Fatigue Life Analysis of Pre-cracked Aluminium Alloy Panel Repaired with UD-CFRP and UD-GFRP Patches

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Abstract

Structural components are known to fail through the growth of a fatigue crack. One effective way to repair a component is by bonding fiber composite patches. In this study a pre-cracked Aluminium skin 6061-T6 of one mm thin plate is repaired by symmetrically bonding patches of fiber reinforced polymer. The repair is simulated through numerical investigations to compare the performance of Unidirectional Carbon Fiber Reinforced Polymer (UD-CFRP) patched specimen with that of Uni-directional Glass Fiber Reinforced Polymer (UD-GFRP) patched specimen for the same stiffness ratio (S) and the same fiber volume fraction (V_f). The J-integral for the max and mini stress of fatigue load is calculated by finite element analysis in Ansys-15. The maximum stress intensity factor (K_{max}) and minimum SIF (K_{min}) are calculated from the relation between J-Integral and SIF for various crack lengths. Then the Paris law is invoked using the relation between ΔK and the crack length (a) to determine the crack length versus fatigue cycles. The comparison of the results of UD-CFRP and UD-GFRP specimens shows that the UD-GFRP patched specimen achieves marginally better performance. However, UD-CFRP patches were much thinner.

Keywords
Unidirectional Carbon Fiber Reinforced Polymer, Uni-directional Glass Fiber Reinforced Polymer, Stiffness ratio, Volume fraction, Stress intensity factor.

1. Introduction
Most of the structural components under dynamic loading are susceptible to fatigue failure. The structural components used in structural components are subjected to time-varying cyclic loads that fail through the fracture, rather than yielding at a stress value below the yield or ultimate strength of materials. Such a failure of components under fluctuating loads is known as fatigue failure. Fatigue failure is characterized by crack initiation and propagation of crack until it becomes unstable. Once the crack becomes unstable the catastrophic failure of components may occur. Hence many structural components require a substantial amount of inspection and defect monitoring at regular intervals.

There are two ways available to deal with cracks when they are found in a structural component so that the weakened structure can regain its strength.
1) repairing of the damaged component or
2) replacing the damaged component.

In the case of structural aerospace components, it is frequently expensive to replace a damaged component with a new one. As a result, in the majority of instances, the damaged component is repaired. Asymmetric patches only apply the configuration patch to one side of the cracked panel, whereas symmetric patches apply the configuration patch to both sides of the fractured panel. A double-sided repair using FRP patches has been found to be more successful than a single-sided repair. This improvement was found because the load transfer from the skin to patches is symmetric. In asymmetric patch out of plane bending moment is induced under the action of applied load in the patched specimen due to shifting of the neutral axis. Whereas in the case of symmetric repair there is no bending moment in the skin so in this study symmetrical patch is taken into consideration. Through a numerical analysis, according to studies, double-sided repair using FRP composite patches outperformed single-sided repair. (Shinde et al.2021).

Generally, UD-GFRP and UD-CFRP is used for repairing of damaged components. While selecting between UD-GFRP and UD-CFRP for the same stiffness ratio and volume fraction which patch to be taken for repairing is studied (Figure 1).
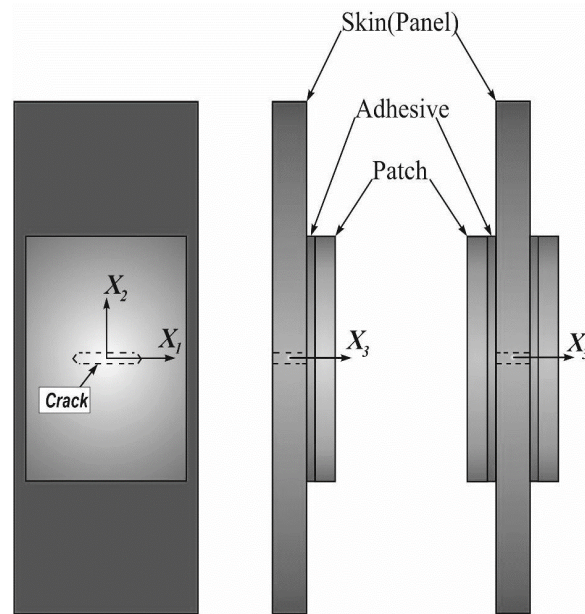

