

## **Experimental and numerical investigation of strengthened cruciform welded joints using FRP**

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### **ABSTRACT**

This paper presents an experimental and finite element study on the fatigue strength using fiber reinforced polymers (FRP) to repair load-carrying cruciform full penetration welded joints. Fatigue tests were carried out on a total of 15 specimens. The stress intensity factor (SIF) were determined for welded joint at weld toe failure. Test results showed that, the patching of FRP materials prolongs fatigue life with sufficient values and at the same time debonding was prevented in case of bearing plate and bolts. The fatigue life was then predicted using fracture mechanics approach. The results showed that the resulting fatigue enhancement agreed well with experimental specimens. The effects of different parameters on fatigue life and SIF at crack tip were also presented. By comparing S-N curves of different parameters with that of AWS2002, it was found that S-N curve of cruciform welded joint shifted from category D to a curve located between category B' – B.

### **1. INTRODUCTION**

Fatigue cracking in existing steel structures such as bridges is becoming an increasingly important due to the natural aging of these structures. In the welded joints, areas of high stress concentration are the most adopted points for fatigue cracks initiation and propagation which are the main reasons of catastrophic failure. These welded joints are weak points for fatigue resistance.

Structural retrofitting with CFRP materials in comparison with conventional retrofitting techniques provides an environmentally friendly and economic way to save and utilize the infrastructures, and, therefore, it became one of the primary interests in civil

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engineering applications. In the last decade, several researches showed that the fatigue lifetime of cracked steel members can be extended using externally bonded Carbon fiber reinforced polymer (CFRP) material. Repair with composite patches reduces the stress field near the defects and retards the crack propagation was considered by (Teng 2012; Zhao and Zhang 2007). FRP has been used to strengthen deteriorated bridges suffering from fatigue cracks to increase fatigue life of bridge girders and truss joints as stated in (Zhao 2013). Large amount of research has been carried out on CFRP bonded steel plates. Experimental results demonstrated that CFRP materials could effectively extend fatigue of defective specimens. (Jones Sean C. and Civjan Scott A. 2003) investigated that the retrofitting efficiency was highly dependent on bond configuration, CFRP stiffness, prestress level and initial damage degree. Stress intensity factor (SIF) at crack tip and fatigue crack propagation have also been studied numerically by (Colombi 2015), where the parametric analysis was performed to optimize this strengthening method. Fatigue design criteria for strengthening metallic beams with CFRP materials were also proposed (Ghafoor 2015), which extended the understanding of CFRP-repaired steel beams. (Wu 2013) conducted testing of steel plates with longitudinal weld attachments on one side, with a particular focus on the application of ultra-high modulus CFRP materials and the influence of strengthening scheme. The fatigue life of the welded joints retrofitted on a single side was increased up to 141% over control ones.

However, studies on the fatigue behaviour of load-carrying cruciform welded joints strengthened by FRP materials are limited. Generally, fatigue damage of welded joints is due to weld-induced imperfections and stress concentration produced by geometric discontinuity. (Chen 2013) constructed finite element models of non-load-carrying cruciform welded joints. SIF were analyzed to evaluate the strengthening efficiency. (Chen 2012) carried out an experimental study of non-load carrying cruciform welded joints subjected to fatigue loading. The study showed the effect of using CFRP sheets as rehabilitation method. Results demonstrated that the fatigue life was twice after adding one layer of CFRP sheet.

This paper covers experimental and numerical investigation on load-carrying cruciform full penetration welded joints repaired with FRP materials fixed with bearing plate & bolts. A total of fifteen specimens were tested axially under tensile fatigue loading. The effect of using FRP materials fixed with bearing plate in enhancing the resistance of cruciform welded joints to fatigue failure and mode failures were demonstrated. Finite element method was adopted to investigate the SIF of mode I ( $K_I$ ). The fatigue life was then predicted using fracture mechanics approach.

## **2. EXPERIMENTAL SECTION**

An experimental study was performed on load-carrying cruciform full penetration welded joints strengthened by FRP materials. The specimens were patched with five layers of FRP materials. The first layer was GFRP sheet which was used as insulator layer between steel and CFRP sheets as suggested by (Cadei 2004) ; (Tavakkolizadeh M. and Saadatmanesh H., 2003). The other four layers were CFRP sheets. The details of experimental program including the full designing of test specimens and properties of materials as shown below.

### *2.1 Material Properties*

EN 10025-3- S355N/NL steel rolled plates of 6 mm thick conforming to the **European Committee for Standardization Eurocode 3(2005)** were used as the base materials in the experiment. An ultimate strength of 489 MPa, a yield strength of 391 MPa and elongation of 28.6% were obtained from standard coupons tensile test. Sika Wrap\_430G and Sika Wrap\_300C with same nominal thickness of 0.17 mm, were selected in the test program as GFRP sheets and CFRP sheets, respectively. Epoxy adhesive, Sikadur\_330, was used to bond the composite. The properties of repairing materials were provided by the manufactures and listed in **Table 1**.

