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Analytical Study of Fatigue Crack Growth Behavior of Steel Structure Reinforced with FRP

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ABSTRACT

The using up of fiber reinforced polymer (FRP) in retrofit and repair in industrial fields is extremely efficient and also capable in increasing service life cycle of the structures. In this paper the investigation on the FRP repairing on crack surface of S235 steel plate which is subjected to tension loading has been carried out. The variation in stress intensity factor (SI) around the crack on the surface of steel plate, is analytically investigated and crack growth rate for steel plate was estimated by considering the stress intensity factor value in the Paris-Erdogan equation. Results recommended that laminate made of carbon fiber reinforced polymer (CFRP) repaired on the crack surface is the most effective one which showed decreased stress intensity value of 328.9Mpa.mm0.5, whereas the unreinforced steel plate with SIF value 389.29Mpa.mm0.5. Compare to the glass FRP with high elasticity modulus, it showed decrease in SIF value 326.95Mpa.mm0.5, results showed that 15-20% reduction in stress intensity (SI) factor when it compares with bare steel plate and with FRP reinforced plate. Finally results showed that reinforcement of FRP on the cracked surface of the steel structure yield good results as increasing its fatigue life by decreasing the expansion of crack at its tip.

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1. Introduction

It is difficult to manufacture a material without any mistakes or faults in it using traditional manufacturing techniques. Not being perfect results from inclusion, different thermal expansion, contamination of melt, or many processes can lead to imperfection. These faults will be the beginning of the cracks. Depending on the dimension and shape of the crack and condition under which, the material is used, the crack grows at a rate that depends on the loading condition and material fracture toughness. This means the fracture or crack could be stable or not. Failure due to fatigue is a mode of failure for structural steel in the field of civil engineering (e.g., bridges, roads, railway, tower, pipe lines, structures which supported by cranes and tanks) [1]. Fatigue load which is applied on the stress concentrated zone, which led to crack propagation in the structures. The growth of cracks throughout the volume yields to the catastrophic fracture. To expand the service life of old steel structure, fatigue defect should be found and repaired. Cracks are formed due to the fatigue load on steel structure, because of varying loads applied for long term and varies in environmental conduction. If we fail to treat the structure in time, that is before the damage gets worse and the structural safe within the service period, it leads to the fatigue failure in the structures.

Reinforcement of Fiber reinforced polymer on the structure is considered as an alternative to the traditional repair techniques on fatigue crack like: bolting, drilling, welding, etc. [2]. It is worth for its advantages like: efficiency, in saving time, cost effective, not having secondary damages and easy to install [3]. Fatigue load which is applied on the stress concentrated zone, which led to crack propagation in the structures. The growth of cracks throughout the volume yields to the catastrophic fracture [4]. The effectiveness of the FRP repair technique significantly decreases the crack propagation and prolongs remaining life span for cracked structures, investigation was conducted on the steel plates. The important load conditions they are: bending, tension or combination of both, loading affect the plates by forming cracks to a greater value [5]. The fatigue characteristic behavior on the metallic structure strengthen with FRP can be evaluated and shows that the characteristic behavior of the structure can be improved by using epoxy-bonded FRP sheet [6].

2. Methods

Figure 1 shows the flow diagram of conducting the analytical investigation to know the efficiency of FRP reinforced plates. In this study, the steel plate is patched with the typical FRP configuration, which is going to be used to find the effects of the fatigue repair efficiency for the steel plate with a crack on it. The repaired models are designed by taking into consideration the modulus of elasticity Ef and the area of cross section of FRP patch Af for all the configurations of the FRP reinforced steel plate. An analytical study on steel plate with a pre-existing crack has been performed to explain the strength and efficiency when steel plate which is having crack on it, get repaired with different patch configuration of FRP at certain stages of crack expansion. The models are cracked steel plates bonded by FRP like carbon fiber reinforce (CFRP) and glass fiber reinforce polymer (GFRP) laminates on the surface of the crack opening. The dimensions and the geometry of the steel plate and FRP cover are taken (Fig.1). The steel plates having length L = 150 mm, width = 60 mm and thickness= 10 mm, with semi-elliptical crack surface on the steel plate with major radius of 5 mm and a minor radius of 2 mm at the center of the steel plate.

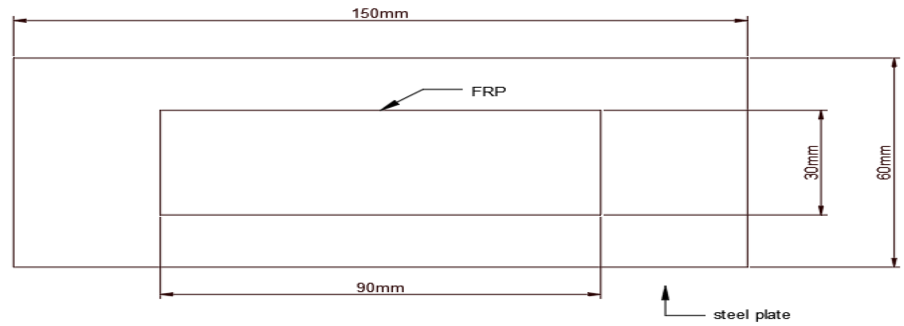


Fig. 1. Steel plate reinforced with FRP laminate.

