NUMERICAL SIMULATION OF CRACK GROWTH IN PRE-CRACKED STEEL BEAM

Thiruvannamalai. M[1)], Balasubramanian. S[2)].

[1)]Assistant Professor, Department of Civil Engineering, MEPCO Schlenk Engineering College, Sivakasi, India.
[2)]PG Student, Department of Civil Engineering, MEPCO Schlenk Engineering College, Sivakasi, India.

Abstract: The important properties of steel are durability and tensile strength, so steel is considered as the most common material for building structures with strength of approximately ten times that of concrete. Over the past few decades, the application of Fiber-Reinforced Polymer (FRP) composites for strengthening steel structural elements has become an efficient increased due to environmental conditions, loading and repairs due to fatigue cracking. FRP can improve both the strength and serviceability behaviour of steel beams via increasing the overall member stiffness analysis. This study covers the strengthen of steel elements conditions under loading including fatigue performance, crack propagation, and failure modes with finite element simulation. FRP strengthening composites initial cracking, reduce the crack growth and extend the fatigue life. In this work is conducted to study the behaviour of steel beam strengthened using Carbon Fiber Reinforced Polymer(CFRP), and Basalt Fiber Reinforced Polymer (BFRP) with different length are laminated under the bottom flange and subjected to fatigue load using ANSYS.The steel beam is modelled in the form of I section with predefined notch. Totally 17 specimens are modelled and analysed to investigate the number of cycles and Stress intensity factor for crack propagation up to 10mm. The efficiency of the FRP wrapping is determined by comparing the behaviour of strengthened pre-cracked beam with the conventional pre-cracked beam

Indexterms:CFRP, BFRP, Fatigue Analysis, Pre-Cracked Beam, ANSYS.

INTRODUCTION

In civil engineering service, aging structures are usually functionally with deficient, may not meet safety standards, and demonstrate the need for repairs. Fatigue damage is one of the main problems for aging steel structure. Over the past decades, Fiber reinforced polymer (FRP) composites have been widely applied to strengthening structures due to their high strength-to-weight ratio, as well as fatigue and corrosion resistance. Steel structures strengthened by FRP composites have also received much attention FRP laminates external bonding can enhance both the ultimate load, stiffness of the steel members and decrease crack growth. When steel structures are subjected to fatigue, however, the long-term mechanical properties of the strengthened steel beams could further degrade.

In this study a notched beam which is an I-section is assumed that damaged section and as the bottom flange of the I-section is the tension zone with maximum strains over it the notch will be created artificially over the bottom flange. Notch will be acting as the point of failure initiation so that the characteristics of the bonded regions of FRP could be studied easily. Fibre reinforced polymer (FRP) such as Carbon fibre reinforced polymer (CFRP) and Basalt fibre reinforced polymer (BFRP) which is selected to wrap over the section as it has better physical properties than many fibers such as Aramidfibre reinforced polymer (AFRP) and Glassfibre reinforced polymer (GFRP). The main objective of this work to analyze behaviour of the steel beam by wrapping with CFRP and BFRP with different length under the bottom flange. The behavior of the steel beam is determined using software for accurate results. The analysis was carried out by software like ANSYS workbench is used to determine the behavior of pre cracked high strength steel beam.

Junhvili,Jun Deng, et.al., (2019) This paper is to study the carbon fiber reinforced polymer(CFRP) external bonding is a strengthening technique for steel structures. This experiment is conducted with 8 beams having notches at centre of the beam and CFRP plate is attached at the bottom of the beam. This experiment was tested with four-point loading. damage occurs due to Overloading near the notch and resulted in bond degradation of the CFRP layer. The strength and stiffness of the overloading damage only suffered from the first 90 WDCs. Comparing the debonding loads of overloading damage, the debonding loads of overloading damage beams with 0,90,180 WDCS decreased by 9.2%, 4.0 %.4.5 % respectively and the ultimate loads decreased by 1.7%,-2.2% and 3.6% respectively.

Mehmet EminDeniza, FiratAydinb.,(2019) This paper shows that the determination of fatigue life of the unidirectional GFRP laminates. Three kinds of stress ratios are performed on specimens with different fiber orientations. The three kinds of stresses are (R= 0.3, 0.1 and -0.1) and different fiber orientations are (0-0, 15, 30, 45, 60, 75°. and 90°) on specimens and GFRP sheets respectively. The fatigue results were obtained in repeated tension- tension and the results were compared with each other. The fatigue life is more in the fiber orientation direction of 0.3. The fatigue life is more in the specimen having 15° orientation angle. The aluminium alloys help GFRP laminates to propagate the crack and to prevent the growth of the crack. The investigation of this paper shows that the fatigue life of the GFRP laminates decreased with the decrease in loading rate.