**Table 1.** Properties of retrofitting materials

<b>Materials</b>	<b>Tensile strength (MPa)</b>	<b>E-Modulus (MPa)</b>	<b>Thickness (mm)</b>	<b>Strain at break of failure (%)</b>
SikaWrap_430G (GFRP)	2300	76000	0.17	2.8
Sika Wrap_300C (CFRP)	3900	230000	0.17	1.5
Sikadur_330 (Epoxy)	30	4500	-	1.2

### *2.2 Configuration and Preparation of Test Specimen*

Cruciform specimen is composed of stiffener plate (160mm×40mm×10mm) welded to two main plates (150mm×40mm×6mm), with the test section of a dog-bone shape as shown in **Fig. 1**. The first layer of GFRP is bonded to the steel surface within 24 hours after sandblasting and cleaning with acetone. Therefore, one GFRP layer and four CFRP layers of 120\*40mm each, were patched using wet lay-up method to the cruciform joint surfaces as shown in **Fig. 1**. The applied thickness of epoxy was restricted to around 0.5mm(**Mall and Ramamurthy, 1989**). Finally, the specimens were cured for two weeks at room temperature.



small stress range (180 MPa) fatigue life is improved by 517%. In addition, for specimens retrofitting with FRP materials fixed with bearing plate and bolts, using large stress range loading (270 MPa) fatigue life is enhanced by 120%, while utilizing small stress range (180 MPa) fatigue life is improved by 437%. The effectiveness of strengthening at the high stress range (270 MPa) showed to be less significantly compared to that at the low stress range (180 MPa). It means that FRP materials distributed stresses away from high stress concentration region at low stress range which subsequently reduced the stress intensity factor around toe crack tip.

**Table 2.** Experimental program and testing results

Specimens	Thickness (mm)	Width (mm)	Tension Stress Range on Weld Toe (MPa)	Fatigue Life (Cycles)	Enhancement (%)
SS-1	6	40	270	66463	--
SCG-1-5	6	40	270	72639	110
SCG-HB-1-5	6	40	270	80104	120
SS-2	6	40	252	71098	--
SCG-2-5	6	40	252	79521	112
SCG-HB-2-5	6	40	252	87293	123
SS-3	6	40	225	95444	--
SCG-3-5	6	40	225	577860	605
SCG-HB-3-5	6	40	225	485968	509
SS-4	6	40	198	118040	--
SCG-4-5	6	40	198	939312	695
SCG-HB-4-5	6	40	198	791824	506
SS-5	6	40	180	222816	--
SCG-5-5	6	40	180	1152765	517
SCG-HB-5-5	6	40	180	973155	437

### 3.2 Modes of Failure

The cracks of all fatigue failure mechanism were observed to start from the intersection of the fusion line with the weld surface at the weld toe. Fatigue cracks propagating and growth from stress concentration point. Failure mode of both un retrofitted and retrofitted specimen were occurred in the same position at the weld toe. Crack initiation and propagation were at the weld toe, where the critical stress concentration point. By comparing the failure shape of the two cases of strengthening, failure surface of retrofitted specimens with FRP materials only shows FRP debonding, while in existence of head plate no debonding occurred and high stroke with alarm sound through FRP rupture were observed. For all failure mode shapes, it can be observed that the crack surface had an apparent smooth region where the crack propagated steadily and a rough region where the specimen fractured suddenly.

### 3.3 S-N Curve of Strengthened Cruciform Welded Joints

Several international standard and design guides as IIW (Hobbacher, 2016) and BS 7608. (1993) recommended that, the classification method is commonly used to evaluate their fatigue design of welded joint is based on structural details. Fatigue design curves for different detail categories are recommended by Structural Welding Code (AWS 2002). S-N plot for test results and (AWS 2002) specification for stress categories A, B, B', C, D, E and E' are shown in Fig. 2. The data points determined from unretrofitted and retrofitted specimens are also plotted in Fig. 2. It observed that the fatigue behaviour of specimens strengthened with stress range of 225 MPa, 198 MPa and 180 MPa were significantly enhanced after retrofitting, while for specimens reinforced with stress range of 270 MPa and 252 MPa showed limited enhancement of fatigue behavior. It cleared that the data points for un retrofitted specimens are approximately located between categories D and C, while the retrofitted data points for most specimens, were situated between category B and A. This implies that the fatigue life was significantly extended after bonded by FRP materials.