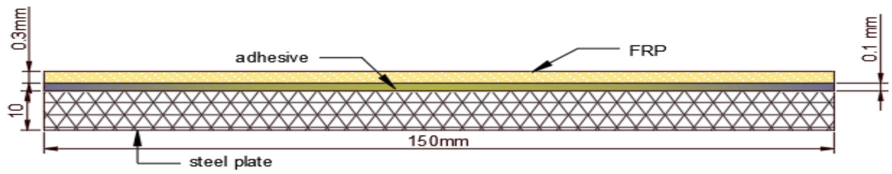


Fig. 2. Steel plate reinforced with fully covered FRP laminate.

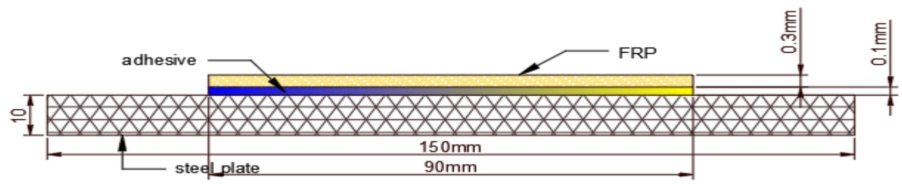


Fig. 3. Steel plate reinforced with partially covered FRP laminate.

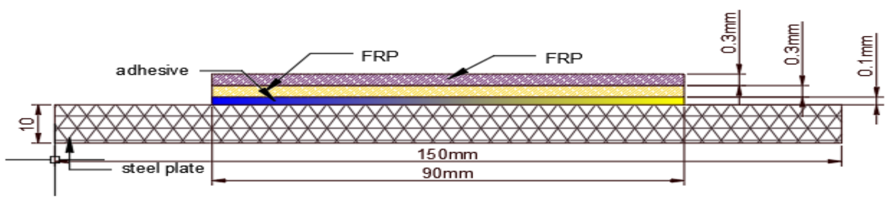


Fig. 4. Steel plate reinforced with partially covered with both FRP laminate.

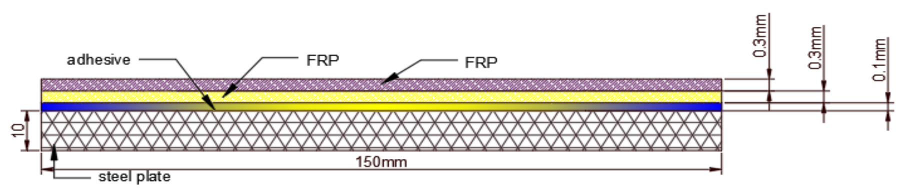


Fig. 5. Steel plate reinforced with fully covered with both FRP laminate.

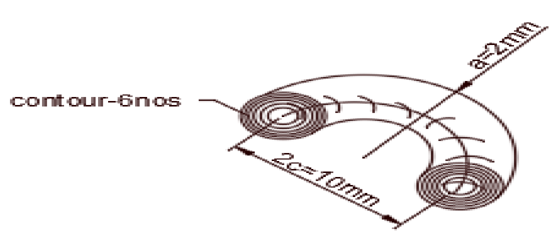


Fig. 6. Semi-electrical crack.

3. Specifying material properties

The steel plate which is adopted is S235 carbon steel grade which is close to the properties of mild steel having material properties [7] as mentioned below in table 1. Layers of CFRP, GFRP laminate and adhesive layer, which is used for the analytical part having material properties [4] mentioned below in table 2-3. Note the material properties of the steel, FRP and adhesive are all provide by each manufacturer.

The specification material properties are given as mentioned in the Table 1-3

Table 1
Material properties of S235 steel.

MATERIAL PROPERTIES	STEEL
E(Pa)	$2.08*10^{11}$
Y(Pa)	$2.76*10^{8}$
T(Pa)	$4.23*10^{9}$
υ	0.3

Note: E is the young's modulus or elastic modulus, T is tensile strength, υ is poison ratio, Y is yield strength.

Table 2
Properties of material for both Glass FRP and Carbon FRP laminates.

MATERIAL PROPERTIES	GFRP	CFRP
E_1(Pa)	$72*10^{9}$	$230*10^{9}$
E_2(Pa)	$72*10^{9}$	$25*10^{9}$
E_3(Pa)	$8*10^{9}$	$25*10^{9}$
υ1	0.28	0.33
υ2	0.28	0.33
υ3	0.28	0.054
G_{12}(Pa)	$4.7*10^{9}$	$5.5*10^{9}$
G_{13}(Pa)	$4.7*10^{9}$	$5.5*10^{9}$
G_{23}(Pa)	$3.5*10^{9}$	$3.9*10^{9}$

Note: Ei is the elastic modulus, G_{ij} is shear modulus along different direction, υ is poison ratio,Y is yield strength.