ArdalanHosseinElyasGhafoor et al. (2019) This paper concludes the strengthened of a historically significant 122-year-old midway metallic bridge using on prestressed bonded carbon fiber reinforce polymer (CFRP) including sets of truck lading test performed before and after strengthening demonstrated that the tensile stresses were reduced by approximately 15% and 44% m the bridge cross-ginders after strengthening by the proposed no prestressed boded and FPUR systems respectively.

Jun Deng et. al., (2016) this paper discussed that the beams with notch up to 6mm in web from bottom flange in two places. An adhesive hollowing is provided at the other side at 120mm from the middle section. The results conclude that the maximum principle stress is double the time at the defect than at the end of the CFRP plate. The maximum stress is observed to be at the middle section than in the one away from it. But by varying the thickness of the adhesive the stress can be distributed evenly along the CFRP.

PierluigiColombi, Giulia Fava, Lisa Sonzogni., (2015) In this paper, carbon fiber reinforced polymer sheets are to strengthen the fatigue crack growth of steel plates is analysed from experimental, numerical and analytical point of view. The specimen with single edge notched tension is strengthened with various reinforcement configurations. The experimental setup results show the reduce crack growth rate and the extension of fatigue life with the reinforcement application. The stress intensity factor (SIF) and the crack opening displacement (COD) profile are developed in numerical modelling (finite element modelling). From the experimental results, the failure of the steel plate is mainly due to the debonding of the steel/adhesive interface and sudden static failure occurs. Due to debonding, the crack size is about 70-80% of the specimen width. The repair of crack is more efficient for short initial degree of damage. The reinforcement fully covers the steel plate for more efficient reinforcement configuration. With the help of finite element model, the stress intensity factor and crack opening displacement are evaluated for increasing the crack length values.

Mohamed Kamruzzaman, MohdZaminJumaat, N. H. RamliSulong, and A. B.M. Saiful Islam.,(2014) The crack that propagates through the steel beam. When a size of the crack for which the net-section is inadequate to carry the load, then rapid fracture growth takes place. To simulate the actual damage caused by corrosion and the expansion of fatigue cracks, several researchers intentionally created notches of different geometry in midspan or other positions on the tension flange of the beams. In addition, the notch assists like a stress concentrator in the damage-sensitive regions to commence a vertical crack at the steel web.

E.Lepretre, S.chataigner., (2006) This paper is shows that the effectiveness of carbon fiber reinforced polymer (CFRP) layer in extending fatigue life of old cracked metallic steel structures. Here, the initial crack lengths are of two different lengths before reinforcement, which represents two degree of fatigue damage, were adopted. The fatigue life was increased by factors ranging from 1.25-2.27. Initial crack length of 7mm and crack length is 13mm. Further investigations are now needed regarding the evaluation.

MATERIALS

Materials:

Materials used in the present work include Steel beam of I section, CFRP, BFRP, and epoxy resin. Were obtained from materials testing and manufacture data sheet. These are summarized in tables. All the CFRP and BFRP laminate adopted in strengthening were 2500mm wide and 1mm thick

Steel beam:

Steel beam of I section (ISMB 200) is built up using thickness of flange plate of 10.8mm and web plate of 5.7mm. The width and height of flange and web plates are 100mm and 178.4mm respectively.

Table (1): Steel properties

Steel Grade	Ultimate strength MPa	Poisson's ratio	Density Kg/m^3	Elastic modulus GPa
Fe250	460	0.3	7850	200

CFRP:

Carbon fibre reinforced polymer (CFRP) has a higher tensile strength and elastic modulus. Due to its high strength to weight ratio, it found its application in aerospace industry than other FRPs. CFRP is also available as high and ultra-high modulus carbon fibers.

BFRP:

Basalt fibre reinforced polymer (BFRP) It has high resistant to alkaline, acidic and salt attack making it more suitable for concrete, bridge and shoreline structures. Basalt fibers are commonly used due to its low cost, high electrical insulating properties and good heat resistance. It has slightly higher tensile strength than both glass fibres. It is also costlier than both.

Table (2): FRP Properties

FRP	Density g/cm^3	Elastic Modulus GPa	Tensile Strength MPa	Thickness 1Layer (mm)	Thickness 2Layer (mm)
CFRP	1.49	121	2231	1	1
BFRP	2.65	50	1240	1	1

Epoxy Resin:

Epoxy is a thermosetting resin. They are formed by a reaction of and epoxide with a hardener to create a very tough, stiff polymer and The viscosity is higher than polyesters. Epoxy is highly used for its extremely low shrinkage, good dimensional stability, higher temperature resistance, good fatigue and excellent adherence to the surface. Surface of epoxy are not known for cosmetic appeal.