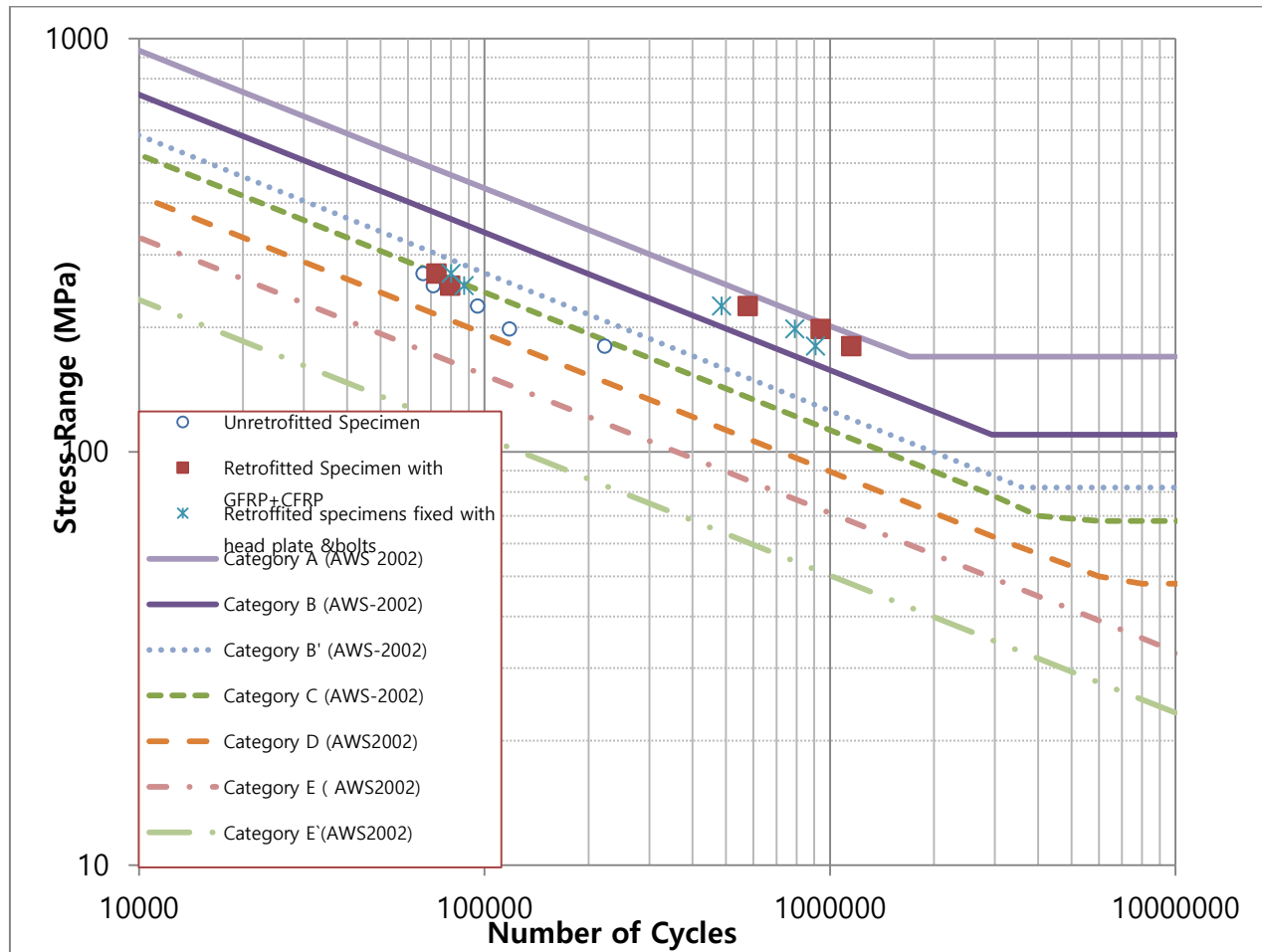


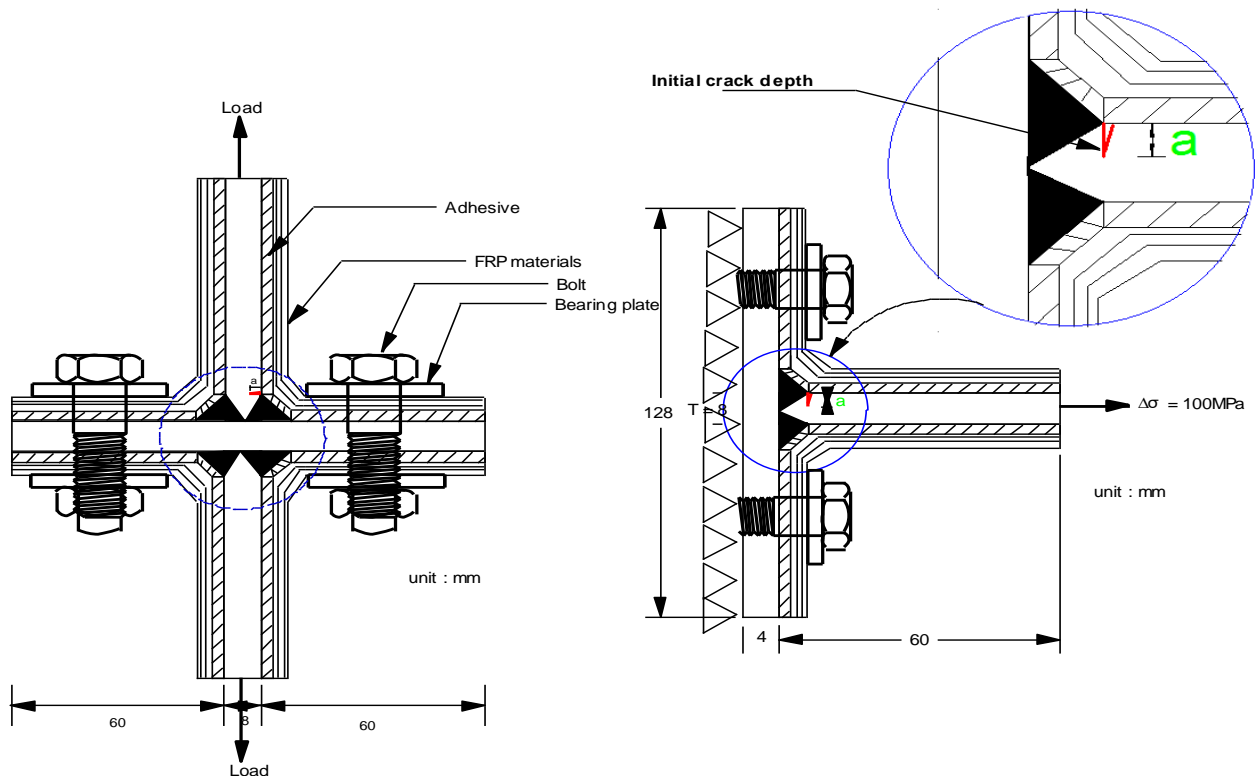
Fig. 2 S-N plot for test results and AWS 2002 detail categories