Table 3
Material properties of resin epoxy.

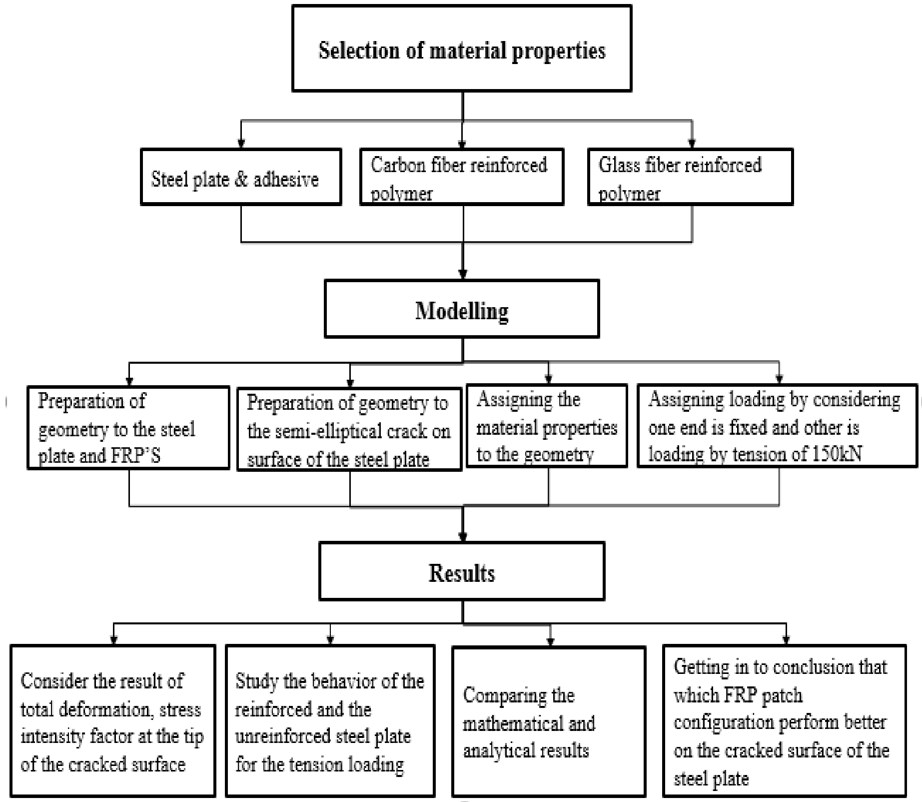
Material Properties	Epoxy Resin
E(Pa)	$2.8*10^{9}$
T(Pa)	$70*10^{6}$
G(Pa)	$1.4*10^{9}$
υ	0.35

Note: E is the modulus of elasticity, tensile strength T, υ is poison ratio, G is shear modulus.

4. Block diagram

Specifying the geometrical properties and defining model geometry.

The geometric properties and details of all the model consider in the study are already mentioned above earlier. This will help to analysis using ANSYS.



Modelled steps to be followed assigning the material properties.

- Creating model in software by creating a plane with known dimension of cross section of the steel plate.
- Create area between those lines.
- Extruding area to specific thickness of steel plate to generate the volume.
- Creating a plane on the face of the existing solid surface for creating FRP area.
- Extruding area to specific thickness of FRP to the thickness of 0.3mm to generate the volume.
- Assigning the material properties to the geometry.
- Creating a contact between FRP and the steel plate.
- To divide volume in to parts for accurate meshing.
- After the meshing fracture part should be created by using fracture tool.
- Fracture should be placed at a particular place using a coordinate condition.

After placing the semi elliptical surface crack on the steel plate.

- That fractured part has to be meshed by using tetrahedron meshing method.
- Meshing the plate and FRP using the sweep meshing method.
- Creating connection in between steel S235 plate and the FRP plane.
- Assigning end condition, one end is fixed and the other end is loaded.
- At last, the analysis has been carried out.

5. Strategy's for modelling

The modeling and analysis are carried out in ANSYS environment. The length, width, and steel plate thickness are 150mm, 60mm and 10mm respectively. The composite laminate with thickness of 0.3mm and the adhesive thickness are 0.1,0.15 & 0.2mm. The length of FRP is 90 mm and width w = 30 mm and thickness t=0.3 mm has been employed in the partially covered patch configuration for both GFRP and CFRP composites.

The crack was developed using the fracture tool in ANSYS. A semi-elliptical cracked area is developed on the steel plate. The semi- elliptical model consists of six concentric contours and subdivisions of eight part on every model around a cracked front surface (Fig. 8). With semielliptical crack on the surface of plate with a minor radius of a = 2mm and a major radius of c = 5mm at the center of the steel plate.