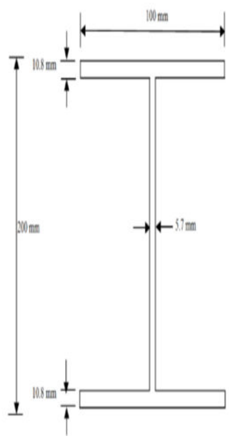
Table (3): Epoxy Resin Properties

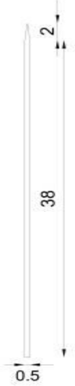
Mechanical properties	Value (MPa)
Tensile strength	24.9
Compressive strength	62.2
Shear strength	24.8
Bond strength	18.6
Tensile modulus	4428

Analytical investigation

Finite element analysis (FEA) is generally used to know the structural performance of the elements due to various loading conditions. Finite element model using ANSYS WORKBENCH its preprocessing and post processing functions into a single integrated platform. Geometry creation and manipulation is fully linked into workbench. The project control is centralized in a visual drag and drop Project schematic graphics area. The control of project can include the analysis chaining or linking it allows the reuse of workflow elements, such as materials, geometry or analysis setup. In addition to that disciplines can be connected with the schematic window and it is comparatively easy and provides more control over the geometry and numbering of modes and element. In practice, the FE simulation is developed to validate the fatigue strength of analytical results. For finding the crack propagation, ANSYS provides an option called, "SMART CRACK GROWTH" which is available only for ANSYS version 19. A 3D linear interface element is used to model the interface between the steel beam and the adhesive layer and between the adhesive layer and the CFRP.

The material properties and geometry are created as per ASTM standard A588 steel beam. The notches are provided at the Centre of the bottom flange of the beam. The fatigue analysis is carried out in normal structural beam and precrackedbeam. It was simulated by ACP Pre of the component system in the ANSYS workbench. Design modeler was used for defining the dimensions of the wrapping. Meshing was done in Model cell of the ACP Pre is used. Then, the fibre orientation was defined in the setup cell, by using the fabrics, element sets, rosettes, orientation selection set and modelling group. In the setup cell the thickness of the FRP has been defined





Fig(1) : Cross sectionFig(2): Cross section
details of steel beam details of notch

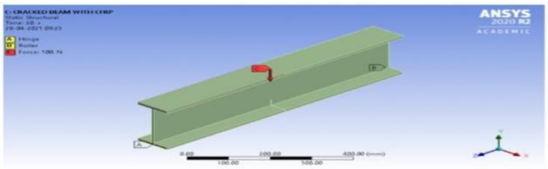
The fractured steel beam is evaluated by using paris' law of crack growth rate. The paris' law material property given for the steel beam is 1e-6 and 3.75 as 'C' and 'm' value respectively. Then the details of the I-section should be given in accordance with the requirements. The dimensions should be given to the flanges and the web of the section and the section is pulling the section along the axis in which the length of the I-section will fall along. Meshing is one of the important parts in finite element modeling. Meshing splits the whole I section into number of elements and nodes. Meshes are of different types. There are three types of meshes are available. The meshes are fine mesh, medium mesh and coarse mesh. The meshes are differing according to the accuracy. Fine mesh gives more acceptable accuracy than coarse and medium meshes to achieve the numerical solution.

The specimen models is created without FRP, with FRP and two layered wrapped FRP Then analysis was done in the ANSYS-WORKBENCH with load such as 1000N, respectively for all the models created The load test was conducted with two ends of the I-beam under fixed conditions and the loading at the exact midsection which is straight above the notch tip where the notch is at the bottoms flange and the loading at the top flange of the beam. After all the examinations of the each and every specimens under loading conditions.

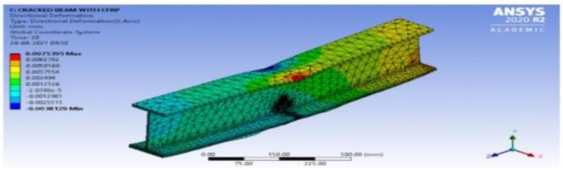
Table (4): Specimen details

Specimen ID	Warping Material	FRP LENGTH(mm) Layer 1	Layer 2
NB	-	-	-
CS1	CFRP	800	-
CS2	CFRP	600	-
CS3	CFRP	400	-
CS4	CFRP	200	-
CD1	CFRP	800	800
CD2	CFRP	600	600
CD3	CFRP	400	400
CD4	CFRP	200	200
BS1	BFRP	800	-
BS2	BFRP	600	-
BS3	BFRP	400	-
BS4	BFRP	200	-
BD1	BFRP	800	800
BD2	BFRP	600	600
BD3	BFRP	400	400
BD4	BFRP	200	200

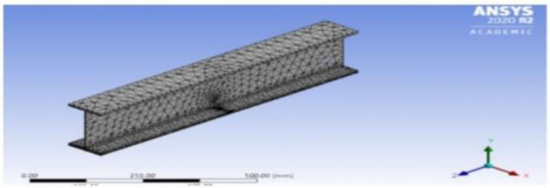
The following are the various test results of the differently wrapped specimen with CFRP and BFRP, wrapping is done with many combinations such as 800mm, 600mm, 400mm, 200mm wrapping under bottom surface and for all the above specimens two layered wrapping was also done and their result was obtained and then compared with conventional unwrapped specimen the comparison was done with the stress acting at notch of the unwrapped specimen and CFRP and BFRP wrapping can be found which gives less stress concentration thus the economical combination and the steel can be found. Thus the aim of this work can be attained which is the economical procedure which consumes less time and less money.



