IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

FINITE ELEMENT ANAYSIS OF CRACKED STEEL WELDED JOINTS RETROFITTED WITH FRP

Elyamani A. Arabi*[1], Tamer H. Sayed[2], Sahour N. Sayed[3], Nahla K. Hassan[2] & Kamal G. Sharobim[1]
[1]Department of Structural Engineering, Suez Canal University, Egypt
[2] Department of Structural Engineering, Ain Shams University, Egypt
[3]Mechanical Design and Production Department, Cairo University, Egypt

DOI: 10.5281/zenodo.1199279

ABSTRACT

The fatigue performance of welded steel connections has been generally enhanced by adhesively FRP materials patching. In this study, load-carrying cruciform welded joints with adhesively bonded FRP materials were investigated regarding the fatigue performance. Full penetration weld was proposed as the type of welding. The (2-D) finite element method (FEM) was utilized and modeled for two cases. The first Case during the preliminary analysis to evaluate the effect of using only FRP materials on SIF (K_I), while the second case was to study the effect of FRP materials fixed with head plate and bolts on SIF (K_I). Stress intensity factors of mode I (K_I) were calculated for unrepaired and repaired specimens with various FRP materials by J-integral approach. In addition, FEA results of the unrepaired cruciform joint were verified with an analytical results approach. The reduction of stress intensity factors with FRP patches fixed with head plate and bolts were clarified. Parametric studies were conducted by linear elastic finite element analysis using Ansys software. The different parameters considered in this study are, FRP patch layers, Young's modulus of adhesives, Young's modulus of FRP materials, and initial crack length. Results are shown graphically for these parameters and stress intensity factor.

Keywords: Stress Intensity Factor (SIF), FEM, FRP materials, Repair, LEFM, Weld toe crack.

I. INTRODUCTION

Fatigue damage of existing metallic structures is a specific case of deterioration and occurs when the structure is subjected to cyclic loading during service life.

With welded joints, stress concentrations occur at the weld toe and at the weld root, which make these regions starting points from which fatigue cracks may initiate[1], [2] . Shen and Clayton [3] stated that all the cracks initiated at the weld end toe, where the maximum stress concentration occur. Several researches assumed & considered toe cracks because it is easier to observe with the naked eye as well as with dye penetration tests, they are often found in many important engineering welded structures. Moreover, there is a high stress concentration located at these points [4].

Many strengthening methods of metallic structures have been proposed to prolong fatigue life. In recent years, repair by adhesively bonded fiber reinforced polymer (FRP) materials for steel structures has shown as a promising retrofitting method. This method has also been used for steel or aluminum structures[5] . In recent years, Chen T et al. [2] conducted fatigue tests on cruciform welded joints; and the local stress approach was used to assess the fatigue improvement of strengthening with CFRP sheets. Exploratory experimental results have shown that a composite patch can also delay crack growth propagation and extend the life of welded joints

In this work the SIFs of cracked load-carrying cruciform welded joints failing from weld toe and bonded with FRP materials have been calculated using a two-dimensional finite element analysis (FEA). The effects of different parameters on stress intensity factor value at the crack tip were studied. In addition, FEA results of the unrepaired cruciform joint were verified with analytical results approach.

II. DETERMINATION OF THE SIF OF CRUCIFORM WELDED JOINTS USING ANALYTICAL METHOD

The geometry configuration of the load-carrying cruciform welded joint considered in this study is made of steel head plate (stiffener plate) which is welded to attach main plates (loading plate) at both sides as shown in Figure 1.

Analytical formulae of the stress intensity factor (SIF) for an elliptical crack at weld toe of cruciform joint K-butt weld, according to Maddox SJ [8], is expressed as:

$$\Delta K = \frac{M_k Y_u}{\emptyset_0} \Delta\sigma\sqrt{a} \qquad (1)$$

where Mk is the stress concentration magnification factor, ΔK is the SIF, Δσ is the nominal tensile stress range applied on the main plate and a, is the crack depth [9]. Ø0 is the complete elliptical integral which is defined as:

$$\emptyset_0 = \int_0^{\frac{\pi}{2}} [1 - (1 - \frac{a^2}{c^2}) \sin \emptyset]^{\frac{1}{2}} d\emptyset \qquad (2)$$

where φ is the parametric angle of ellipse and c is half of the crack length of the semi-elliptical weld toe crack.