The geometries which are created in the ANSYS tools. A rectangular solid with a surface element is created with a specific dimension and with the proper thickness. In this the rectangular solid model represents a steel plate and a rectangular surface act as bonded FRP composite. The tetrahedron method of meshing is used to mesh the components and also the sweep meshing method is used in steel plate and FRP, because this will control the number of elements or anodes. Then a surface crack is applied with a mesh using the tetrahedral method (Fig. 7). The size of contour is 4.8 mm. size of meshing is controlled by 1mm. The adhesive epoxy resin adopted with tetrahedron meshing method, while the method of sweep meshing is adopted in front of crack and on adhesive epoxy resin layer. The next step is to create contact between the steel plate and the FRP in order to have uniform loading. The perfect bond between steel plate and the FRP is assumed in the study, contact surface using contact 174 and target 170 elements.

The boundary conditions have to be assigned first before the analysis. After that, the tension load is applied to the steel plate by keeping one end fixed and adding a load of 150 kN on the other end. The parametric study, including cyclic tension loading, has been applied to investigate the stress intensity factor at the crack tip in steel plate that is patched with FRP. Via the contour integral method, one can calculate SIF along the crack front.

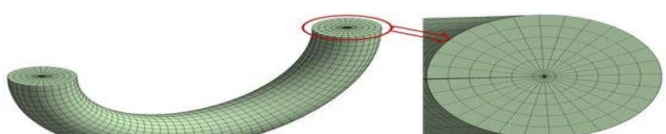


Fig. 7. Semi-elliptical crack.

5.1. Configuration of patches

Four types of patch configurations are adopted in this study, as shown in Fig. 2 to Fig. 5.

Totally seven models are prepared in the FEM software.

- On the bare steel plate without any reinforcement of FRP, the model will not stand.
- In the first case, the steel plate is fully covered with composites of both CFRP and GFRP.
- In the second case, steel plate is partially covered on the cracked surface with the composite made from both CFRP and GFRP.
- In the third case, layers of GFRP and CFRP are patched on the steel plate, fully and partially patched steel plate, both cases having been analyzed.

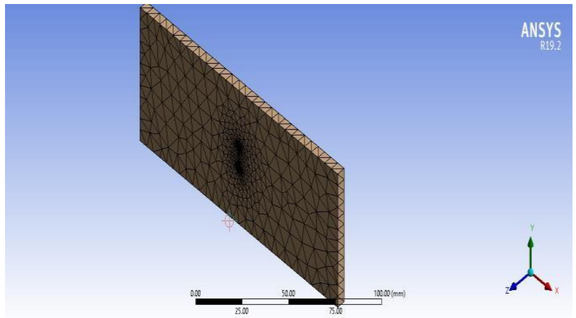


Fig. 8. Meshed steel plate.

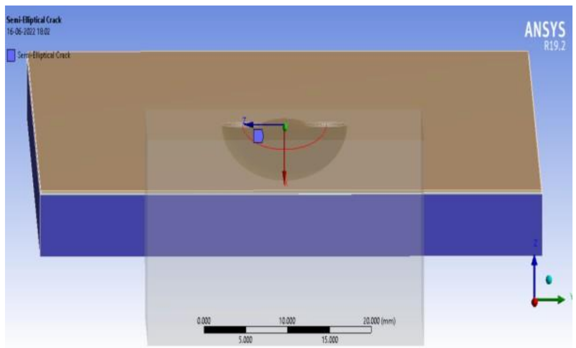


Fig. 9. Layer of FRP and adhesive on the semielliptical cracked steel plate.

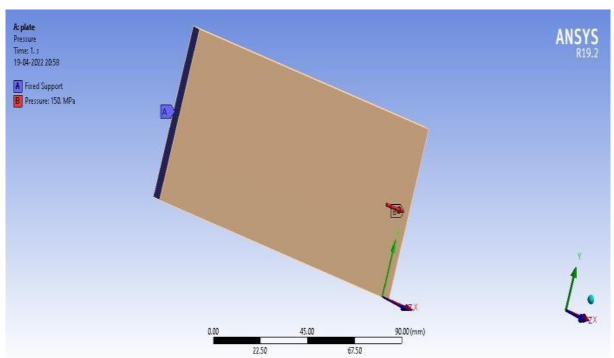


Fig. 10. Loading condition on plate.

6. Results

6.1. Different configurations of reinforcement

Three different reinforcement configurations have been used in this study, i.e., fully covered FRP patches on the surface of cracked model, partially covered FRP patches on the surface of cracked model and a layer of CFRP and GFRP reinforced on the steel plate.

6.2. Comparison with CFRP reinforced surface cracked steel plate

The steel plate has been fully reinforced as well as partially covered over the surface crack. In both cases, the stress intensity has been observed, because of the elastic modulus property of the CFRP. It shows better results in both cases when compared to the unreinforced cracked surface steel plate with a maximum stress of 389.29MPa by decreasing the stress and strengthening to withstand the loading. When it comes to the comparison between fully and partially covered CFRP sheets, the fully covered CFRP sheet on the cracked surface steel plate with a maximum stress of 328.9MPa shows a better result than the partially covered CFRP sheetwith a maximum stress of 335.6 MPa. Fig. 11 shows the stress variation to the crack length at thetip of crack on the steel plate surface. From the graph, it is clear that a fully reinforced steel plate is better than a partially reinforced steel plate.