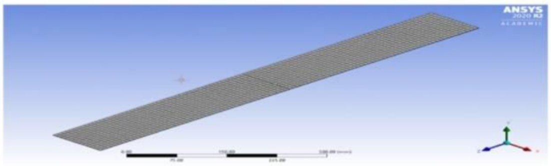
Fig(3): Loading and support condition



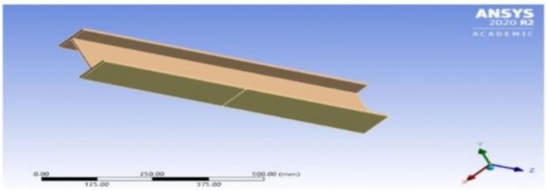
Fig(4): Deformation



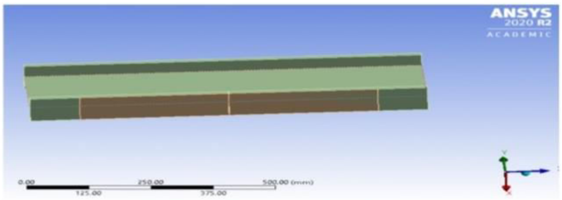
Fig(5): Meshed steel beam with refined mesh



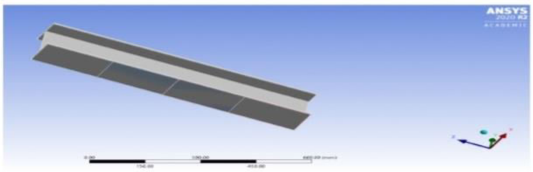
Fig(6): FRP Orientation



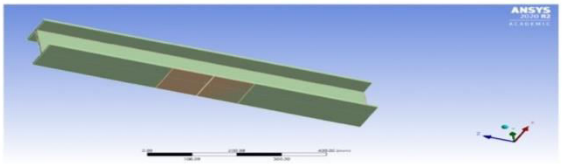
Fig(7): Pre cracked beam with 800mm FRP



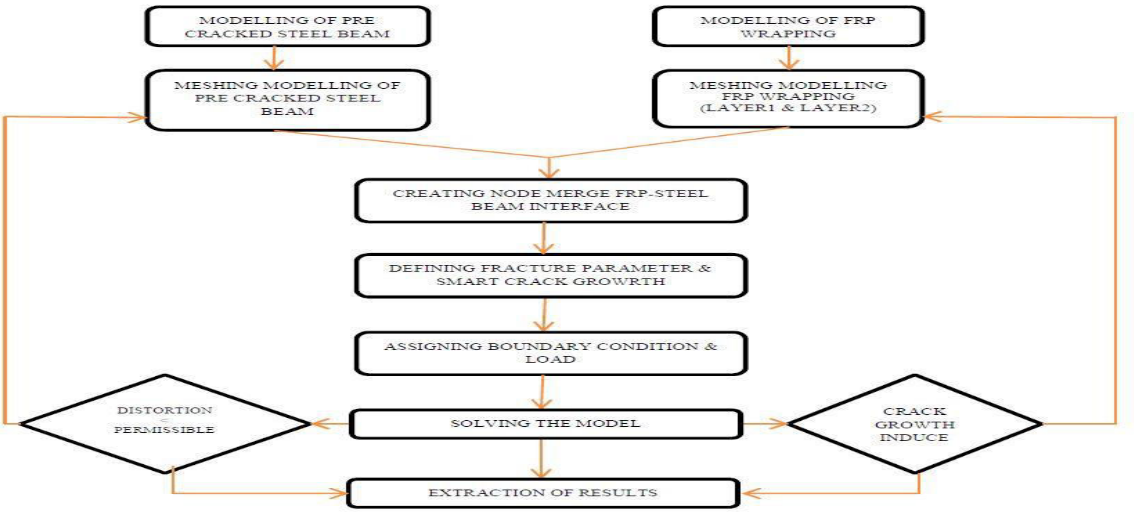
Fig(8): Pre cracked beam with 600mm FRP



Fig(9): Pre cracked beam with 400mm FRP



Fig(10): Pre cracked beam with 200mm FRP



Figure(11): Schematic procedure of the fracture beam analysis in ANSYS

Table (5): Equivalent alternating K1 range for CFRP and BFRP strengthened beam

CRACK	WITHOUT FRP	CARBON FIBRE-REINFORCED POLYMER							
		SINGLE LAYER				DOUBLE LAYER			
		CS1 800mm	CS2 600mm	CS3 400mm	CS4 200mm	CD1 800mm	CD2 600mm	CD3 400mm	CD4 200mm
0	0	0	0	0	0	0	0	0	0
1	6.40	19.12	19.30	21.42	22.65	1.32	14.19	5.27	6.06
2	6.54	81.69	81.26	89.05	133.20	4.91	14.74	14.08	22.30
3	6.67	160.12	149.70	168.46	253.81	11.48	14.52	18.02	33.53
4	6.92	155.14	146.19	163.81	313.98	11.03	15.45	19.47	36.94
5	7.18	165.37	154.18	176.05	330.35	11.49	15.48	20.27	39.33
6	7.42	164.37	154.28	173.46	334.41	11.78	15.31	21.10	41.88
7	7.68	162.07	152.92	171.62	338.52	11.69	15.16	21.79	43.77
8	7.95	161.59	151.42	171.43	336.18	11.58	15.14	22.43	45.71
9	8.20	161.64	150.65	171.71	335.21	11.49	15.06	23.03	47.92
10	8.48	161.82	150.19	169.84	335.60	11.40	14.93	23.79	50.01

CRACK	WITHOUT FRP	BASALT FIBRE-REINFORCED POLYMER							
		SINGLE LAYER				DOUBLE LAYER			
		BS1 800mm	BS2 600mm	BS3 400mm	BS4 200mm	BD1 800mm	BD2 600mm	BD3 400mm	BD4 200mm
0	0	0	0	0	0	0	0	0	0
1	6.40	16.69	19.30	21.42	22.65	1.32	14.19	5.27	6.06
2	6.54	149.31	81.26	89.05	133.20	4.91	14.74	14.08	22.30
3	6.67	163.28	149.70	168.46	253.81	11.48	14.52	18.02	33.53
4	6.92	170.14	146.19	163.81	313.98	11.03	15.45	19.47	36.94
5	7.18	179.37	154.18	176.05	330.35	11.49	15.48	20.27	39.33
6	7.42	164.67	154.28	173.46	334.41	11.78	15.31	21.10	41.88
