ply Vs Cross-ply)

Figure 7 shows that the variation of G_I, G_{II} and G_{III} with respect to the S.E.R.R. for Angle-ply (+45°/-45°)s and cross-ply (0°/90°)s under Mechanical loading. As represented in Figure 7, the shearing mode energy release rate (G_{II}) is more and the shearing action of the laminate with cut-out will be minimized by arranging the fibre in cross layup. For the case of G_I, the Angle-ply laminated yielded maximum SERR as compare to Cross-ply laminate. In the case of G_{II}, the Angle-ply laminate setup showed maximum SERR and Cross-ply laminate showed minimum SERR. In the G_{III} case, the Cross-ply SERR is maximum and angle-ply SERR is minimum. Therefore, the cross-ply is significant useful and good results for mode I and II failure while for mode III angle play having an important role as compare to crass-ply.

TABLE 1. Material Properties considered 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}**	**α1 (10^{-6}/°C)**	**α2 = α3 (10^{-6}/°C)**
147	10.3	10.3	7.0	3.48	7.0	0.27	0.51	0.27	-0.9	27

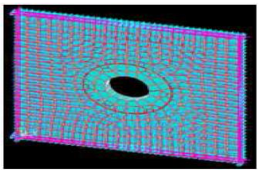

Figure 6. Boundary Conditions applied for the composite laminate

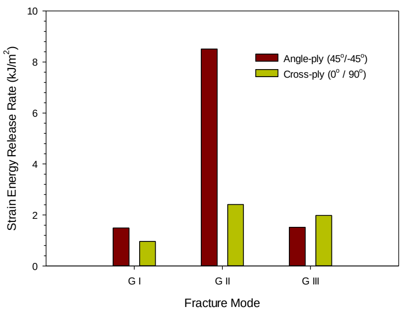

Figure 7. Modification in SERR with different modes of fracture under Mechanical Load of 5 MPa for Angle-ply and Cross-ply

3. 2. Thermal Load (Angle-ply Vs Cross-ply)

Figure 8 shows the change in SERR with the increase of temperature under thermal load for different layup of composite laminas. The three different mode of fracture is considered for investigating the effect of thermal loading on different layup of composite laminas. The GI, GII, &GIII are the fracture modes consider for change in SERR with respective temperature under thermal loading for different layup of composite laminas. The investigation is based on the temperature range 30^0C to 180^0C. The SERR is check for the point of 50^0C temperature interval point under the given temperature range. Figure 8 mode I, II and III shows the SERR results with respect to fracture mode G_I, G_{II}, &G_{III} respectively for the angle-ply (+45°/-45°)s and cross-ply (0°/90°)s . The similar kind of graphical trend observed of all three type of fracture mode I, II and III. The angle-ply gives better results in terms of SERR for all three mode of fracture as compare to cross-ply. The fracture mode II is having maximum SERR for angle-ply and cross ply as compare to remaining mode. Mode III and II are having results of SERR followed by mode I. The mode I having SERR range 0.0002 to 0.0064

kg/m^2 for angle and cross-ply composite laminas. Similarly, the results of SERR range (0.03 to 0.8 kg/m^2) and (0.0005 to 0.015 kg/m^2) for mode II and III respectively.

Figure 8 mode I show the approximately 10, 8.3 and 7.9 time higher SERR for cross-ply as compare to angle-play. Similarly, mode II results show the approximately 11.52, 9.59 and 8.72 time higher SERR for cross-play as compare to angle-ply. At mode III the SERR approximately 8.5, 8.4 and 6 times higher for cross-ply as compare to angle-play. The SERR at mode II is higher side for all temperature points for cross-ply as compare to angle-ply. Therefore, angle-ply is more reliable as compare to cross-ply for change in temperature from range 30^0C to 180^0C as SERR concern.

3. 3. Thermal Load in Mixed Mode (Angle-plyVsCross-ply) Figure 9 shows the variation of SERRfor mixed mode i.e. (G_I/G_T, G_{II}/G_T and G_{III}/G_T) with the increase of temperature under thermal load for different layup of composite laminas. There is a falling in G_I/G_T with respect to the temperature and a slight higher value is observed for cross-ply $(0^o/90^o)_S$ of fibre angle. Similar type observations and graph trend appear for G_{II}/G_T with respect to temperature for cross-ply and angle-ply. There is ascending trend in G_{III}/G_T with respect to the temperature and slight higher value is observed for cross-ply $(0^o/90^o)_S$ of fibre angle. G_{III}/G_T ratio shows the reverse trend as compare to result obtained for G_I/G_T & G_{II}/G_T this is because of less contribution of G_{III} for overall fracture of given composite laminas i.e. angle-ply and cross-ply. The ratio G_{II}/G_T result shows the maximum variation

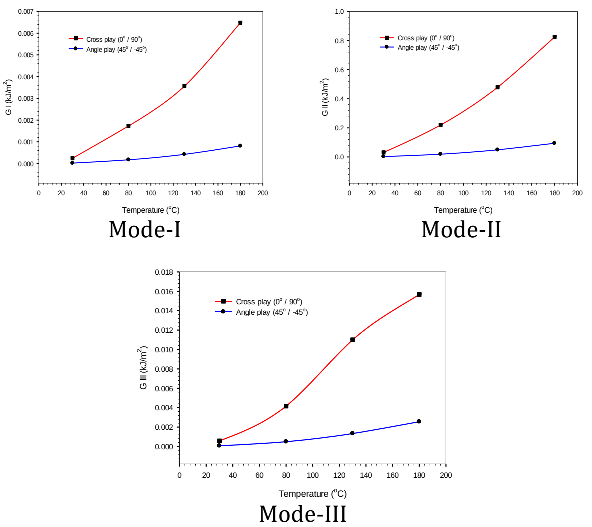

Figure 8. Discrepancy in SERR with the increase of temperature under Thermal Load between different layup configurations in three different modes