Table 8
Stress intensity factor.

DIFFERENT CONFIGURATION	MINIMUMSIF(K1) MPa·mm$^{0.5}$	MAXIMUMSIF(K1) MPa·mm$^{0.5}$
Steel plate without strengthen	274.2	389.29
Steel plate fully covered withCFRP	228.83	328.9
Steel plate partially covered withCFRP	232.98	335.6
Steel plate fully covered withGFRP	224.82	326.95
Steel plate partially covered withGFRP	234.15	337.34
Steel plate fully covered withCFRP along with GFRP	207.23	310.41
Steel plate partially covered withCFRP along with GFRP	222.98	323.9

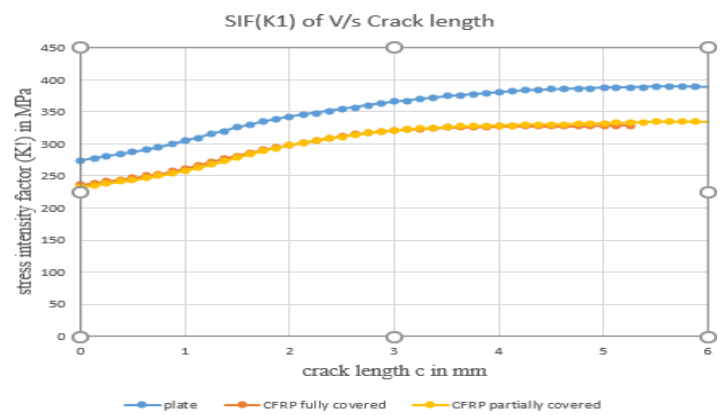


Fig. 11. SIF V/s crack length with CFRP reinforced graph.

6.3. Comparison with GFRP reinforced surface cracked steel plate

The steel plate has been fully reinforced as well as partially covered over the surface crack. In both the cases, the stress intensity has been observed. GFRP shows good results in both cases when it compares to an unreinforced cracked surface steel plate with a maximum stress of 432.4MPa by decreasing the stress and strengthening to withstand the loading. A comparison between fully and partially covered GFRP sheets reveals that the fully covered GFRP sheet on the cracked surface steel plate with a maximum stress of 325.43MPa shows a better result than the partially covered GFRP sheet with a maximum stress of 333.48MPa. Fig. 12 shows the stress variation at the crack tip with length of crack on the steel plate surface. From the graph, it is clear that a fully reinforced steel plate is better than a partially reinforced steel plate.

6.4. Comparison with both CFRP and GFRP reinforced surface cracked steel plate

Here the comparison is between two types of FRP layers, that is, carbon and glass fibre reinforced polymer sheet on the same cracked steel plate. The steel plate has been reinforced fully as well as partially covering the surface crack. In both cases, the stress intensity has been observed. Comparatively, CFRP and GFRP are both good in terms of their elastic strength. By comparing it to the unreinforced cracked surface steel plate with a stress of 432.4 MPa. The stress gets reduced and the plate strengthened to withstand the loading. Fully and partially covered FRP sheets: the fully covered FRP sheet on the cracked surface steel plate with a maximum stress of 325.43MPa shows a better result than the partially covered FRP sheet with a maximum stress of 333.48MPa, but when it compares with the single reinforced FRP, it shows a little less decrease in stress intensity value than the single sheet of CFRP or GFRP reinforcement. Fig. 13 shows the variation of stress at the tip of th with crack length on the surface steel plate.

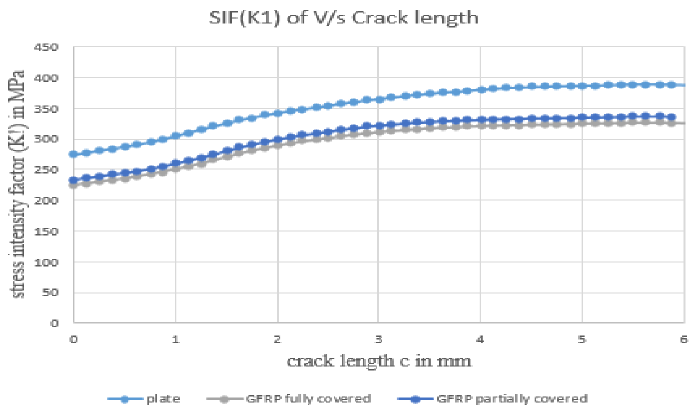


Fig. 12. SIF V/s crack length with GFRP reinforced graph.