Figure 1. Asymmetric patch repair and Symmetric patch repair

1.1 Objectives

- To compare the performance of UD-Carbon Fiber patched specimen with that of UD-Glass Fiber patched specimen for same stiffness ratio (S) and the same fiber volume fraction (V_f) by numerical simulation method.
- To find the stress intensity factor for both the specimen for the crack length 10 mm to 17 mm using the FEA software Ansys-15.
- To determine the number of fatigue life cycles using Paris law for both UD-Carbon Fiber patched specimen and UD-Glass Fiber patched specimen, this results to be compared.
- To use above results for selection of patched material between UD-CFRP and UD-GFRP

2. Literature Review

Composite patching of cracks in aluminium structures has been studied to a great extent. There have also been several studies looking into how a composite patch affects a cracked structure. Utilising composite patches to repair damaged structures has been the subject of numerous experimental and computational research. The research of the impact of the size and form of the composite patches was prioritised along with the lowering of the stress intensity factor (SIF).Many studies are conducted on using UD-CFRP and UD-GFRP for repairing damaged component without replacing it. Fatigue life improvement of cracked aluminum 6061-T6 plates repaired by composite patches (Yousefi et al.2021).

Shinde et,al. (2015)experimental investigation to symmetrically attach CFRP patches to stop an edge crack in a 1 mm thick specimen of Al 6061-T6. When subjected to a stress that was greater than the aluminium plate's yield stress, they discovered that the specimens did not fail in the patched area. A split at the interface caused the specimen to fail at one of the patch's leading edges. Shinde et al. (2018)A thin panel of aluminium with a centre crack that was fixed using a composite patch attached exclusively to one face was the subject of experimental and numerical research. We noticed the quasi-static strength and manner of failure. The extremely sharp skin crack point did not expand during the experiments. The patch pulling away from the skin caused the failure. Regarding small patches, the separation started at the crack edges, increased as a result of the added tension, and finally resulted in total separation. Khan et al. (2021) according to the crack growth characteristics, specimens fixed with triangle patches grow cracks at a much faster rate than specimens repaired with other patch forms. Additionally, it can be inferred that increasing the surface contact area between the patch and the cracked plate will lengthen the fatigue lifetimes of the restored structures.Ch. Ramakrishna.et al (2017) performed numerical study by using Finite Element Analysis for the center crack aluminium plate repaired with composite patches. They have considered three types of specimens for study- unpatched, asymmetrically patched and symmetrically patched specimen. bonded composite patches reduces the SIF and crack tip stresses by very large amount. Therefore, it retards or eliminates the crack growth. Also, rectangular patches are most efficient as they reduce the SIF by highest amount. The symmetric patch configuration is the most efficient over un-symmetric because, as it reduces the SIF by highest value. Toudeshky et al. (2007) this work examines the behaviour of centrally fractured aluminium panels fixed using single-side composite patches in mode-I condition in terms of computational and experimental fatigue crack growth.

Prajapati (2019) at room temp and at a high temp (80°C), the influence of stiffness ratio on the fatigue life of thin, pre-cracked aluminium alloy 6061-T6 panels mended with one-sided composite patches was quantitatively examined. At 80°C, fatigue life was shown to be longer than at room temperature. With the increase in stiffness ratio, the stress intensity factor was reduced and fatigue life was increased. Toudeshky et al. (2013) With the aid of cohesive elements and various loadings, it was investigated the key parameters for the patch's detachment from the skin. The onset and spread of debonding in the adhesive layer during asymmetrical repair under cyclic loading circumstances were also studied using FEA. Benyahia etal. (2015) studied behaviour in bonded composite patches used to patch up cracks in aluminium alloy sheets 2024-T3 both experimentally and numerically. Aluminum broken plate was fixed with a carbon/epoxy patch. The numerical study demonstrates that the patch repair significantly lowers the SIF at the fracture front. Damaged structure's fatigue life might be greatly increased, especially if the patch is applied at short crack lengths. Kumar (2000), the ideal symmetrical composite patch design for centre crack aluminium plate repair was quantitatively evaluated. The best patch design is skewed, followed by a rectangle patch that is second best and more efficient than elliptical, circular, and square patches.