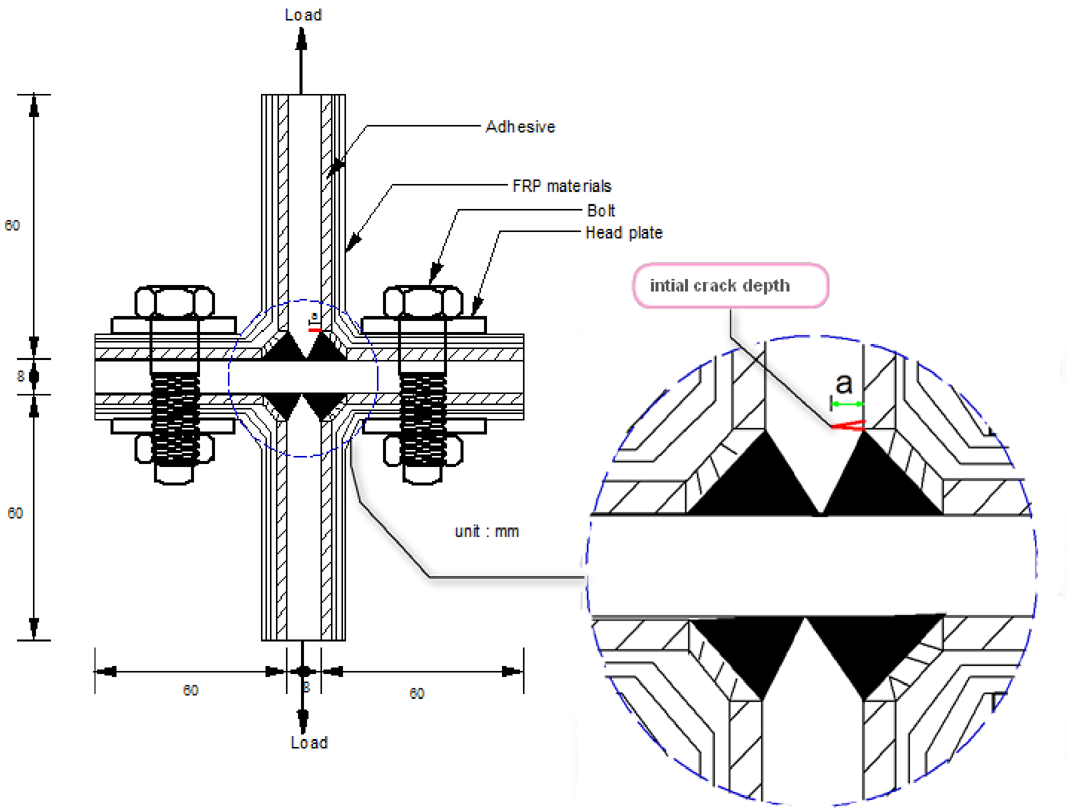

Figure 1: Load-carrying cruciform joint with a crack at weld toe

In this study the M_k-factor functions are based on continuous edge cracks, hence, the crack aspect ratio is zero, a /2c = 0, and Ø0 = 1. The correction term Yu for a single-edge crack in a plate under tensile loading, Eq. (3), given by Brown and Srawley [10] is applied:

Yu=1.99-0.41(aT)+18.7(aT)2-38.48(aT)3+53.85(aT)4 (3)

Where T is the main plate thickness. The expression formulae from International Institute of Welding (IIW) has been employed, where the factor Mk values for different welded joint has been introduced by IIW [11]. The formulas for load-carrying cruciform K-butt welded joints are presented as follows:

$$M_k = C.\left(\frac{a}{T}\right)^k \qquad M_k \leq 1 \tag{4}$$

$$C = 0.7061 - 0.4091\left(\frac{H}{T}\right) + 0.1596\left(\frac{H}{T}\right)^2 + 0.3739\left(\frac{W}{T}\right) - 0.1329\left(\frac{W}{T}\right)^2 \tag{5}$$

$$k = - 0.2434 - 0.3939\left(\frac{H}{T}\right) + 0.1536\left(\frac{H}{T}\right)^2 + 0.3004\left(\frac{W}{T}\right) - 0.0995\left(\frac{W}{T}\right)^2 \tag{6}$$

Where:
W ≡ is the weld leg length on the main plate
H ≡ is the weld leg length on the head plate, respectively,
T ≡ is the main plate thickness and a is the initial crack length from the weld toe.
By substituting Eq. 4 and Eq. 3 in Eq. 1, SIFs can be calculated for cruciform joints with weld toe failure. Aforementioned equations are only applicable to welded joints without FRP as repair material. The analytical equations for retrofitting of cruciform joints are not available yet. Subsequently, finite element analysis (FEA) is presented to obtain SIFs of cruciform welded joint patched with FRP materials in the following sections. Taking into consideration the different parameters as mentioned before.