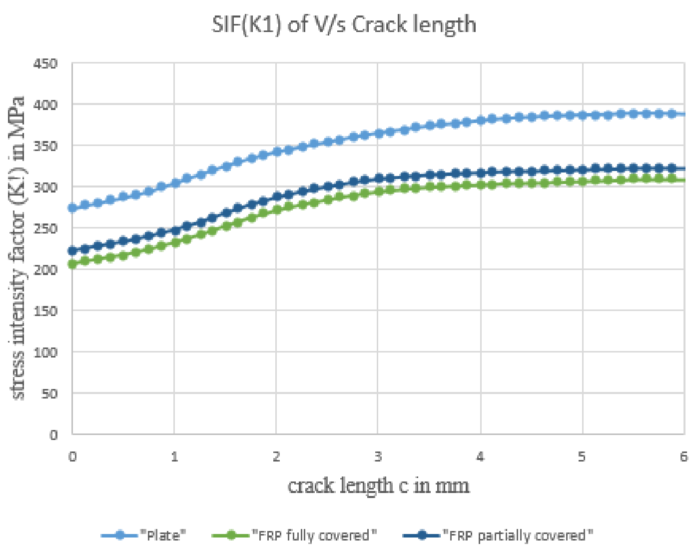


Fig. 13. SIF V/s crack length with FRP reinforced graph.

6.5. Comparison of stress intensity factors

Stress intensity is an important parameter at the crack tip. The FRP reinforcement efficiency of different configurations showed in Fig 12-14. This shows the SIF variation of the cracked steel plate along with crack extension repaired by FRP patch configurations 1, 2 and 3.

As in the case of modulus of elasticity, the GFRP having higher modulus than CFRP, because of the effect of higher modulus Fig. 14 showing that GFRP has better efficient than CFRP,but with the normal modulus only CFRP showing reasonable efficiency than the GFRP. By this case modulus of elasticity is important parameter to resist the expansion of the cracks on the steelplate.

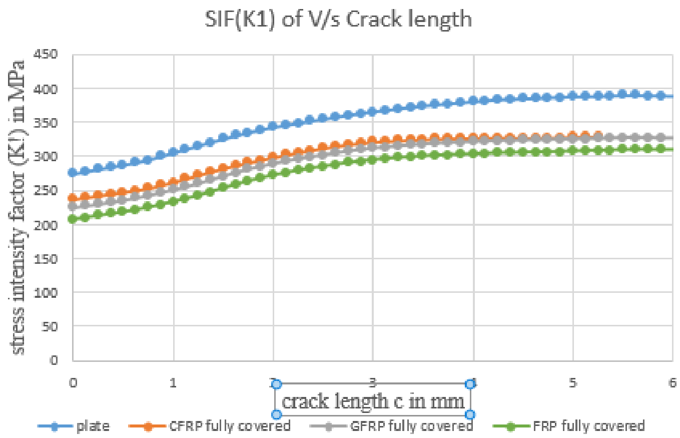


Fig. 14. SIF V/s crack length with FRP reinforced graph.

The stress intensity (SI) factor variation at the tip of crack can explain the FRP repair effect on different configurations of 1, 2 and 3. The thickness for third configuration is larger than first and second configurations. Whereas in third configuration, one layer 0.3mm thick of CFRP and one layer 0.3mm thick of GFRP are reinforced on the steel plate with a total thickness of 0.6mm. From the results, stress value at fractured tip increases with a rise of crack length c. When the cracks length c is small, the value of stress intensity K is the same in each configuration this is because of FRP 's constraint effect sheets on the steel crack, which is neglected when cracks are small. K for configuration 3 is lower because of thicker layers than the remaining configurations. But this indicates that the variation in thickness won't be same in all the time, asthickness of FRP increases when the crack length increases and when the patch didn't covers thecrack, results in faster increase in stress value in the partially covered steel plate crack with FRP.

6.6. Adhesive thickness

The adhesive epoxy resin layer develops bond between the steel base and FRP bond sheet,which is considered as weak layer in strengthened system [8]. Stress distribution and the efficiency of strengthened plate with the adhesive epoxy layer, using different thicknesses of adhesive are analyzed. Adhesive epoxy resin thickness ranges from 0.1 to 0.2mm are used. Fig. 15-16 showed that increase in the adhesive thickness contributes insignificant reduction in the stress (SIF). The adhesive's epoxy layer stress distribution is very much dependent on its depth of the epoxy adhesive layer especially when the epoxy resin depth increases from 0.1mm - 0.15mm, the stress slightly reduced after 0.15 mm adhesive thickness, but as the adhesive thickness increases, the stress intensity factor at the edge of crack increases because of adhesion failure. In this study, the adhesive thickness has to control up to relative thinner level in order to avoid the effect of adhesion failure.