#### 4. FINITE ELEMENT MODELLING

Two-dimensional finite element analysis was developed to simulate the experimental tests and to obtain the SIF (KI) of cracked load-carrying cruciform welded joints retrofitted with FRP materials at crack tip. The commercial software package ANSYS APDL 14.5 was employed.

##### 4.1 Specimens and material properties

The basic geometry of the cruciform welded joint considered in this study is shown in Fig. 3. A stiffener plate is welded with main plates using full penetration weld. The thickness of stiffener plate (128x40) and main plate (60x40), are 8 mm. Dimensions of bearing plate is 40\*40\*5 mm. Diameter of the bolt is 10mm. The weld leg lengths, H and W, is 6 mm; and, the flank angle was set as 45°. The horizontal plate is subjected to a uniaxial tensile load. An initial crack of depth “a” perpendicular to the loading axis was supposed to exist at the weld toe. The steel specimen’s surfaces are adhesively bonded with GFRP sheet for first layer & other four layers with CFRP sheets. The adhesive thickness is 0.55 mm that was measured by (Chen et al., 2013), and the thickness of the CFRP sheets is 0.167 mm. The Young’s modulus of the steel is  $2.04 \times 10^5$  MPa, and Poisson’s ratio is assumed to be 0.3. The moduli of GFRP and CFRP sheets are  $76 \times 10^3$  MPa and 4500 MPa respectively.



(a) Load-carrying Cruciform joint

(b) Half model 2-D due to symmetric

Fig. 3 S-N plot for test results and AWS 2002 detail categories

#### *4.2 Mesh Description and Boundary Conditions*

The cruciform welded joint together with the adhesive and FRP materials fixed with bearing plate and bolts were simplified to a two-dimensional (2D) plane strain model due to symmetrical configuration and boundary conditions. The FE model was meshed with PLANE183 which is a higher order 2-D. A symmetric boundary condition was defined for all nodes at left end, therefore, the translation degrees of freedom in X direction ( $U_x$ ) is restrained. To ensure the accuracy of the results considerable care was utilized in the region of weld toe by using very fine meshing. To compute the stress intensity factors and numbers of cycles to failure, Nominal stress of 100 MPa was applied to the main plate. The J-integral technique is used to calculate the SIFs. The direction of crack growth was assumed perpendicular to the main plate and propagated through plate thickness until failure.

#### *4.3 Stress Intensity Factors(SIF)*

Finite element analysis was employed to determine the SIF for J-Integral approach. The J-Integral calculation is based on the domain integral approach and is performed during the solution phase of the analysis. Usually, a circular contour path, around the crack tip, is defined with a set of internal points. And the integration along the contour path can be accomplished.

Analytical analysis was first carried out for un-retrofitted surface-cracked specimens of various crack depths for load carrying cruciform full penetration welded joint. The analytical formula results are compared with the numerical results of stress intensity factor (SIF) using the J-integral approach. It can be noted that the numerical results are in good agreement with analytical results as shown in Fig. 4. Theoretical equations for strengthened cruciform joints are not available yet. Therefore, numerical analysis was presented to obtain SIFs.

Fig. 5. showing the relation between SIF( $K_1$ ) at different crack depth for number of FRP layers. It can be seen that SIF significantly reduced with the GFRP & CFRP retrofit. SIF were 175.9 MPa mm<sup>1/2</sup> for initial crack depth ratio ( $a/T = 0.05$ ), 445.4 MPa mm<sup>1/2</sup> for crack depth ratio ( $a/T = 0.35$ ) and 634.2 MPa mm<sup>1/2</sup> for final crack depth ratio ( $a/T = 0.5$ ) for unrepaired specimens. However, the SIF changed from 152.7 MPa mm<sup>1/2</sup> for initial crack depth ratio ( $a/T = 0.05$ ) to 328.4 MPa mm<sup>1/2</sup> for crack depth ratio ( $a/T = 0.35$ ) and 414.9 MPa mm<sup>1/2</sup> for final crack depth ratio ( $a/T = 0.5$ ) for specimens repaired with five layers of CFRP.