7	7.68	162.27	152.92	171.62	338.52	11.69	15.16	21.79	43.77
8	7.95	155.59	151.42	171.43	336.18	11.58	15.14	22.43	45.71
9	8.20	158.64	150.65	171.71	335.21	11.49	15.06	23.03	47.92
10	8.48	159.37	150.19	169.84	335.60	11.40	14.93	23.79	50.01

Table (6): Equivalent STRESS INTENSITY FACTOR (SIFS) range for CFRP and BFRP Strengthened beam

CRACK	WITHOUT FRP	CARBON FIBRE-REINFORCED POLYMER							
		SINGLE LAYER				DOUBLE LAYER			
		CS1 800mm	CS2 600mm	CS3 400mm	CS4 200mm	CD1 800mm	CD2 600mm	CD3 400mm	CD4 200mm
0	0	0	0	0	0	0	0	0	0
1	88.98	56.36	90.14	52.624	73.021	6.44	6.80	5.56	93.694
2	461.73	110.62	118.29	180.4	235.44	63.63	66.16	59.63	290.56
3	417.97	110.31	116.17	204.3	255.13	146.06	155.52	136.24	324.02
4	481.55	109.85	126.34	219.71	290.1	158.02	160.89	145.97	360.59
5	481.87	109.4	124.06	202.59	252.24	167.26	165.21	155.43	333.29
6	487.84	109.07	123.41	210.99	275.72	169.16	167.66	153.54	345.88
7	494.46	108.9	121.94	206.25	275.95	165.69	166.10	151.58	362.45
8	502.35	108.88	120.46	208.31	269.02	165.73	169.57	150.84	368.08
9	506.55	108.94	121.08	206.22	273.82	166.38	172.46	150.64	380.17
10	513.97	114.74	120.51	206.93	273.63	164.68	174.82	150.10	367.77

CRACK	WITHOUT FRP	BASALT FIBRE-REINFORCED POLYMER							
		SINGLE LAYER				DOUBLE LAYER			
		BS1 800mm	BS2 600mm	BS3 400mm	BS4 200mm	BD1 800mm	BD2 600mm	BD3 400mm	BD4 200mm
0	0	0	0	0	0	0	0	0	0
1	88.98	72.36	99.36	63.25	82.36	6.67	5.36	5.87	130.23
2	461.73	117.72	115.34	193.83	245.61	82.90	49.36	107.00	285.59
3	417.97	112.62	123.23	200.02	254.8	64.93	152.36	201.18	314.19
4	481.55	107.31	133.55	211.28	298.09	142.64	151.61	247.90	340.38
5	481.87	110.21	138.82	223.4	266.32	155.27	165.68	238.81	363.59
6	487.84	109.15	115.34	200.29	265.11	154.23	177.04	235.99	328.29
7	494.46	111.37	120.81	206.69	277.08	154.84	181.06	231.28	351.88
8	502.35	109.59	131.14	213.05	287.36	154.18	179.70	224.46	354.45
9	506.55	109.48	115.26	210.41	279.36	151.53	181.86	229.40	368.38
10	513.97	112.36	126.08	209.32	274.07	151.42	184.62	228.06	381.07

