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Finite Element Study of Cracked Steel Circular Tube Repaired By FRP Patching

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Abstract

As the development and application of fiber reinforced polymer (FRP) composite materials to different engineering structures are increasing gradually, composite fiber patching techniques are being considered as alternatives to traditional methods of strengthening and fatigue crack repair in steel structures, such as the boom members of draglines. In general, the dragline boom members are in the form of circular tube type structure, therefore, application of FRP patching is usually bonded on one side (the outside surface) of the tube structure. In order to examine the efficiency of the repair by single-side patching of FRP material to tube structures, finite element study of cracked steel tube structure is conducted. The objectives of the finite element study are (1) to study the reduction of stress intensity factor (SIF) of cracked steel tube member repaired with FRP patching and (2) to predict the fatigue life of welded steel tube member repaired with FRP patching. The cracked steel circular tube was modeled by using 3-D brick elements and the adhesive and FRP patching were modeled by using shell elements. The adherend stiffness ratio ($E_{frp} t_{frp} / E_s t_s$) of this study is about 0.34. Comparison of the SIF of cracked steel circular tube with and without FRP patching showed that the SIF was reduced significantly for models with FRP patching and the reduction was more than 50%. Prediction of the fatigue life of cracked circular tube member with and without FRP patching was carried out by means of the Paris equation. Due to the significant reduction of SIF for members with FRP patching, it is shown that the corresponding predicted fatigue life is increased significantly as well. In particular, the increase of fatigue life is about 22 times for model with CFRP sheet patching when the circumference half crack length grows from 25.4 mm (1 inch) to 63.5 mm (2.5 inch).

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1. Introduction

A host of some of the largest surface mining equipment in the world is used in oil sand mining operation in Northern Alberta, Canada. Production at the Syncrude mining site in Fort McMurray, Alberta is reliant on the operational reliability of heavy equipment. One of the heavy equipment used in the site is the draglines (Figure 1). Due to the increased loading on these structures and a harsh environment, cracking of boom members has become a major problem. Traditionally, repair of the crack is done by re-welding the cracked section, however, in most instances; fatigue cracks reappear in the weld fill areas. As the application of FRP material to strengthen and repair of structures becoming more popular nowadays, FRP patching is considered as one of the possible alternative repair procedures for repairing the cracked steel members (Kennedy and Cheng 1998). In order to examine the efficiency of the repair by patching of FRP material to tube structures, a finite element study of cracked steel tube structures was conducted and presented. The objectives of the study are (1) to examine the reduction of stress intensity factor (SIF) of cracked steel tube structures repaired with FRP patching using finite element analysis and (2) to determine the fatigue life of welded steel tube members analytically based on the finite element results.

2. Finite Element Model Of Cracked Circular Tube Structure

A cracked circular tube was modeled by means of finite element method. The total length of the steel tube is 4000 mm with a circumferential through-wall crack located at the mid-span on only one side of the tube. The outside diameter (D) of the steel tube is 400 mm and the thickness (t) of the tube was 9.5 mm. As a result, the thickness to outside diameter ratio (t/D) for the circular tube is 0.024. It was assumed that repair of the cracked tube was made when the half circumferential through-wall crack length was 25.4 mm and the prediction of the fatigue life was terminated when the final half circumferential through-wall crack length was 63.5 mm. The cross section dimension and the illustration of the circumferential through-wall crack are shown in Figure 2.