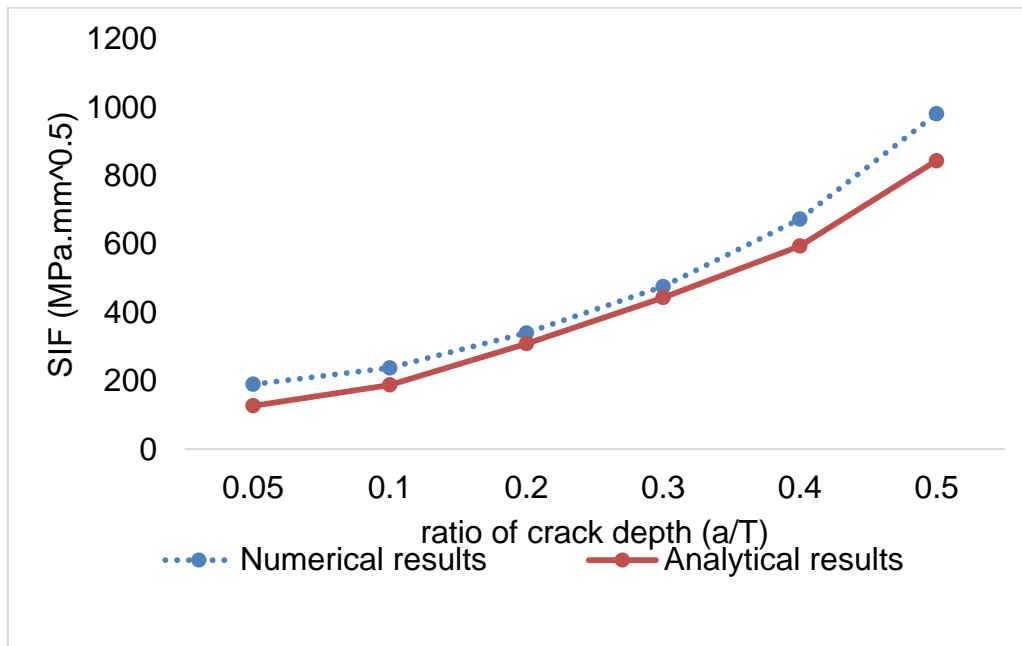


Fig. 4 Comparison of analytical and numerical results of SIF(K<sub>I</sub>)

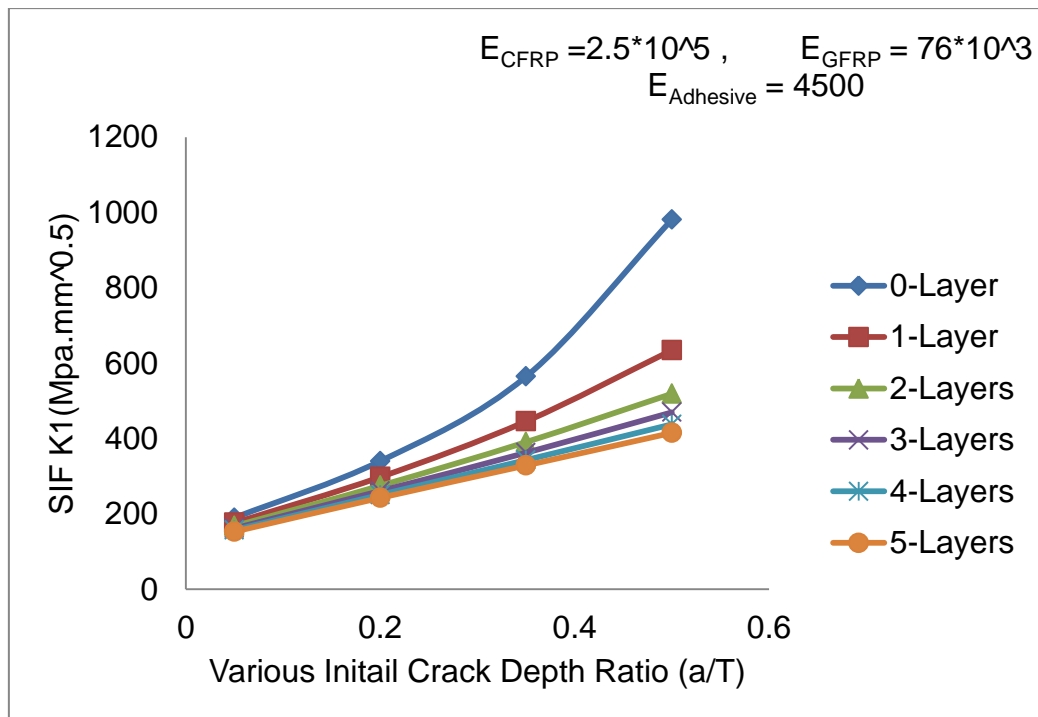


Fig. 5 Relation of SIF (K<sub>I</sub>) with respect to the initial crack depth

## 5. FATIGUE LIFE

The linear elastic fracture mechanics (LEFM) method is adopted in this research for the prediction fatigue life. The determination of fatigue life has been carried out using a cycle by cycle approach implemented with MATLAB software program. The basis for the calculation of fatigue life is given by Paris law (Paris and Erdogan 1963) and Forman (Forman 1967) Eqs. (1) and (2).

$$\frac{da}{dN} = C (\Delta K)^m \quad \text{for} \quad \Delta K_{th} < \Delta K = K_{Ic} \quad (1)$$

$$\frac{da}{dN} = \frac{C \Delta K^m}{(1-R)(K_C - K_{max})} \quad (2)$$

Table 3 illustrate summary of the initially assumed values for various model parameters considered in this study to predict fatigue life of cruciform welded joint.