III. FINITE ELEMENT ANALYSIS

Due to cost and time-consuming of fatigue tests, theoretical analysis is considered an efficient way to assess fatigue life improvement with regard to repair effects. The commercial finite element package ANSYS APDL 14.5 is used for linear elastic finite element analysis of cruciform welded joint in this study.

Geometry and Material Properties

The basic geometry of the cruciform welded joint considered in this study is shown in Figure 1. A steel head plate (stiffener plate) is welded with horizontal plates (loading plates) at both sides. The thickness of Horizontal plate and head plate, are 8 mm, 5mm, respectively. Dimensions of head plate is 40*40mm. Dimeter of the bolt is 10mm. The weld leg length, 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 is supposed to exist at the weld toe.

The steel specimen's surfaces are adhesively bonded with GFRP sheets as first layer & other four layers were bonded with CFRP sheets. The adhesive thickness is 0.55 mm that was measured by Chen T et al. [2], and the thickness of the CFRP sheets is 0.167 mm. The Young's modulus of the steel is $2.04*10^5$ MPa, and Poisson's ratio is assumed to be 0.3. Th moduli are $76*10^3$ MPa and 4600 MPa for the GFRP and adhesive, respectively. Also $2.5*10^5$ MPa and 3000 MPa for the CFRP and adhesive, respectively. The Poisson's ratio was also assumed to be 0.3 for the CFRP and adhesive.

Mesh Description and Boundary Conditions

The cruciform welded joint together with the adhesive and FRP materials (GFRP + CFRP sheets) are simplified to a half 2D model, due to symmetric conditions. The FE model was meshed with PLANE183 which a higher order 2-D, 8-node or 6-node element is and having two degrees of freedom at each node. A symmetric boundary condition was defined for all nodes at the left end, which is the mid-thickness of head plate, therefore, the translation degrees of freedom in X-direction (Ux) is restrained. To provide system stability in vertical direction or Y-direction, the lowest node in the symmetric line nodes is restrained in Y-direction (Uy). A uniform load of 100 MPa is applied to the FE model at the horizontal end of the steel plate. Uniform pressure was directly achieved on the line, which is the end of the main plate. The uniform stress of 100 MPa is transferred to the elements and then to the nodes. The boundary conditions of cruciform joint are shown in Figure 2.

The values of stress intensity factor (SIF), is calculated by the J-integral method which can be fulfilled with finite element (FE) analysis [12] according to the defined crack-tip node component and the crack-plane normal for toe crack.

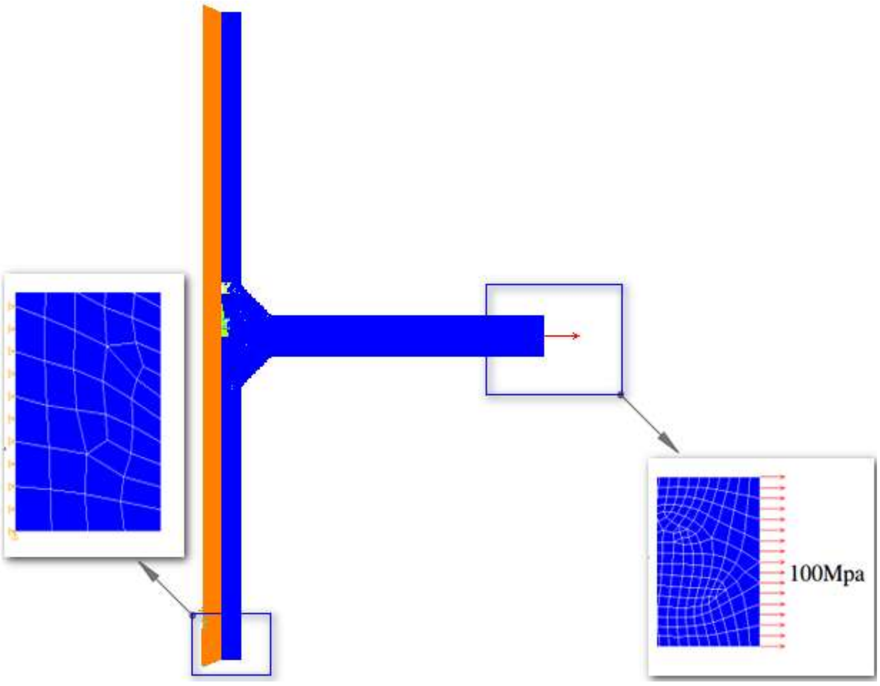

Figure 2: Mesh configuration and boundary conditions for toe crack

IV. STRESS INTENSITY FACTOR CALCULATION USING FEA

The FE Ansys program is used to calculate the opening mode SIF using fracture mechanics approach. The influence of stress intensity factor (K_I) on fatigue crack growth is based on the maximum tangential stress criterion by Erdogan and Sih [13]. This criterion assumes that the predicted propagation path of the fatigue crack is perpendicular to the maximum principal stress and the crack grows under opening mode.