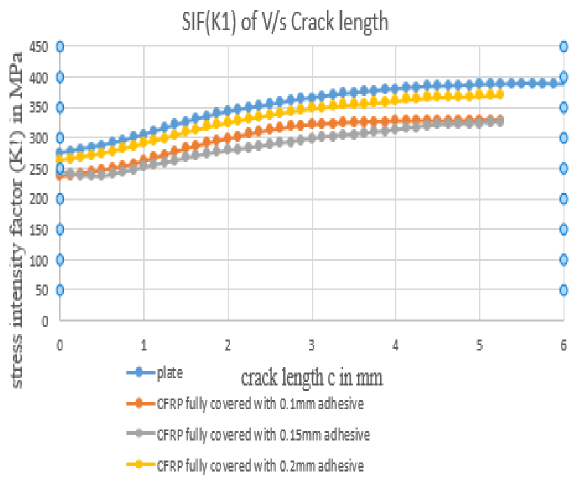


Fig. 15. SIF V/s crack length graph of fully patched CFRP reinforcement with different adhesive thickness.

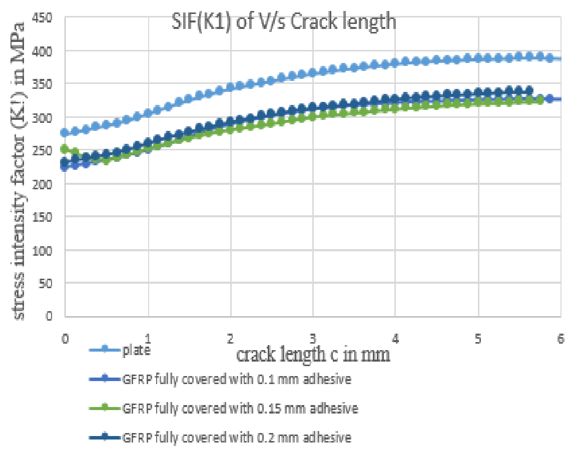


Fig. 16. SIF V/s crack length graph of fully patched GFRP reinforcement with different adhesive thickness.

6.7. Raju newman empirical solution of stress intensity factor calculation on semielliptical crack in steel plate

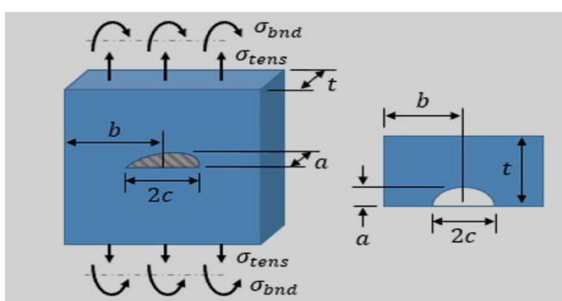


Fig. 17. Semi-elliptical crack calculation.

Stress intensity $$K = (Yt\sigma t + Yb\sigma b)\sqrt{\pi a} \quad (1)$$

Tension loading $$Yt = F\sqrt{\frac{1}{Q}} \quad (2)$$

Bending loading $$Yb = H \cdot Yt \tag{3}$$

The F function is described by:

$$F = [m_1 + m_2(\frac{a}{t})^2 + m_3(\frac{a}{t})^4] f\omega\, f\phi\, g \tag{4}$$

$$H = H_1 + (H_2 - H_1)(sin\phi)^p \tag{5}$$

Φ= 0° at crack length c tip, Φ=90° at crack depth a tip, (full crack depth).

Theoretical analysis has been carried out to understand the mechanism of FRP repair on the cracked steel plate. Out of tension on the FRP repaired steel plate can be calculated by using formuals [9]:

$$M = \left(\frac{F}{ts}\right) [\int_{\left(\frac{\Delta t}{2}\right)}^{\left(\frac{ts}{2}\right)+\left(\frac{\Delta t}{2}\right)} tdt - \int_{\left(\frac{\Delta t}{2}\right)}^{\left(\frac{ts}{2}\right)-\left(\frac{\Delta t}{2}\right)} tdt] \tag{6}$$

$$\Delta t = [\left(\frac{t-ts}{2}\right)] \tag{7}$$

$$t = ts + tc + tg + ta \tag{8}$$

$$\sigma b = \frac{M}{w} = \frac{M}{b.t^2/6} \tag{9}$$

$$\sigma t = \frac{Es.ts}{Ests+Ectc+Egtg+Eata} \sigma o \tag{10}$$

Where:

σt =tension stress, σb= stress due to bending, a = depth of crack, c= half of length of crack, b=half-width of steel plate, t= thickness of the steel plate, ts=thickness of the steel plate, Δt= distance between centroid plate, t=thickness of composite reinforced plate, tc=thickness of CFRP, tg= GFRP thickness, ta=thickness of adhesive layer, Ec ,Es, Ea, Eg= Carbon-FRP, tension modulus of steel , epoxy resin adhesive and Glass-FRP along it length respectively [3].