Existing literature shows that an adhesively bonded composite patch is an effective and economic technique in terms of increasing strength and fatigue life. The fatigue life of broken structures is greatly extended by the bonded composite repair. Fatigue behaviour of pre-cracked aluminium skin with symmetric carbon fiber patches for different patch length, width, thickness and shape is investigated numerically. Also effect of increasing load was studied for different patch configurations. Effect of increasing crack length was also investigated for double ply configurations. Patch length and width were also varied accordingly.

3. Specimen Configuration
3.1Aluminium Plate 6061-T6 with a pre-crack
A specimen of aluminum one mm thickness have center pre-crack is chosen for this study. The specimen was addressed as skin in this study. The dimensions of aluminum skin were 335mm x 50mm x 1mm with a center crack of $2a = 20$ mm (ASTM E647-15a, 2015). The tips of the pre-crack were sharpened before the patch was applied through a tension-tension fatigue load (Table 1). The elastic-plastic behavior of the skin was considered with a modulus of elasticity of 70.2 GPa, the ultimate tensile strength is 315 MPa, with a yield stress 290 MPa (Figure 1 and Figure 2).
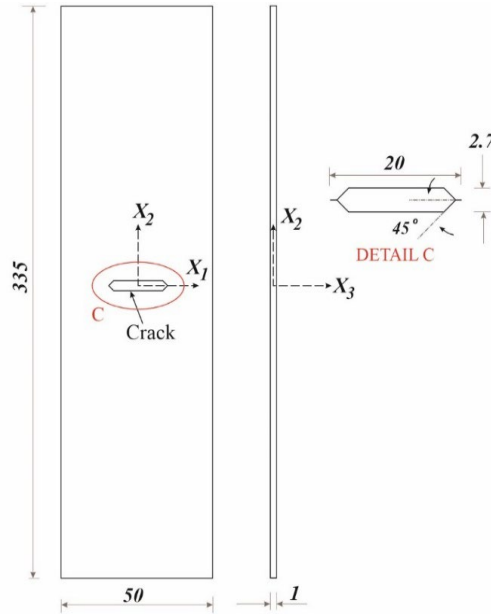
Figure 2. Aluminium Skin configuration

Table 1. Properties of Aluminium 6061-T6

Sr. No.	Properties	Magnitude
1.	Modulus of Elasticity (E)	$70.22\ GPa$
2.	Yield stress (σ_{ys})	$290.3 \pm 6.0\ MPa$
3.	Ultimate tensile strength (σ_{uts})	$314.8 \pm 3.5\ MPa$
4.	Poisson's ratio	0.33

3.2 UD glass Fiber
The FRP patch was reinforced with 300 gsm unidirectional glass fibre fabric. The carbon sheet's fibres were adhered to one another using a binder. It is like stitching the fibers in such a way that unidirectional fibers are kept intact in their places. The properties of the UD glass fiber are:$E_c = 73\ GPa$, $\nu = 0.22$ and $\rho_g = 2540\ kg/m^3$.

3.3 UD- Carbon Fiber
The 200 gsm unidirectional carbon fibre cloth that made up the FRP patch served as strength. Through the use of an adhesive, the carbon sheet's fibres were fixed in place. It is like stitching the fibers in such a way that unidirectional fibers are kept intact in their places. The properties of the UD carbon fiber as obtained from the supplier are:$E_c = 231\ GPa$, $\nu = 0.2$, $\rho_c = 1860\ kg/m^3$

3.4 Woven GFRP Ply
Woven GFRP ply of 56 gsm was used for GFRP ply, properties of the glass fiber woven fabrics as obtained from the supplier are: $E_g = 17\ GPa$, $\rho_g = 2500\ kg/m^3$

The orthotropic GFRP and CFRP plies' elastic constants are derived from Halphin-Tsai equations shown in Table 2, these constants are used in Ansys-15 in numerical investigation for determining the SIF. (Agarwal et,al 1990)

3.5 Composite patch configuration of UD-CFRP and UD-GFRP repaired patch specimen

Numerical analysis for determining the thickness of each single ply fiber and total thickness patch by keeping the Volume fraction and stiffness ratio constant respectively.