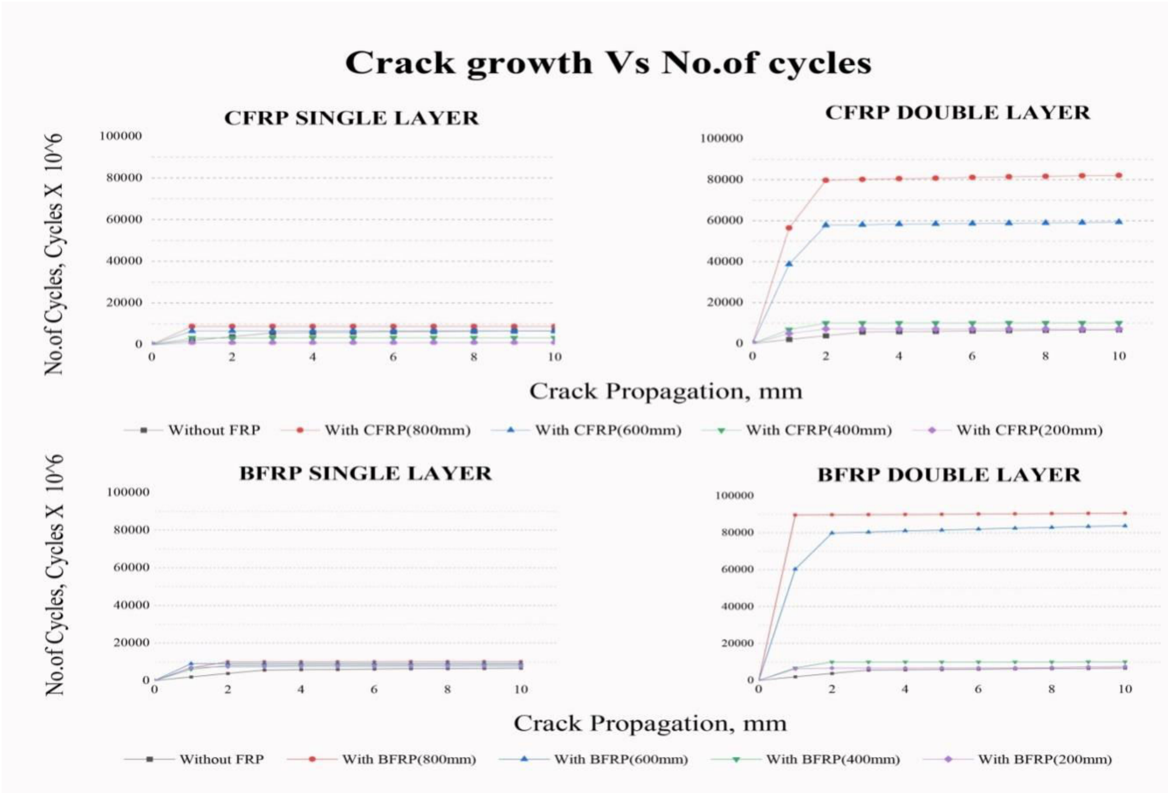


Figure (12): Crack growth Vs no. of cycles

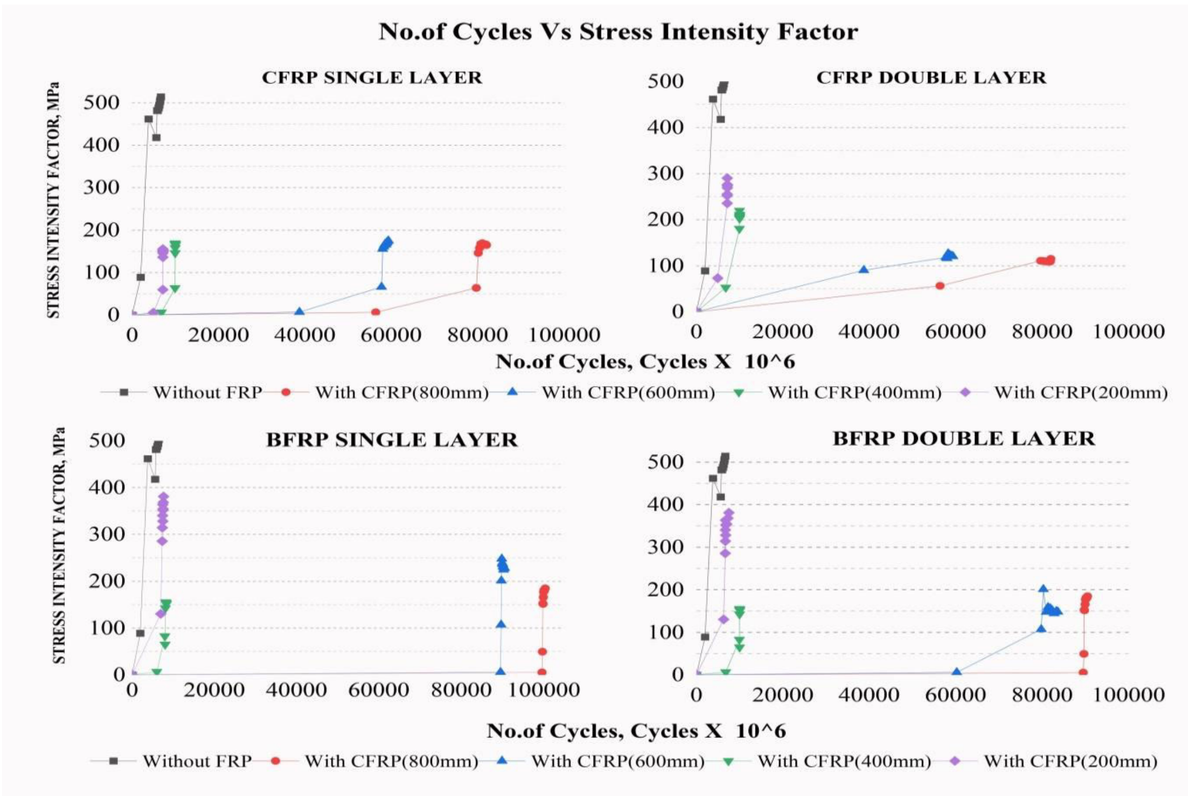


Figure (13): no. of cycles Vs Stress Intensity factor

RESULTS AND DISCUSSIONS

The analytical study of the pre-cracked steel beam was created and studied using the no. of cycles and the crack propagated till 10mm from notch. The CFRP and BFRP strengthened beams are studied for wrapping 100%, 75%, 50% and 25% in single and double each layer having thickness of 1 mm under the flange of I section steel beam.. The bond between 2 layers was made same as that of steel beam and FRP interface. The tables 5 and 6 shows the results for alternating K1 range and Equivalent SIFS range for crack propagation strengthened, using CFPR & BFRP and their respective percentage increase in no. of cycle. Graph shows the difference wrapping length of FRP with respect and no. of cycles in.

- The number of cycles is increased when with FRP length is increased and average percentage increase is calculated for each FRP in various lengths. From the graph the following conclusions are drawn,
- BD1 shows increase in no. of cycle in than any other FRP wrapping. This is due to the fact the transverse property of the basalt is good than carbon.
- BD1 shows the highest increase in no. of cycle in an average of 7.19% than BD2 and NB of 72.56% respectively. This shows that the increase in no. of cycles for fully wrapped FRP increase the percentage by 5.82% for BFRP to CFRP respectively.
- It was also observed that double layers of CFRP and BFRP laminate (i.e. CD1, CD2, BD1 and BD2) shows, increase in no. of cycle by 66.18%, 72.90%, 64.82% and 69.36% of single layers of CFRP and BFRP laminate respectively when compared to beam without FRP has less no.of cycles.