The stress intensity factors for unrepaired welded joint under 100 MPa stress range are determined numerically as given in Figure 3. The numerical results of stress intensity factor (SIF) using the J- integral approach are compared with the analytical formulas results as presented in the previous section. It can be noted that the numerical results are in good agreement with analytical results.

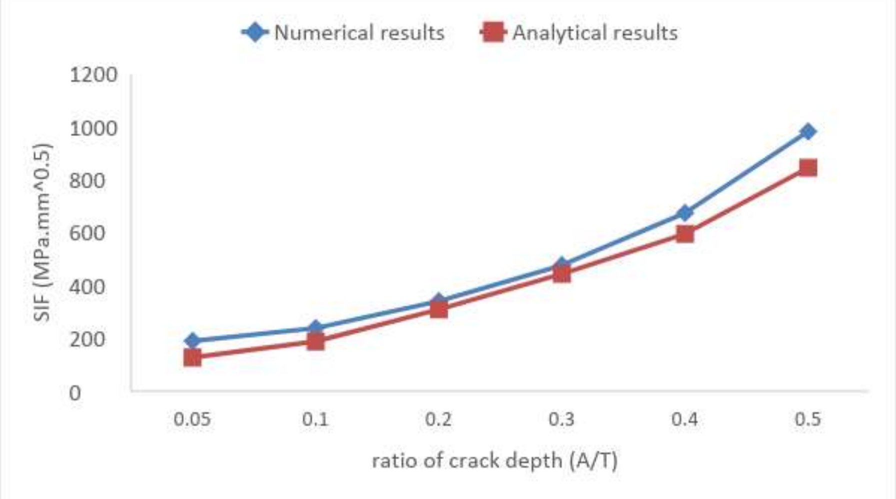

Figure 3: Comparison of theoretical and finite element results of SIFs

V. RESULTS AND DISCUSSION OF FINITE ELEMENT PARAMETRIC STUDY

In this section, the effect of different parameters on stress intensity factor value at crack tip is presented. These parameters are: number of FRP layers, Young's modulus of adhesives, Young's modulus of carbon fibers, thickness of adhesives and initial crack length.

1. Effect of the FRP Materials on stress intensity factor

The effect of FRP layers on stress intensity factor at various crack depth is illustrated in Figure 4. In general, the stress intensity factor (SIF) is reduced as the number of FRP layers increase.

When the crack propagates at weld toe, the reduction of SIF is more clarified after adding one layer of GFRP for deep initial crack depth (a/T = 0.5), while a small reduction is shown for small initial crack depth (a/T = 0.05). When the initial crack length was (5%) the plate thickness, SIF decreases from 189.4MPa mm$^{1/2}$ (unpatched) to 152.7MPa mm$^{1/2}$ after adding five layers of CFRP, while for initial crack length (50%) of plate thickness, SIF (KI) is reduced from 980.7 MPa mm$^{1/2}$ (unpatched) to 634.2 after adding one layer of GFRP and reduced to 411.6 MPa mm$^{1/2}$ after adding five layers of CFRP.