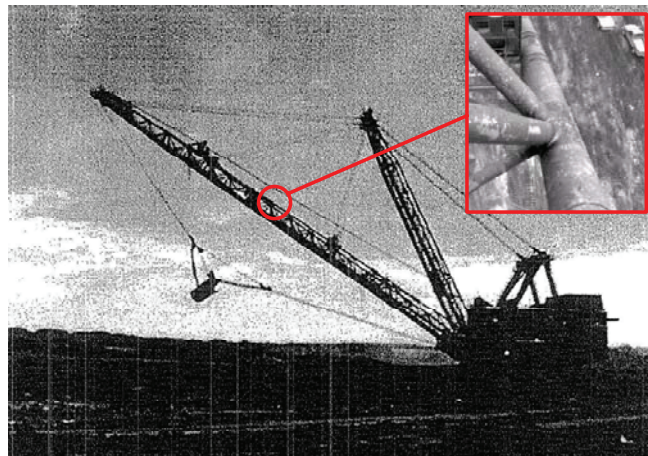


Figure 1 Cluster in dragline boom

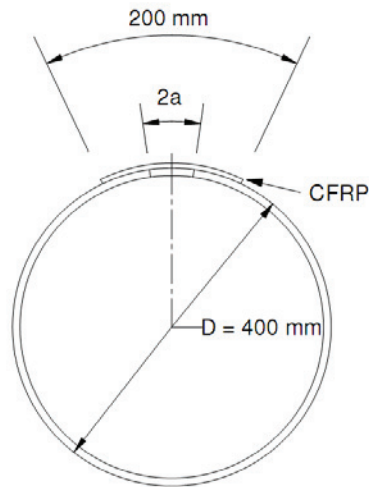


Figure 2 Section dimension of tube member

Due to symmetry, only a quadrant of the steel tube was modeled. The modified three layers model technique which was proposed by Lam et al. (2008) was adopted for modeling the cracked steel circular tube with FRP patching. In the modified three layers model, the cracked steel tube was modeled by 3-D brick elements (C3D20 in ABAQUS 2004) and the adhesive and FRP patching were modeled by shell elements (S8R in ABAQUS 2004). At the location of crack tip, 3-D collapsed node elements were used and the stress intensity factor (SIF) around the crack tip was obtained using the contour integral method (Rice 1968). Typical finite element model of cracked steel tube is shown in Figure 3. Symmetrical boundary condition was assigned at the plane of symmetry along the longitudinal and circumferential direction and a uniform axial stress of 100 MPa was assigned at the far end of the steel tube.

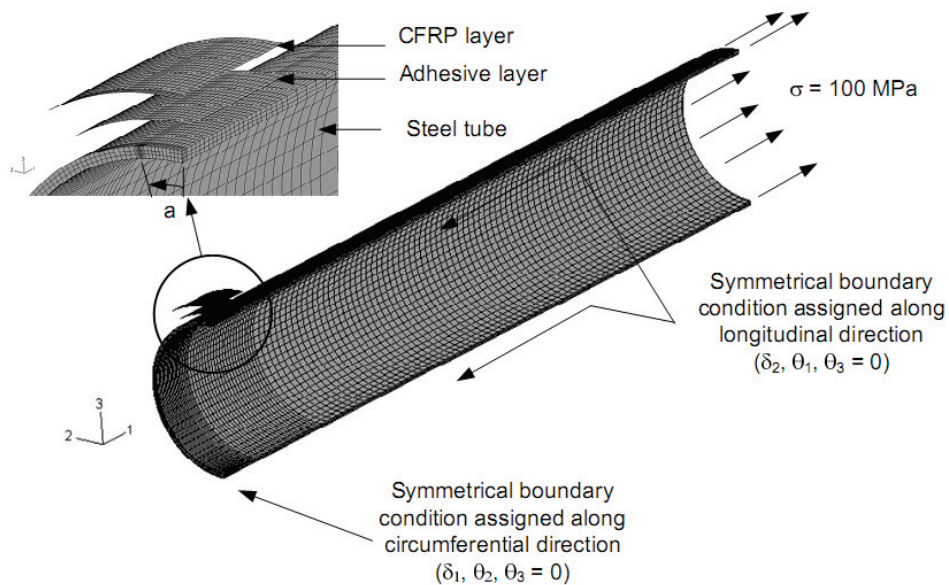


Figure 3 Typical finite element mesh of cracked steel circular tube member with FRP patching

Typical material properties for steel, adhesive and FRP patching as shown in Table 1 were assigned to the finite element models. The material properties of FRP were obtained from the study by Kenny and Cheng (1998) in which the material property of the carbon fiber composite (Mitsubishi Chemical Co. 1999) was tested. The average thickness of the CFRP sheet per ply after applied the matrix is about 0.23 mm. In the finite element model, the total thickness of 5.06 mm of CFRP was assigned. As a result, the axial stiffness ratio of the FRP to steel plate ($ETR = E_s t_s / E_{CFRP} t_{CFRP}$) is about 0.34. The thickness of adhesive used in the finite element model is 0.06 mm.

Table 1: Material properties of steel, adhesive and CFRP of tube model

Steel tube	Elastic modulus	$E_s =$	200,000 MPa
	Poisson's ratio	$\nu_s =$	0.3
CFRP sheet composite	Longitudinal elastic modulus	$E_{frp1} =$	128,000 MPa
	Transverse elastic modulus	$E_{frp2} =$	6,900 MPa
	Poisson's ratio	$\nu_{frp} =$	0.17
	Shear modulus	$G_{frp} =$	4,480 MPa
Adhesive for CFRP sheet	Elastic modulus	$E_a =$	3,000 MPa
	Poisson's ration	$\nu_a =$	0.34
	Shear modulus	$G_a =$	1,120 MPa

3. Finite Element Results of Cracked Circular Tube Structure With And Without Cfrp Patching

In order to verify the finite element results, the stress intensity factor (SIF) of cracked steel circular tube structure without FRP patching was compared with the prediction proposed by Lacire et al. (1999). For circular tube subjects to axial stress only, the normalized SIF is predicted by the following equation.

$$\frac{K_I}{\sigma_t} = F_t \sqrt{\pi R_m \theta} \quad (1)$$

where K_I is the SIF, σ_t is the axial far end stress, R_m is the mean radius of the tube, θ is half of the circumferential angle of crack and F_t is the geometrical factor which is related to the tube thickness (t), R_m and θ (Lacire et al. 1999).