By using the below equation of Volume fraction (V_f) the thickness of single ply fiber is obtained, by keeping the volume fraction 0.5, we get UD-CFRP single ply thickness0.2mm and UD-CFRP single ply thickness is 0.24 mm

$$V_f = \frac{gsm}{\rho \times t_{sp}}$$

Table 2. Orthotropic elastic constants of CFRP and GFRP plies

Material	E_1 (GPa)	E_2 (GPa)	E_3 (GPa)	ν_{12}	ν_{23}	ν_{13}	G_{12} (GPa)	G_{23} (GPa)	G_{13} (GPa)
UD-CFRP ply	117	14.16	14.16	0.28	0.28	0.37	4.03	5.15	5.15
UD-GFRP Ply	34.76	10.71	10.71	0.32	0.42	0.32	3.18	3.77	3.18
Woven GFRP ply	17	17	9.75	0.2	0.4	0.4	3.5	2.98	2.98

Here, t_{sp}= Thickness of single ply of composite fiber
ρ = Density of composite fiber

Now to determine Modulus of patch (E_p) of UD-CFRP and UD-GFRP by using below relation:

$$E_p = E_f V_f + E_m V_m (\text{ Mallick.2010})$$

Similarly by using the below equation of Stiffness Ratio (S) the thickness of total patch(t_p) is obtained, by keeping the stiffness ratio, we get the total thickness of UD-CFRP patch as 0.8 mm and total thickness of UD-GFRP patch as 2.4 mm.

$$S = \frac{E_p \times t_p}{E_s \times t_s}$$

Here, t_p= Total thickness of composite patch
t_s = Thickness of aluminium skin,
E_s = Modulus of aluminium skin.

Therefore, the number of plies in UD-Carbon fiber and UD-Glass fiber specimen are obtained from relation (t_p/t_{sp}),

So, the total number of plies in UD-CFRP specimen are four of total thickness 0.8mm, therefore for symmetrical specimen two plies on each side having of 0.4 mm thickness each ply having thickness of 0.2mm. Similarly, the total number of plies in UD-GFRP specimen are ten of total thickness 2.4 mm, therefore for symmetrical specimen five plies on each side having of 1.2 mm thickness each ply having thickness of 0.24 mm.

To avoid galvanic corrosion caused by direct contact of the aluminum skin and carbon fiber plies, a thin separation layer of Woven GFRP ply having a thickness of 0.08 mm was kept between the carbon fiber plies and the skin's surface, the effect of Woven GFRR on SIF is negligible. Table 3 and Table 4 show the length of patches of CFRP Patched specimen and GFRP Patched specimen respectively,

Table 3. Specimen Configuration of symmetrical CFRP Patch

Specimen Name	Woven GFRP length in millimetres	CFRP ply length in milli metres on each side of skin	
		1st	2nd
S-84	96	84	72