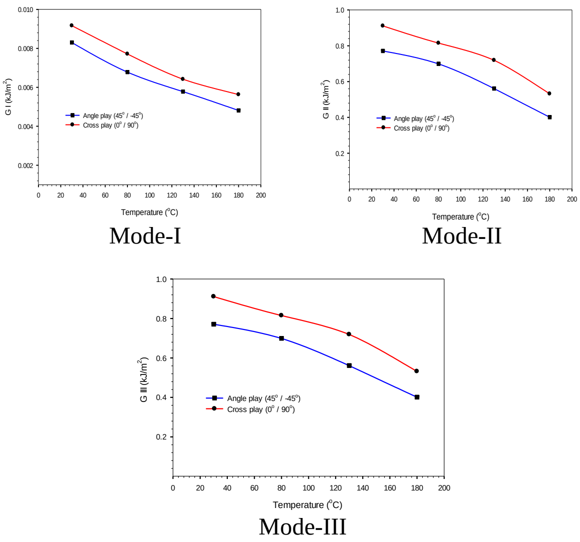

Figure 9. Difference in SERR with the increase of temperature under Thermal load between different layup configurationsof mixed mode fracture in three different modes

between the angle-ply and cross-ply because mode II having maximum SERR for both the type of angle composite laminas.

3. 4. Validation for Circular Cut-out The results obtained by FEA are validated with results available in published literature. Table 2 shows that the SERR values for cross-ply ($0^o/90^o$) and angle-ply ($+45^o/-45^o$) layup are 0.02 J/m^2 and 0.003 J/m^2, respectively machetes with published literature of Ramesh Babu and Pradhan [22]. The percentage error between results of present investigation and publishes literature are within the considerable range under 5%.

4. CONCLUDING REMARKS

In mechanical loading conditions, G_{II}, i.e., mode II shows the maximum SERR for both angle and cross-ply composite laminas compared to G_I & G_{III}. This is because mode II is base on sliding movement and

TABLE 2. SERR due to Thermal Load of Mode I (G_I) for different fibre layup configuration of circular cut-out

Layup configuration	**SERR Value obtained SERR (J/m^2)**	**SERR Value Ramesh Babu& Pradhan (22) SERR (J/m^2)**	**Percentage Error**
Cross-ply ($0^0/90^0$)	0.0206	0.02	2.91 %
Angle-ply ($+45^0/-45^0$)	0.00305	0.003	1.64 %

action. Angle-ply shows less SERR for mode I and II, but at mode III, cross-ply shows less SERR for mode III composite laminas subjected under mechanical loading conditions. G_{III}, the cross-ply value is higher than angle-ply in normal load.

Same composite laminas are tested for the thermal loading condition result shows an increase in SERR with respect to increases in temperature. The forgiven composite material increase in temperature toughness and stiffness decreases, i.e., an increase in SERR. In thermal loading mode II, results show the approximately 11.52, 9.59, and 8.72 times higher SERR in cross-play compared to angle-play for temperature 80ºC, 130ºC & 180ºC, respectively.

In mixed mode and thermal loading conditions, G_I/G_T and G_{II}/G_T show the same trend of SERR results. G_{III}/G_T mixed-mode III shows a reverse trend as compare to other modes this is because less contribution of SERR in mode III, i.e., GIII in G total mode, i.e., in G_T

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Persian Abstract

از قبل مواد ترکیبی انتشار ترک یک مشکل خرابی منظم در کاربردهای مختلف مهندسی خصوصاً در بدنه هواپیما است. اجزای بدنه هواپیما تحت شرایط بارگیری حرارتی و مکانیکی مختلفی قرار دارند. آزمایش خرابی اجزای هواپیماها به دلیل شرایط مختلف حرارتی و مکانیکی بسیار دشوار ، زمانبر و پرهزینه است. میزان انتشار انرژی کرنش (SERR) پارامتر قابل توجهی برای مواد کامپوزیتی است و کیفیت مواد کامپوزیتی به مقادیر SERR بستگی دارد. تحقیق حاضر بر اساس تجزیه و تحلیل ANSYS برای یافتن مقدار سرعت انتشار انرژی کرنش با استفاده از تکنیک بستن ترک مجازی (VCCT) برای درک رفتار شکست لایه کامپوزیت. ترک دایره ای موجود در وسط صفحه کامپوزیت و تحت فشار و بارگذاری دما برای ورقه های مختلف ساختار کامپوزیت زاویه دار (ورق ضخیم و ورق زاویه ای) است. زاویه پیچ در حالت I و SERR II کمتری را نشان می دهد در حالی که ضربدری در شرایط بارگذاری فشار ثابت SERR کمتری را در حالت III نشان می دهد. حالت II در دمای ۳۰ ، ۱۳۰ و ۱۸۰ درجه سانتیگراد حداکثر SERR را در مقطع نسبت به حالت I و III نشان می دهد. SERR برای حالت مخلوط با در نظر گرفتن حالت کلی شکستگی و اعتبارسنجی بر اساس ادبیات منتشر شده برای SERR به دلیل بار حرارتی حالت I (GI) برای پیکربندی های مختلف شکل دهی فیبر برش دایره ای ، مشاهده گردید.