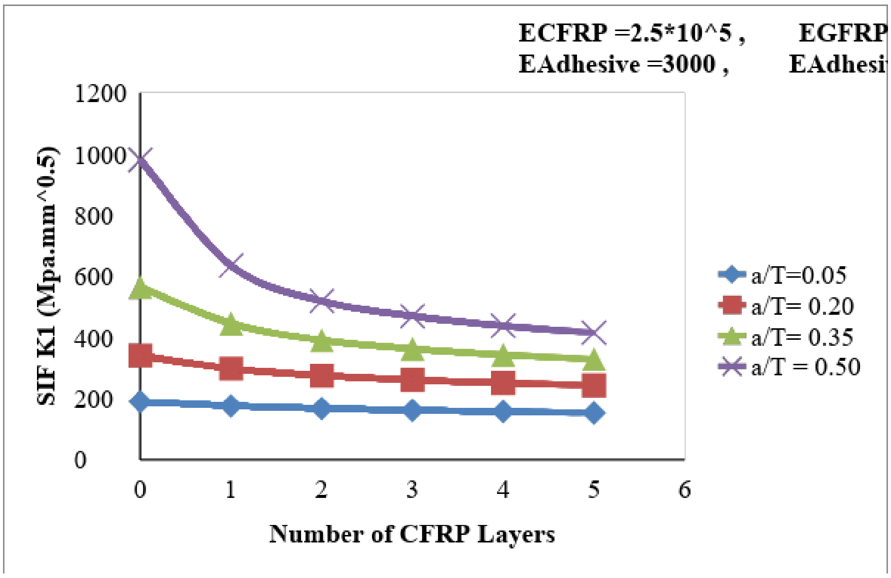

Figure 4: Relation between SIF with respect to the number of GFRP & CFRP layers

2. Effect of the Initial Crack Length on SIF(K1) for Various Number GFRP & CFRP Layers.

Figure 5 shows the relation between SIF(K1) at different crack depth for a number of FRP layers. It is known that SIF increases with propagation of the crack and is significantly reduced with the FRP materials retrofit. SIF(K1) were 189.4 MPa mm$^{1/2}$ for (a = 0.4mm), 564.2 MPa mm$^{1/2}$ for (a = 2.8 mm) and 980.7 MPa mm$^{1/2}$ for crack depth reached half the plate thickness (a = 4 mm) for unrepaired specimens. However, the SIF(K1) changed from 152.7 MPa mm$^{1/2}$ (a = 0.4mm), to 326.6 MPa mm$^{1/2}$ (a = 2.8mm) or 411.6 MPa mm$^{1/2}$ (a = 4mm) for specimens patched with five layers of FRP.

Figure 6 represents the SIF ratio, R, between specimens repaired with FRP and un repaired steel specimens. When specimens were retrofit with one layer of GFRP, the ratio decreased from about 0.93 to 0.65 (a decrease of about 30%) when the initial crack depth increased from five percent to half of the plate thickness. When it arrives to the specimens retrofit with five layers of CFRP, the ratio R decreased from about 0.8 to 0.42 (a decrease of about 47.5%) when the initial crack depth increased from five percent to half of the plate thickness.