- The results show the number of cycles gets increases when the length of the wrapping is increased. Thus, it is observed that they directly proportional.
- CFRP behaves better at longitudinal direction and its performance gets reduced when transformed to transverse direction, even the performance of CFRP is observed to be much better when compared with BFRP.
- From the table 5 & 6, it is observed that the equivalent stress intensity factor range is directly proportional to the no. of cycle as the SIFS range value increased; no. of cycle is also increased.

Validation:

Let us consider 40mm crack propagation for without FRP validation of the results obtained from the analysis. By using the Paris' law formula,

$$\frac{da}{dN} = C\Delta K^m,$$

Where, 'a'=Crack length,

da/dN = Crack Growth rate,

C and m are material constant, and

ΔK= range of stress intensity factor during the fatigue cycle, i.e.,

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

LHS:	RHS:
da= 2-1,	C=1e-6,
$dN=(3.815-1.98)x10^9$	m=3.75,
$=1.835 \times 10^9$	ΔK= 0.13
$da/dN= 1/1.835 \times 10^9$	$C(\Delta K)m=(10^{-6})*(0.135)^{3.75}$
$=5.449 \times 10^{-10}$	$=5.479 \times 10^{-10}$

LHS = RHS

Error = -0.54%

The overall error estimate for the validation is shown in Table 8.

Table 8 Error estimate of beam without FRP

Crack Extension mm	ΔK	N	Error
	MPa	cycle	%
1	6.40	1980149090	-0.54
2	6.54	3815019520	-3.62
3	6.67	5597035390	-6.14
4	6.92	5789518400	6.77
5	7.18	5936118510	5.25
6	7.42	6136111100	3.86
7	7.68	6298785100	-2.85
8	7.95	6432605100	4.26
9	8.20	6606516150	8.43

CONCLUSION

Based on the analytical study, the fracture behavior of pre-cracked beam with different length of CFRP and BFRP wrapping.The FRP strengthening is found to enhance the structural behaviour of the precracked steel beam.From study, carbon fibre reinforced polymer (CFRP) gives better than tensile strength basalt fibre reinforced polymer (BFRP).