**Table 3** Assumed Parameters Values for LEFM analysis

Parameter	Value	Units	Reference
$a_i$	0.1	mm	(Mashiri 2001)
$a_f$	50% of plate thickness	----	(Mori 1997; Swamidias 1989)
C	$1.7 \cdot 10^{-13}$	mm/cycle	(Hobbacher 1996; Nykänen 2007)
m	3	----	(Hobbacher 2016b; Institution 2005; Yu 2015)
$\Delta K_{th}$	91.7	MPa.mm <sup>1/2</sup>	(Construction 1995)
$K_C$	3475	MPa.mm <sup>1/2</sup>	(Chen 2014; Yu 2016)

## 6. Parametric Study with the LEFM Model

The fracture mechanics method was then used to perform several parametric studies on load-carrying cruciform welded joints. The effects of several parameters on crack propagation life were investigated. S-N curves were constructed for strengthened cruciform welded joint with FRP materials fixed with bearing plate and bolts considering the effect of different parameters.

Fig. 6 shows the effect of number of CFRP layers on (S-N) curves, while table 5 shows its effect on Cf and m values. Fig. 7 shows the effect of adhesive thickness on (S-N) curves, while table 6 show their effect on Cf and m values

The figures illustrate that a significant enhancement in the fatigue life occurred due to FRP materials strengthening. Table 4 show Cf and m values for different details category adopted in AWS2002. By comparing S-N curves from LEFM analysis of different parameters with that of AWS2002, we can find that S-N curve of un retrofitted

specimen is shifted from category D to a curve located between category B' and B. The amount of shift varies according to the enhanced parameter

Table 4.  $C_f$  and  $m$  values according to AWS2002 detail categories

Detail Category	$m$	$C_f$
A	3.0	$81 \times 10^{11}$
B	3.0	$39 \times 10^{11}$
B'	3.0	$19.9 \times 10^{11}$
C	3.0	$14.4 \times 10^{11}$
D	3.0	$7.3 \times 10^{11}$

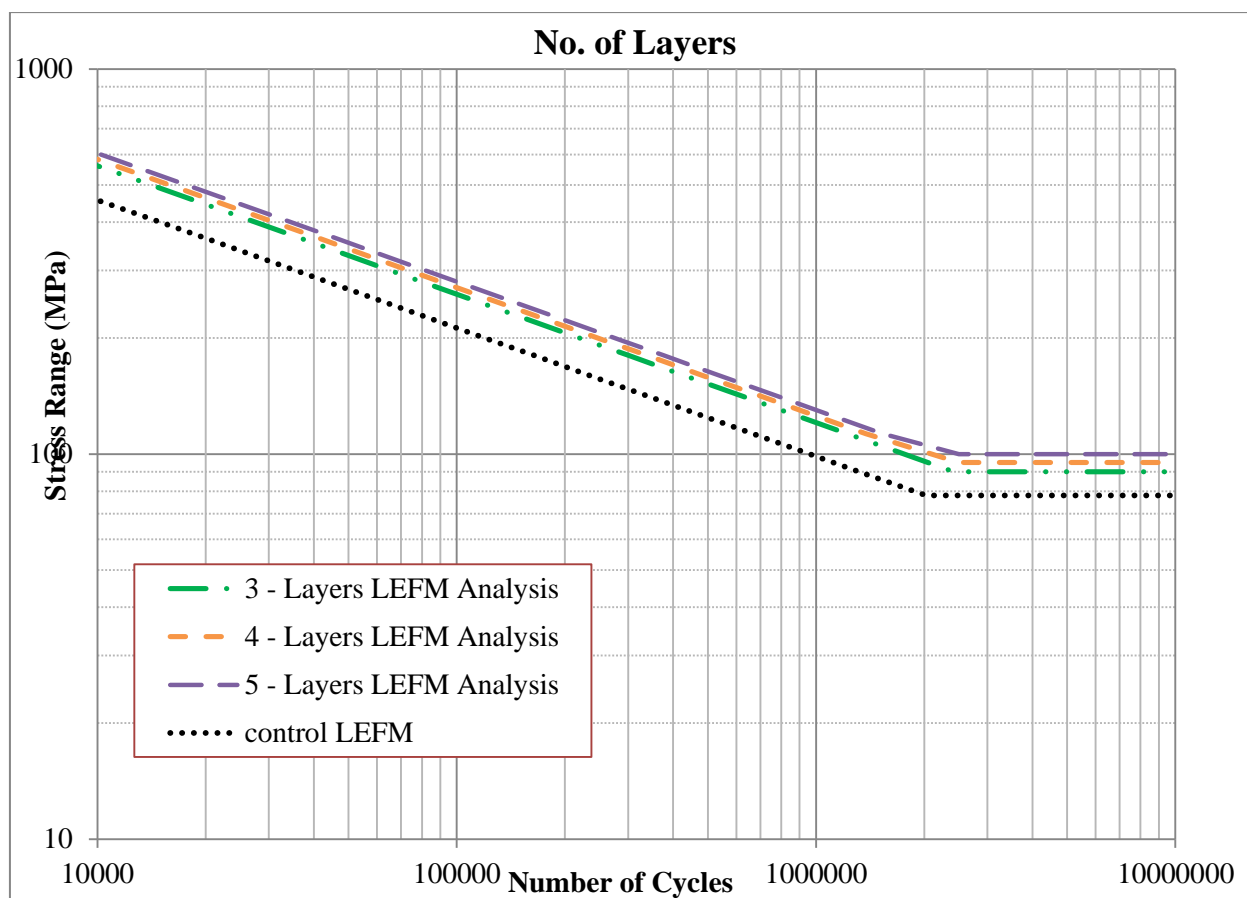
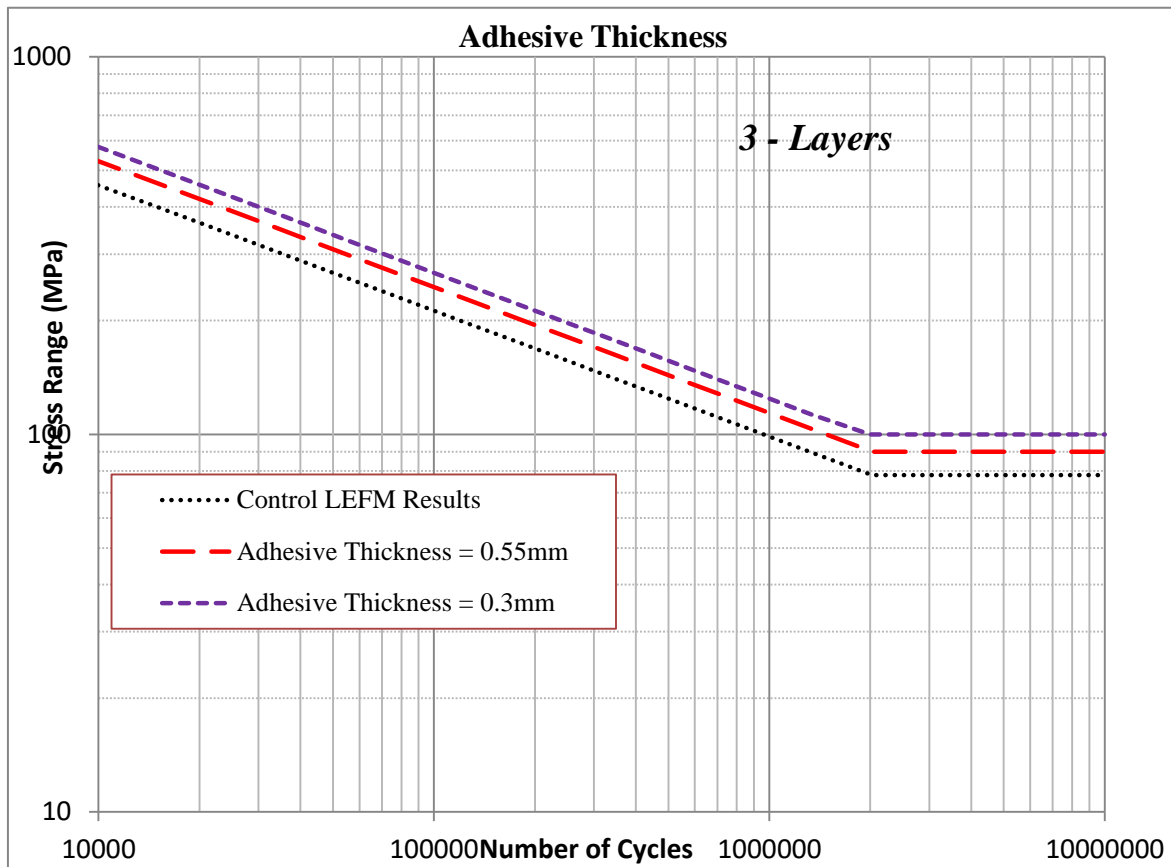