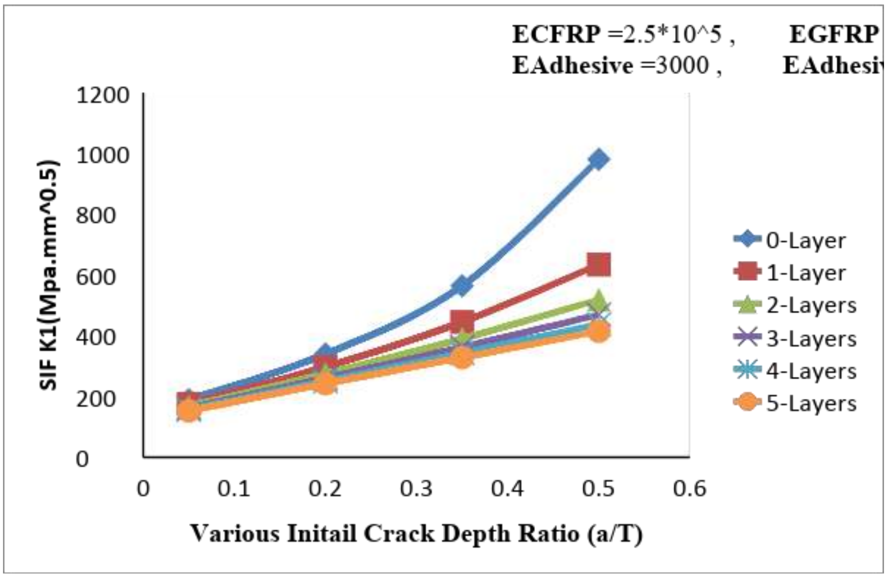

Figure 5: Relation of SIF (KI) with respect to the initial crack depth

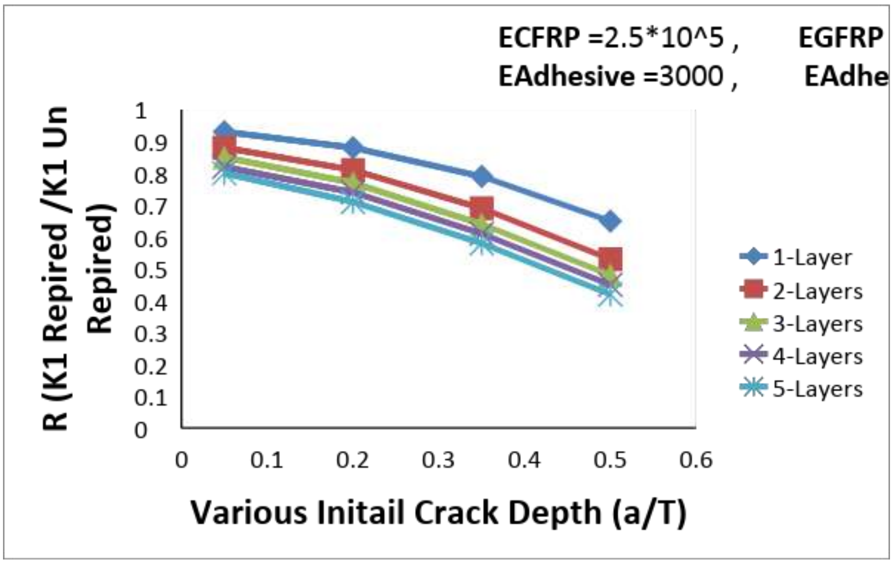

Figure 6: Relation between reduction of SIF (K1) with at different Crack depth ratios (a/T)

3. Effect of Adhesive young modulus on SIF(K1) for Various Initial Crack Lengths

Figure 7 shows the relation between SIF (K1) obtained by finite element analysis and Adhesive modulus for various values of initial crack depth(a/T) for weld toe crack. The relation is conducted using three layers, first layer of GFRP and other two layers of CFRP sheets and constant values of E_{CFRP} = 2.5x105 MPa, E_{GFRP} = 76*10^3 MPa, and $E_{Adhesive}$ = 4600MPa of GFRP sheets. To evaluate the effect of the adhesive young modulus on SIF, models patched by one layer of GFRP and other four layers of CFRP sheets were analyzed with different moduli of adhesive, having value of 1500MPa, 3000MPa, 4500MPa, 6000MPa and 7500MPa. The results show that K_1 at the crack tip was considerably reduced by a high adhesive modulus. This reduction is clear in deeper crack length (a/T=0.5) than in smaller one. When the adhesive modulus increased from 1500MPa to 7500MPa, K_1 is reduced from 499.7MPa mm$^{1/2}$ to 433.7MPa mm$^{1/2}$ with reduction value of 14% for deeper crack length (a/T = 0.5). While K_1 decreased from 168.7 MPa mm$^{1/2}$ to 157.7MPa mm$^{1/2}$ for small crack length (a/T = 0.05) with reduction value of 7 %.

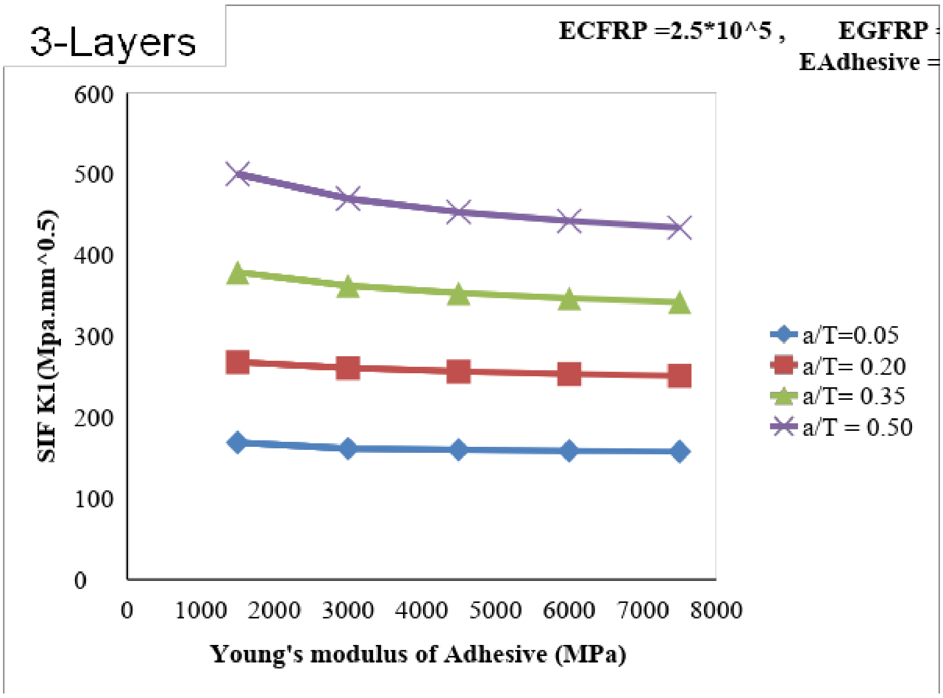

Figure 7: Relation of SIF with respect to the adhesive young modulus of (3-layers).