Table 4. Specimen Configuration of symmetrical UD-GFRP Patch

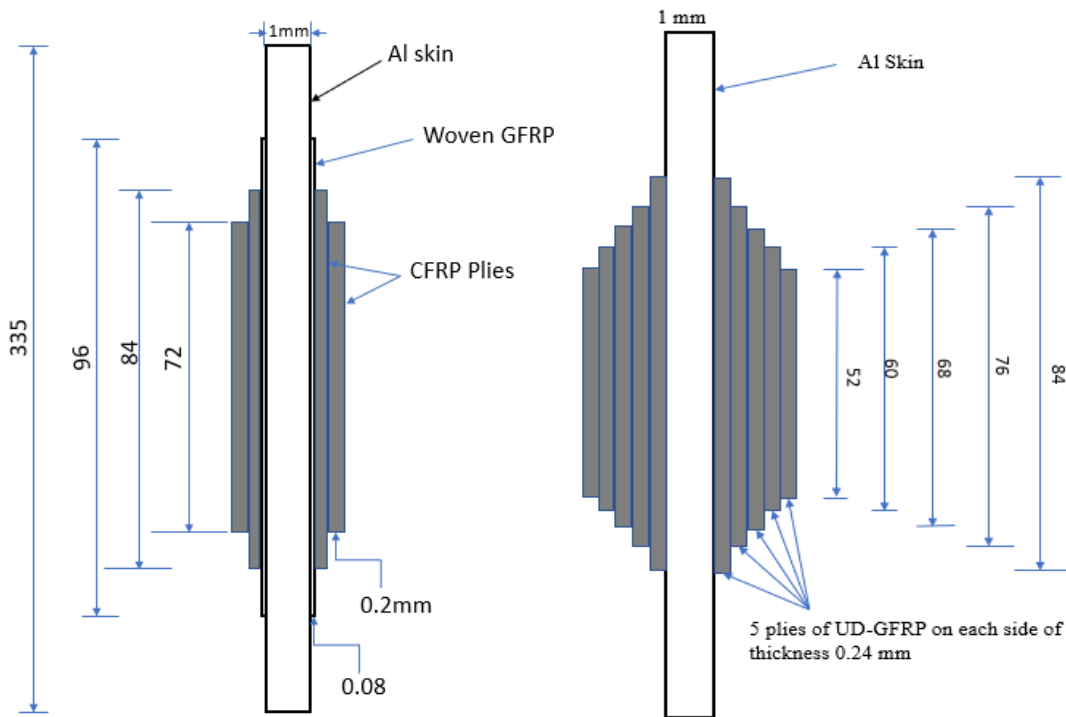| Specimen Name	Length of UD-GFRP plies in mm on each side of skin				
	1	2	3	4	5
S-84	72	60	50	42	34

Figure 3. a. UD-CFRP patched specimen   b. UD-GFRP patched specimen

It is seen that in Figure 3.a. shows the geometrical configuration of UD-CFRP patched specimen having length ply drop of 12 mm and in the Figure 3.b. shows the geometrical configuration of UD-CFRP patched specimen having length ply drop of 8 mm.

4. Numerical Analysis

In this study, a thin pre-cracked Aluminium panel with the symmetric FRP patch is modelled in ANSYS Workbench 15.0. In Figure 4.a. the aluminium skin had measurements of 335 mm × 50 mm with 1 mm thickness. The specimen dimensions follow the ASTM E-647 standard. The specimen was symmetric about axis $X_1, X_2, and\ X_3,$ In order to conserve calculation time and memory, only a quarter of the ABCD model was taken into account for analysis. The crack tip is located at point T in the quarter model of a repaired specimen is shown in Figure 4(b). Under uniaxial cyclic loads, a fractured aluminium panel fixed with a FRP composite patch has undergone numerical simulation of

the crack propagation process. The numerical simulation determines the curve of the crack length on the unpatched side of the cracked panel versus the number of cyclic loading (Sekine et al.2005).
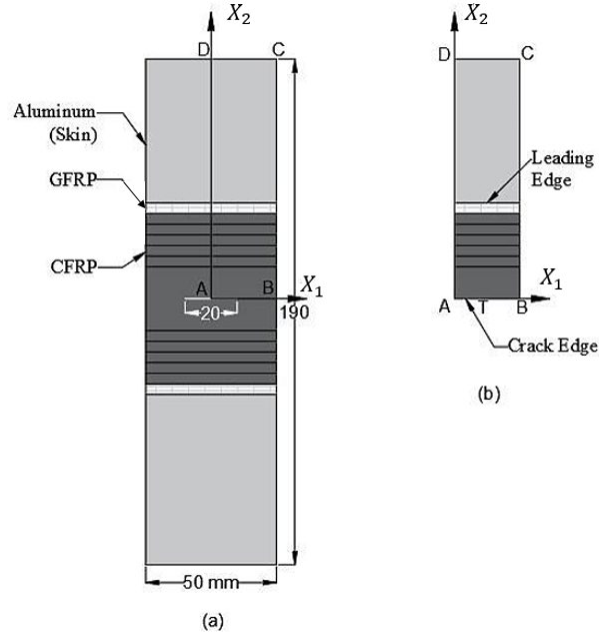