- Since the aim of the work is study the crack growth in precracked steel beam with CFRP & BFRP used in the wrapping process of a repairing and rehabilitation work through finding the stress intensity factor and no of cycles at the notch of each specimen was studied. Concentration at the notch compare to all other wrapping and equivalent stress intensity range increases by depends up on the length of the wrapping.

- Steel beam is wrapped by full, half, three by four and a quarter of its length and then for all these cases were considered for CFRP and BFRP and compared with unwrapped beam. Wrapping is done under the bottom of the flange.
- But the without FRP wrapping on bottom flange has high stress i intensity factor (SIFS) is found to be reduced up to7.5% of its value, when the double layer of CFRP and BFRP.
- Hence 0-degree fibre orientation should be preferred in all type of FRP employed for strengthening of the pre cracked steel beam. The orientation and type of FRP plays a major significant role in the strengthening of structural elements.
- BFRP strengthened beam withstand a greater number of cycles for double layer when compared with CFRP single layer, double layer & single layer of CFRP in transverse direction.
- Compared to the control specimen, wrapped specimens have high no. of cycles and SIFS range is decreased when length of the FRP is increased.
- From the graph (figures 11), the CD1 and CD2 act as ductile material as when compared with other laminates. Similarly, CS1, CS2 has the less slant lines to horizontal axis which shows the flexibility of the laminate than other laminates.
- The result obtained from ANSYS analysis is validated theoretically with Paris law and error percentage lies between -10% to +10%

Future Scope of the Project:

- To find the optimized FRP wrapping length for steel beam retrofitting pre-cracked steel beam.
- The work can be further proceed effectively with more specimen with different shapes with various sizes and various loading and wrapping conditions. Thus even better conclusions over our result can be made.

REFERENCES

1. Al-Mosawe, A., Al-Mahaidi, R., and Zhao, X.-L. **"Effect of CFRP properties, on the bond characteristics between steel and CFRP laminate under quasi-static loading"**, Elsevier Construction Building Material, (2015)98, 489–501.
2. Boshra El-Taly, **"Repairing steel beams with different notch levels using composite materials",** Asian Journal of Civil Engineering, Springer, published in September 2018
3. Colombi, P., Poggi, C. (2006) "An experimental, analytical and numerical study of the static behavior of steel beams reinforced by pultruded CFRP strips", Compos B Eng, 37(1), 64–73.
4. E.Ghafoori, M. Motavalli, J. Botsis, A. Herwig, M. Galli, **"Fatigue strengthening of damaged metallic beams using prestressedunbonded and bonded CFRP plates"**, Elsevier, International Journal of Fatigue 44 (2012) 303–315
5. Elchalakani M, Fernando D.Plastic**"Mechanism analysis of unstiffened steel I-section beams strengthened with CFRP under 3-point bending",** Journal of Thin-Walled Structures, Elsevier 2012;57(1):58–71
6. ElyasGhafoori and MasoudMotavalli, **"Innovative CFRP-Prestressing System for Strengthening Metallic Structures",** American Society of Civil Engineer, Journal of Compositesfor Construction, (2015) ASCE, ISSN 1090-0268/04015006(14)
7. ElyasGhafoori, MasoudMotavalli, **"Lateral-torsional buckling of steel I-beams retrofitted by bonded and un-bonded CFRP laminates with different pre-stress levels: Experimental and numerical study",** Elsevier, Construction and Building Materials 76 (2015) 194–206
8. Ghazijahani, T. G., Jiao, H., & Holloway, D. **"Fatigue experiments on circular hollow sections with CFRP reinforced cutouts",** Elsevier Journal of Constructional Steel Research, (2015)106, 322–328.
9. Gunalan, S., &Mahendran, M.**"Web crippling tests of cold-formed steel channels under two flange load cases"**, Elsevier, Journal of Constructional Steel Research, (2015) - 110, 1–5.
10. Hui Jiao, FidelisMashiri, Xiao-LingZhao, **"A comparative study on fatigue behaviour of steel beams retrofitted with welding, pultruded CFRP plates and wet layup CFRP sheets"**, Elsevier, Thin-Walled Structures 59 (2012) 144–152
11. K. Narmashiri, N.R. Sulong, M.Z. Jumaat, **"Failure analysis and structural behaviour of CFRP strengthened steel I-beams"**, Constr. Build. Mater. 30 (2012) 1–9.
12. Kabir, M. H., Fawzia, S., Chan, T. H. T., Gamage, J. C. P. H., and Bai, J. B. (2016). **"Experimental and numerical investigation of the behaviour of CFRP strengthened CHS beams subjected to bending",** Elsevier, Engineering Structures 113, 160–173.
13. M. Shahraki, M.R. Sohrabi, G. Azizian, K. Narmashiri, **"Experimental and numerical investigation of strengthened deficient steel SHS columns under axial compressive loads",** Structural Engineering Mechanics. 67 (2) (2018) 207–217.

★★★