4. Effect of CFRP young modulus on SIF(KI) for Various Initial Crack Lengths

Figure 8 shows the reduction (R) performed for SIF at different Crack depth ratio for various CFRP Young's modulus (E_{CFRP}). The SIF (KI) was determined by numerical analysis in order to estimate the effect of the CFRP modulus. The specimens were strengthened with three layers of CFRP to estimate the effect of CFRP modulus on SIF (K1). All other parameters were taken constants. Values of $E_{Adhesive}$ = 3000 MPa, E_{GFRP} = 76*10^3MPa and $E_{Adhesive}$ = 4600MPa except for the CFRP modulus, which were taken as 1.0*10^5 N/mm^2, 2.5*105 N/mm^2, 4.0 *10^5 N/mm2, and 5.5*10^5 N/mm^2, respectively. In general, the results show a high value of CFRP moduli resulted in small SIF(K1). SIF reduced from 272.8MPa mm$^{1/2}$ to 246.9 MPa mm$^{1/2}$ (decrease about 10%) when E_{CFRP} increases from 1.0x105 MPa to 5.5 x105 MPa for crack length 0.2 the plate thickness. While it is reduced from 512.8 MPa mm$^{1/2}$ to 429.5MPa mm$^{1/2}$ (decrease about 17%) when is E_{CFRP} is increased by same values for deeper crack length (a/T= 0.5) of the plate thickness.

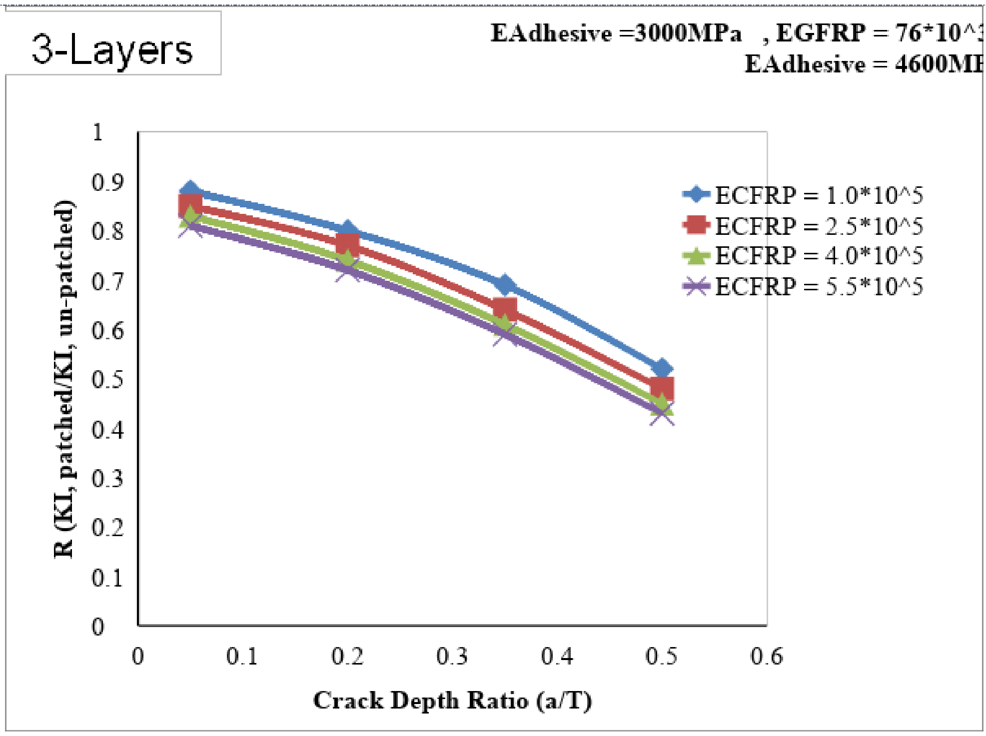

Figure 8: Effect of the CFRP moduli on reduction of SIF (K1) at different Crack depths ratio