Figure 4.a. 5-ply thick polymer composite patch used to repair the specimen 4.b.A quarter model

4.1 Meshing

Solid 186 elements were used to mesh the skin. 20 noded iso parametric elements make up the solid 186 elements. The 0.2 mm element size is constant along the X_1-direction, or the skin's width direction. To increase the precision of FEM analysis, the tiny a 0.25 mm element size was selected up to a skin length of 12 mm along the X_2 direction from the crack plane from 12 mm to 36 mm with X_2 direction, the mesh size of 1 mm was maintained; however, for both UD-Carbon Fiber and UD-Glass Fiber, the mesh size of 2 mm is employed from 36 mm onward.

The aluminium skin's thickness direction X_3 and the UD-GFRP plies' thickness direction X_3 were both uniformly measured in terms of element size at 0.1 mm and 0.04 mm, respectively. Along the X_3-direction, or the thickness direction of UD-CFRP plies, the element size of 0.02 mm was uniform. Particularly near crack tip and crack faces, the patch has the potential to detach from the skin. The nature of the separation between a patch and the skin was investigated using the CZM model.

In Cohesive Zone Material Model, which is employed when adhesively bonded joints are present, interface bonding is weak component that fail when a fatigue load is applied. As a result, a few pieces of the patch could come away from the skin. Particularly near the crack tip and crack faces, the patch has the potential to detach from the skin (Turan et al.2007). The nature of the separation between a patch and the skin was investigated using the (CZM) model.

4.2 Loading conditions

The maximum load applied (σ_{max}) half of the skin material's yield stress was thought to apply to the specimen($0.5 \times \sigma_{ys}$)which was equal to 145 MPa (σ_{max}=145 MPa). The stress ratio (R) considered was 0.1. Hence minimum load applied ($\sigma_{min.}$) was 14.5 MPa. Numerical simulations were carried out on the specimen with different patch configurations having crack lengths of a=10, 11, 12, 13, 14, 15, 16, and 17 mm, to first determine the J-integral values for the loading of σ_{max} and $\sigma_{min.}$ Using a formula of stress intensity factor $K_I = \sqrt{J_I E}$ values of max SIF (K_{max}) and min SIF (K_{min}) were determined, and then the difference in stress intensity factor (ΔK) was calculated.

4.3 Boundary conditions

On the faces AD and BT in Figure 5, the symmetric boundary conditions were used. The fatigue specimen was pulled using two forces in the experiments, having hinge joints at each end. However, Saint-Venant's principle states that the load applied by the pin becomes uniform at a distance which is approximately equal to the width of the specimen. As a result, as illustrated in Figure 5, During the numerical analysis, a uniform load in the X_2 -direction was applied at nodes on the end face CD.
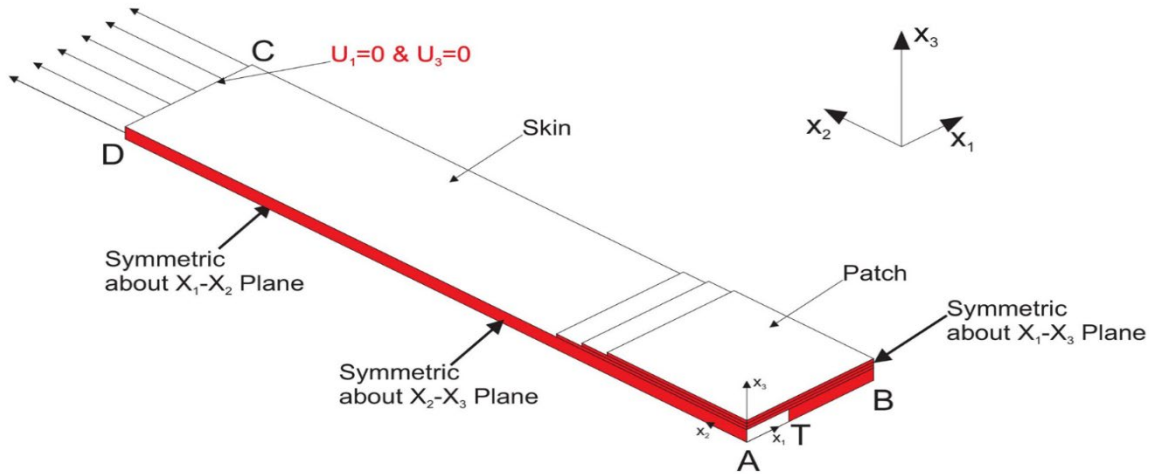