Fig. 6 S-N curves from LEFM analysis considering number of FRP's layers for weld toe

Table 5.  $C_f$  and  $m$  values considering number of CFRP layers

No. of Layers	$m$	$C_f$	Category enhancement
Control LEFM Analysis	3.0	$9.8 \times 10^{11}$	D
Three	3.0	$18.2 \times 10^{11}$	
Four	3.0	$20.6 \times 10^{11}$	
Five	3.0	$22.8 \times 10^{11}$	B' - B



**Fig. 7** S-N curves from LEFM analysis considering adhesive thickness for weld toe crack propagation

**Table 6.**  $C_f$  and  $m$  values considering Adhesive thickness for crack propagation

Thickness of Adhesive	$m$	$C_f$	Category enhancement
Control LEFM Analysis	3.0	$9.8 \times 10^{11}$	D
Adhesive Thick = 0.55mm	3.0	$18.2 \times 10^{11}$	
Adhesive Thick = 0.30mm	3.0	$26.6 \times 10^{11}$	B' - B

## 7. CONCLUSIONS

By comparing S-N curves from LEFM analysis of different parameters with that of standard code AWS2002, it is found that S-N curve of cruciform welded joint is shifted from category D to a curve lay between category B and B'.

A thinner adhesive could lead to better fatigue enhancement performance.

The fatigue life increased from Category C to category B when the adhesive thickness was decreased from 0.55 mm to 0.3 mm.