VI. CONCLUSION

Two cases of finite element modelling were achieved. The first case is the load carrying cruciform welded joints only patched with of FRP materials. While the second case, FRP material fixed with head plate & bolts in same joint were assessed and carried out. The influence of head plate and bolts on crack propagation had shown a little effect in comparison with using only FRP materials. The effect of Stress intensity factors (SIF) of mode I (K1) at crack tip was calculated using the finite element method by J-integral approach for the two cases. To demonstrate the efficiency of these calculations, cruciform welded joint was investigated and developed numerically & analytically. The results of analytical method and FEM showed good correlation, although some deviations existed with small and large crack depth. The reductions in the stress intensity factor (SIF) were obvious for the two cases. Parametric studies were conducted with the finite element linear elastic analysis using Ansys software. These parameters are the FRP patch layers, Young's modulus of adhesives, Young's modulus of carbon fibers and initial crack length. Results are shown graphically for these parameters and (KI).

The following conclusions can be made:

- The FRP patch layers, had a direct effect on the decreases SIF(KI), the reduction of SIF ranged between (16 - 45) %.
- Using first layer of GFRP to five layers of CFRP the reduction effect of SIF(K1) became more significant with increased initial crack depth.
- The effect of adhesive modulus was insignificant, the reduction reached 7% for small crack depth, while reached 14% for deeper crack length.
- A higher GFRP or CFRP modulus resulted in more reduction in SIF(K1), this reduction in SIF ranged between (10-17) %.

VII. ACKNOWLEDGEMENTS

The authors would like to thank Dr. Chahinaz Saleh (The supervisor of lab Mechanical Design and Production Department, Faculty of Engineering, Cairo University) for fatigue test of specimens.

VIII. REFERENCES

[1] A. K. Motarjemi, A. H. Kokabi, A. A. Ziaie, S. Manteghi, and F. M. Burdekin, “Comparison of the stress intensity factor of T and cruciform welded joints with different main and attachment plate thickness,” Eng. Fract. Mech., vol. 65, no. 1, pp. 55–66, Jan. 2000.

[2] T. Chen, Q.-Q. Yu, X.-L. Gu, and X.-L. Zhao, “Study on fatigue behavior of strengthened non-load-carrying cruciform welded joints using carbon fiber sheets,” Int. J. Struct. Stab. Dyn., vol. 12, no. 01, pp. 179–194, Jan. 2012.

[3] W. Y. Shen and P. Clayton, “Fatigue of fillet welded A515 steel,” Eng. Fract. Mech., vol. 53, no. 6, pp. 1007–1016, Apr. 1996.

[4] N. Karlsson and P.-H. Lenander, “Analysis of fatigue life in two weld class systems,” Div. Solid Mech. Linköping Univ., p. 296, 2005.

[5] S. S. J. Moy, FRP Composites: Life Extension and Strengthening of Metallic Structures. Thomas Telford, 2001.

[6] Z.-G. Xiao and X.-L. Zhao, “Cfrp repaired welded thin-walled cross-beam connections subject to in-plane fatigue loading,” Int. J. Struct. Stab. Dyn., vol. 12, no. 01, pp. 195–211, Jan. 2012.

[7] Y. Fouad, N. K. Hassan, and T. H. Sayed, “Fatigue Life of Cruciform Welded Joint Strengthened with CFRP.” Unpublished, 2016.

[8] S. J. Maddox, “An analysis of fatigue cracks in fillet welded joints,” Int. J. Fract., vol. 11, no. 2, pp. 221–243, Apr. 1975.

[9] T. Nykänen, G. Marquis, and T. Björk, “Fatigue analysis of non-load-carrying fillet welded cruciform joints,” Eng. Fract. Mech., vol. 74, no. 3, pp. 399–415, Feb. 2007.

[10] W. Brown and J. Srawley, “Plane Strain Crack Toughness Testing of High Strength Metallic Materials,” Jan. 1966.

[11] A. Hobbacher, Recommendations for Fatigue Design of Welded Joints and Components. Springer, 2015.

[12] T. L. Anderson and T. L. Anderson, Fracture Mechanics: Fundamentals and Applications, Third Edition. CRC Press, 2005.

[13] F. Erdogan and G. C. Sih, “On the Crack Extension in Plates Under Plane Loading and Transverse Shear,” J. Basic Eng., vol. 85, no. 4, p. 519, 1963.

CITE AN ARTICLE

Arabi, F. A., Sayed, T. H., Sayed, S. N., Hassan, N. K., & Sharobim, K. G. (n.d.). FINITE ELEMENT ANAYSIS OF CRACKED STEEL WELDED JOINTS RETROFITTED WITH FRP. *INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY*, *7*(3), 398-406.