Figure 5. Loading and boundary conditions on specimen

5. Results and Discussion

A tension-tension fatigue loading with a R=0.1 stress ratio was applied to the repaired specimen with σ_{max}= 145 MPa and σ_{min}= 14.5 MPa, and the specimen was loaded in mode I. The maximum load applied was 50% of the yield stress of Al 6061-T6.

From the fracture mechanics module of Ansys, J integral was evaluated at initial pre-crack length of 20 mm for both σ_{max} and σ_{min}. The equivalent relation between stress intensity factor and J-Integral ($K = \sqrt{J \times E}$) was invoked to determine K_{max} corresponding to σ_{max} and K_{min} for σ_{min} . Then, ΔK was obtained as:

$$\Delta K = K_{max} - K_{min}$$

It is important to note that the Paris Law is used to assess a specimen's fatigue life:

$\frac{da}{dN} = C(\Delta K)^m$ (Kumar.2014)

In the expression, $\frac{da}{dN}$ is the fatigue load's crack propagation rate per cycle, while material constants of the skin's composition are C and m. (Kumar. 2014). Thus, the fatigue life of a specimen depends directly only on ΔK. In fact, the comparison of ΔK is an effective way to compare the performance of different types of specimens.

Numerical investigation is carried out to find out:

1) UD-CFRP and UD-GFRP patched specimen fracture lengths of 10 to 17 mm were simulated to determine the SIF (ΔK) and compare ΔK for the two specimen.
2) The fatigue cycles (N) for fracture lengths of 10 to 17 mm in both UD-CFRP and UD-GFRP patched specimens were calculated using the Paris law in order to compare the fatigue cycles (N) for the two specimens.

5.1 Graphical Results

For comparison between both the UD-GFRP and UD-CFRP patched specimen, Stress intensity factor (ΔK) values were obtained from simulations for the crack lengths of 10 to 17 mm. A plot of ΔK vs. crack length (a) is presented in Figure 6. This plot shows an increase in ΔK value with the crack length. In graph it is observed that for crack length from 10 mm to 17 mm ΔK values for UD-CFRP is marginal higher than UD-GFRP.
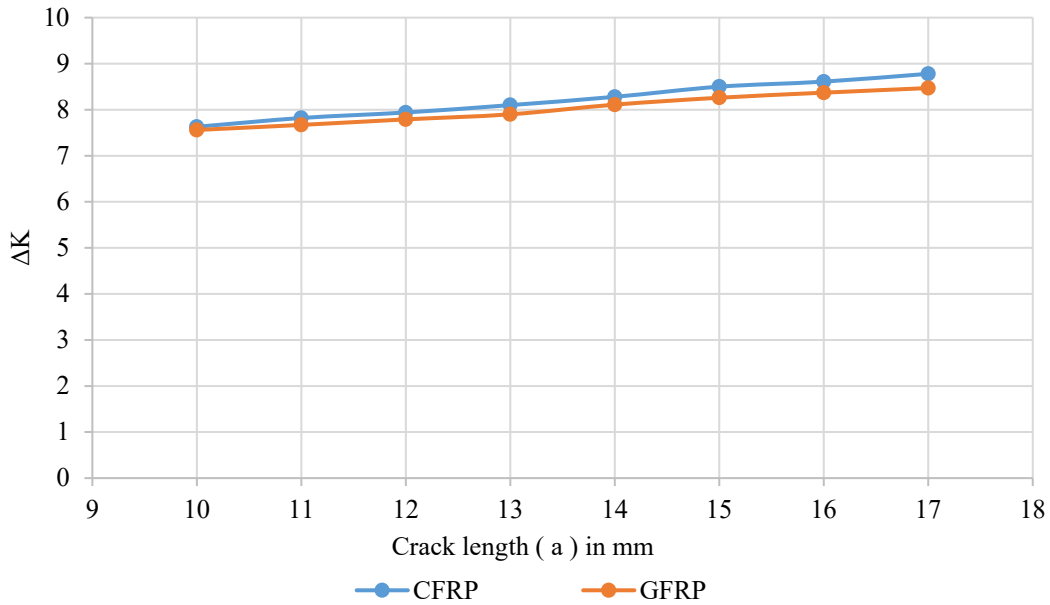
Figure 6.Crack length (a) vs Stress intensity factor(ΔK)