An expression for the calculation of the SIF of a semielliptical crack under strengthened conditions proposed by adopting Python language

6.8. Crack growth analysis

Stress intensity (SI) factor considered as major parameter for analytical and numerically analysis of crack extension. According equation of Paris Erdogan the crack extension can be explained by using equation:

$$\frac{dl}{dN} = [(C.\Delta K)^m] \tag{11}$$

Where:

(dl/d/N)- the crack growth rate.
m and C are Paris constants

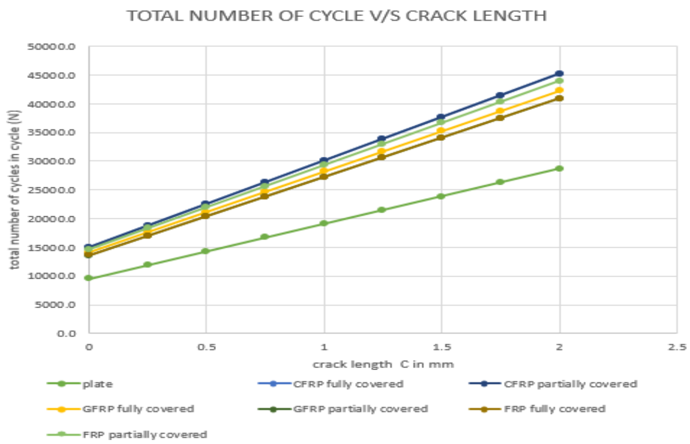


Fig. 18. Total number of cycle v/s crack length graph for fully covered FRP plates.

Fig.18 represent comparison between patch configuration and FRP laminates results on the surface crack growth. Fig.18 indicates that CFRP, which is fully laminated to the surface crack, significantly decreases the surface crack extension and increases the remaining fatigue life of the crack plate. After the CFRP, GFRP layer which is fully covered on the crack surface presentsbetter performance, but comparing the modulus of elasticity of both FRP, GFRP ha highest modulus value than CFRP but with the normal modulus it shows better results than GFRP, Forthe model without reinforcement, the fatigue life is around 270000 cycles, starting from c = 0.5mm to c = 10mm. Using FRP laminates with a thickness of 0.3mm, fatigue life was prolonged to $4.1*10^4$ cycles. similarly The fatigue life of the CFRP laminate reinforced on the steel plate was increased by ranging from 1.2 to 7.9 over unreinforced steel plates [8].

7. Conclusions

Surface crack extension is considered as serious effect on metallic structure. The surface steel crack expansion is repaired with different configurations of FRP and subjected to tension loading. FE software ANSYS is implemented to study the stress factor and crack propagation of 3-D semi-elliptical crack surface in a rectangular steel plate repaired with FRP laminates.

The conclusions for this analysis:

- In this study the single FRP strengthened method on the surface crack significantly extend the fatigue life, the steel plate's bond length and width are 150mm and 60mm respectively. The layer of FRP patch with bond length and width of 150 mm and 60mm respectively. Where the full covered FRP reinforcement shows maximally increase in the service life with a value CFRP reinforced plate's stress factor of 228 - 328 $MPa \cdot mm^{0.5}$, whereas the unreinforced plate with SIF value 274.2-389.29.
- As the width of the FRP patch decreases, the strengthened effect gradually decreases as well.
- While preventing prolongation of cracks on the steel plate with composite reinforcement is more efficient using CFRP and GFRP with fully covered laminate shows good results compared to partially covered steel plate. The cracked steel plate reinforced with both CFRP and GFRP to the same steel shows a decrease in stress intensity (SIF) factor and rise in fatigue life, but when it relates to the CFRP patch, the CFRP laminate singly shows better results than the double layer of the FRP laminate.
- The fatigue life of the CFRP sheet reinforcement on steel plate increase by $1.5*10^4$ cycles to

$4.5*10^4$ over an unreinforced steel plate.

- As the a/B ratio increases, the strengthened FRP effect on the steel plate also decreases.
- The analytical study shows that the stress factor K is less depend on the parameters like:
- adhesive epoxy resin thickness and tensile modulus of CFRP. Epoxy resin adhesive layer has to maintain at relatively thin level.
- An expression in order to compute the stress intensity factor K and crack propagation of semi elliptical cracks under strengthened conditions is proposed by considering the python program and the analytical and mathematical analysis given up to 20% error in the stress intensity (SI) factor K at the crack edge on the steel model and strengthened the FRP plate.
- Crack propagation process also reduced by the FRP strengthening method, it becomes effective by reducing the SIF at surface portion and it is showing less effect on the deepest portion. So that it is recommend in reinforcement or repairing the surface of cracked metallic structure as for as possible in order to increase in service life and fatigue life extension before the crack penetrate wall's thickness.

In this paper the intension is to find the stress intensity factor of both the reinforced and unreinforced steel plate, the result obtained in analytical work and the numerical analysis using Raju-Newman equation gives the values which is 15-20% lower values, than those obtained in the numerical work. Thus using of CFRP with lower modulus showed better results by decreasing SIF value from $389.29Mpa^{0.5}$ to $328.9Mpa^{0.5}$. Then for GFRP with higher modulus showed the SIF value of $326.95Mpa^{0.5}$ and also using of fully covered laminate of FRP decreases the stress intensity factor at the tip of crack, on the steel plate than that of partially covered laminate. Using of adhesive layer at very thin level avoid the adhesion failure.

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