## REFERENCES

- British Standards Institution, and European Committee for Standardization. (2005), Eurocode 3, design of steel structures: part 1-1: *General rules and rules for buildings*. British Standards Institution, London.
- Cadei, J. M. C., Stratford, T., Duckett, W. G., Hollaway, L. C., and Association, C. I. R. and I. (2004), *Strengthening metallic structures using externally bonded fibre-reinforced polymers*. CIRIA.
- Chen, T., Yu, Q.-Q., Gu, X.-L., and Nie, G.-H. (2013), "Stress intensity factors (KI) of cracked non-load-carrying cruciform welded joints repaired with CFRP materials," *Compos. Part B Eng.*, **45**(1), 1629–1635.
- Chen, T., Yu, Q.-Q., Gu, X.-L., and Zhao, X.-L. (2012), "Study on fatigue behavior of strengthened non-load-carrying cruciform welded joints using carbon fiber sheets," *Int. J. Struct. Stab. Dyn.*, **12**(01), 179–194.
- Chen, T., Zhao, X.-L., Gu, X.-L., and Xiao, Z.-G. (2014), "Numerical analysis on fatigue crack growth life of non-load-carrying cruciform welded joints repaired with FRP materials," *Compos. Part B Eng.*, **56**, 171–177.
- Colombi, P., Fava, G., and Sonzogni, L. (2015), "Fatigue crack growth in CFRP-strengthened steel plates," *Compos. Part B Eng.*, **72**(Supplement C), 87–96.
- Construction, J. S. of S. (1995), *Fatigue design recommendations for steel structures*, Japanese Society of Steel Construction.
- Forman, R. G., Kearney, V. E., and Engle, R. M. (1967), "Numerical Analysis of Crack Propagation in Cyclic-Loaded Structures," *J. Basic Eng.*, **89**(3), 459–463.
- Ghafoori, E., Motavalli, M., Nussbaumer, A., Herwig, A., Prinz, G. S., and Fontana, M. (2015), "Design criterion for fatigue strengthening of riveted beams in a 120-year-old railway metallic bridge using pre-stressed CFRP plates," *Compos. Part B Eng.*, **68**(Supplement C), 1–13.
- Hobbacher, A. (2016a), *Recommendations for Fatigue Design of Welded Joints and Components*, IIW Collection, Springer International Publishing, Cham.
- Hobbacher, A., (1996), International Institute of Welding, Joint Working Group XIII-XV, and Welding Institute, *Fatigue design of welded joints and components: recommendations of IIW Joint Working Group XIII-XV*. Abington in association with the Welding Institute, Cambridge, England.
- Institution, B. S. (2005). BS 7910:2005: *Guide to methods for assessing the acceptability of flaws in metallic structures*. British Standards Institution, London.
- Institution, B. S., Staff, B. S. I., and Confiant, R. (1993), *Code of Practice for Fatigue Design and Assessment of Steel Structures*. British Standards Institution.
- Jones Sean C., and Civjan Scott A. (2003), "Application of Fiber Reinforced Polymer Overlays to Extend Steel Fatigue Life," *J Compos. Constr.*, **7**(4), 331–338.
- Mall, S., and Ramamurthy, G. (1989), "Effect of bond thickness on fracture and fatigue strength of adhesively bonded composite joints," *Int. J. Adhes.*, **9**(1), 33–37.
- Mashiri, F. R., Zhao, X. L., and Grundy, P. (2001), "Effects of weld profile and undercut on fatigue crack propagation life of thin-walled cruciform joint," *Thin-Walled Struct.*, **39**(3), 261–285.
- Mori, T., Zhao, X.-L., and Grundy, P. (1997), "Fatigue Strength of Transverse Single-sided Fillet Welded Joints," *Aust. Civ. Eng. Trans.*, **39**(2/3), 95.

- Nykänen, T., Marquis, G., and Björk, T. (2007), "Fatigue analysis of non-load-carrying fillet welded cruciform joints," *Eng. Fract. Mech.*, **74**(3), 399–415.
- Paris, P., and Erdogan, F. (1963), "A Critical Analysis of Crack Propagation Laws," *J. Basic Eng.*, **85**(4), 528–533.
- Swamidas, A. S. J., Cheema, P. S., and Muggeridge, D. B. (1989), "Fatigue strength of fillet-welded cruciform joints," *Can. J. Civ. Eng.*, **16**(2), 162–171.
- Tavakkolizadeh M., and Saadatmanesh H. (2003), "Fatigue Strength of Steel Girders Strengthened with Carbon Fiber Reinforced Polymer Patch," *J. Struct. Eng.*, **129**(2), 186–196.
- Teng, J. G., Yu, T., and Fernando, D. (2012), "Strengthening of steel structures with fiber-reinforced polymer composites," *J. Constr. Steel Res.*, **78**, 131–143.
- Wu, C., Zhao, X. L., Al-Mahaidi, R., Emdad, M. R., and Duan, W. H. (2013), "Fatigue tests on steel plates with longitudinal weld attachment strengthened by ultra-high modulus carbon fibre reinforced polymer plate," *Fatigue Fract. Eng. Mater. Struct.*, **36**(10), 1027–1038.
- Yu, Q.-Q., Chen, T., Gu, X. L., and Zhao, X.-L. (2016), "Boundary element analysis of edge cracked steel plates strengthened by CFRP laminates," *Thin-Walled Struct.*, **100**, 147–157.
- Yu, Q.-Q., Chen, T., Gu, X.-L., and Zhang, N.-X. (2015), "Fatigue Behaviour of CFRP Strengthened Out-of-Plane Gusset Welded Joints with Double Cracks." *Polymers*, **7**(9), 1617–1637.
- Zhao, X.-L. (2013), *FRP-strengthened metallic structures*, CRC Press.
- Zhao, X.-L., and Zhang, L. (2007), "State-of-the-art review on FRP strengthened steel structures," *Eng. Struct.*, **29**(8), 1808–1823.