Using fatigue cycles data; a semi-log plot showing the number of fatigue cycles (N) vs. crack length (a)was plotted. Figure 7 presents a vs. N plot, it is observed in graph that number of fatigue cycles for UD-GFRP is marginal higher than UD-CFRP for10 to 17 mm in length, crack. The fatigue cycles numbers at 17 mm for symmetrical UD-GFRP patch repaired specimen has 4.56 % more number of fatigue cycles compared to symmetrical UD-CFRP repaired patch specimen.
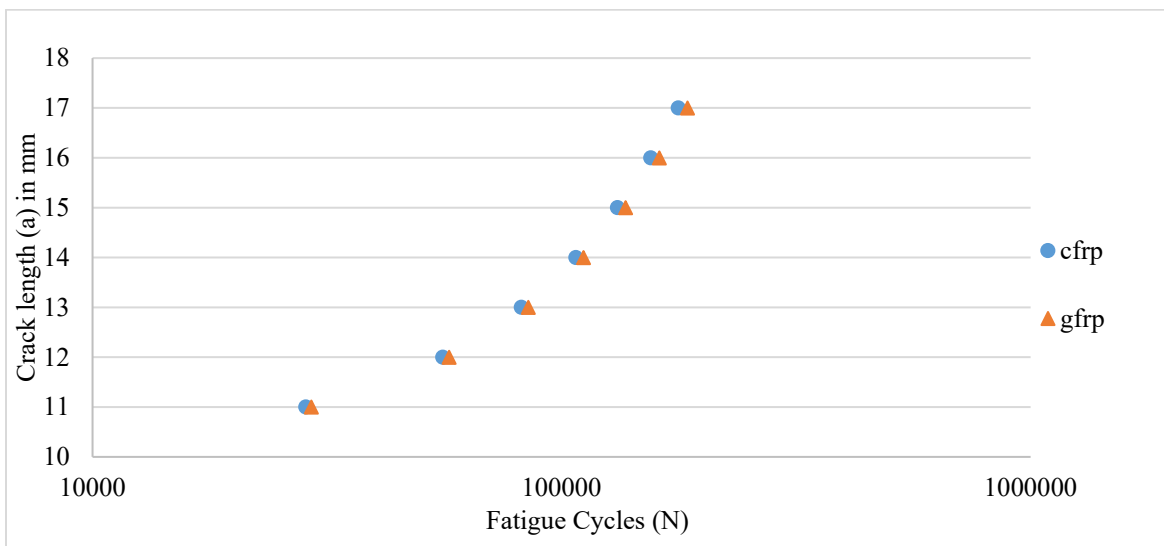

Figure 7. Length of crack (a) vs Fatigue Cycles (N)

6. Conclusion
A thin centered pre-crack skin of aluminium 6061-T6 is repaired using symmetrical UD-CFRP specimen and symmetrical UD-GFRP patch specimen. The stiffness ratio as well as volume fraction have been kept constant. The stress intensity factor of both specimen under fatigue load were found to be marginally same in the numerical simulation. Fatigue life of UD-GFRP of GFRP patch specimen was found to be 4.56 % higher than that of UD-CFRP

patch specimen. The patch of UD-GFRP specimen was much thicker about 3 times compared to UD-CFRP specimen. Thus repair through CFRP patch is recommended for repair of skin were weight of the patch and thickness of the patch is required to be small.

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