By assigning four different circumferential half crack lengths (a) equal to 25.4 mm, 38.1 mm, 50.8 mm and 63.5 mm, finite element models of cracked steel circular tube with and without CFRP patching were formed and analyzed. Comparison of the finite element results of the normalized SIF and the prediction of Lacire et al. (1999) is shown in Figure 4. It is shown that the finite element results are generally in good agreement with the prediction of Lacire et al. (1999). Since the 3-D brick elements were used for modeling the cracked circular tube, variation of SIF across the thickness along the crack tip were obtained in the finite element analysis while the equations proposed by Lacire et al. (1999) does not reflect this variation. The normalized SIF value across the thickness of the tube with different circumferential half crack length is shown in the same figure for models with CFRP patching. It is shown that the normalized SIFs of the patched side of model with different crack lengths are all less than the value of the model without CFRP patching. Meanwhile, plot of normalized SIFs versus crack length for models with and without CFRP patching is shown in Figure 5. It is shown that significant reduction of the SIF is observed for models with CFRP patching and the maximum reduction is about 54%.

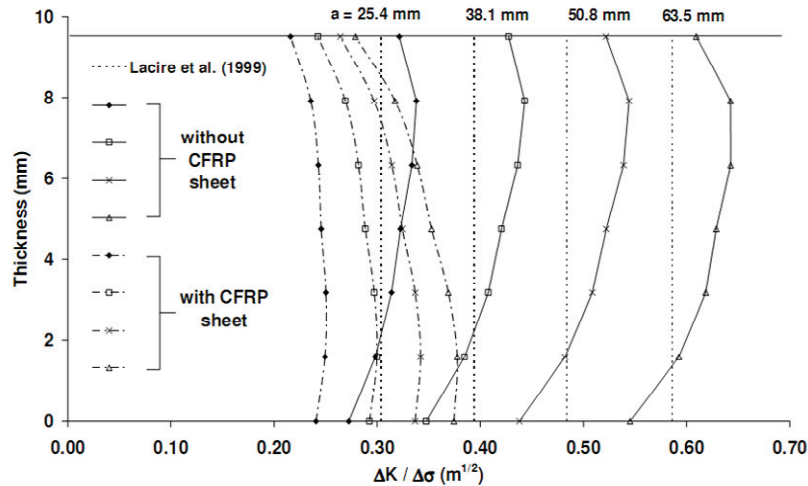


Figure 4: Comparison of FE results of normalized SIF of cracked steel circular tube with and without CFRP sheet patching for various circumferential half crack length

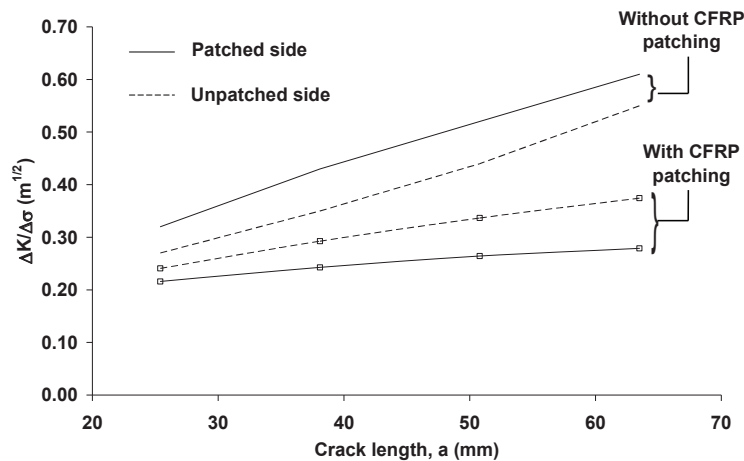


Figure 5: The normalized SIFs of cracked steel circular tube with and without CFRP patching versus half crack length

4 Fatigue Life Prediction Of Cracked Steel Tube Structure With Cfrp Patching

In order to examine the increase of fatigue life of welded steel circular tube member due to the application of CFRP patching, prediction of the fatigue life of welded steel circular tube member with and without CFRP patching was carried out. The Pairs equation (Pairs and Erdogan 1960) was used to predict the fatigue life and the general form of the equation is shown as follows:

$$N = \int_{a_i}^{a_f} \frac{1}{C(\Delta K_{eff})^m} da \quad (2)$$

where N is number of cycle, a_i is the initial crack length, a_f is the final crack length, C and m are the material constants of steel and K_{eff} is the effective stress intensity factor range. K_{eff} is used in Equation 2 instead of K in order to account for the effect due to crack closure behaviour which existed

in steel plates with crack on the weldment region (Elber 1971). The effective stress intensity factor range (ΔK_{eff}) for cracked tube without CFRP patching is predicted according to following equation:

$$\Delta K_{eff} = (\sigma_{max} - \sigma_{op}) F_t \sqrt{\pi R_m \theta} \quad (3)$$

where F_t is the geometrical factor (Lacire et al. 1999) and σ_{max} is the far end maximum stress and σ_{op} is the opening stress. Detail discussions about the prediction of the opening stress as a function of crack length and the original stress range can be found in Lam et al. (2008).

For cracked circular tube with CFRP patching, plot of the geometrical factors $F_{t,CFRP}$ is shown in Figure 6 and $F_{t,CFRP}$ was calculated based on the following equation:

$$F_{t,CFRP} = \frac{\Delta K}{\Delta \sigma \sqrt{\pi R_m \theta}} \quad (4)$$

where ΔK values were obtained based on the finite element results of the patched side of cracked steel circular tube with CFRP patching.

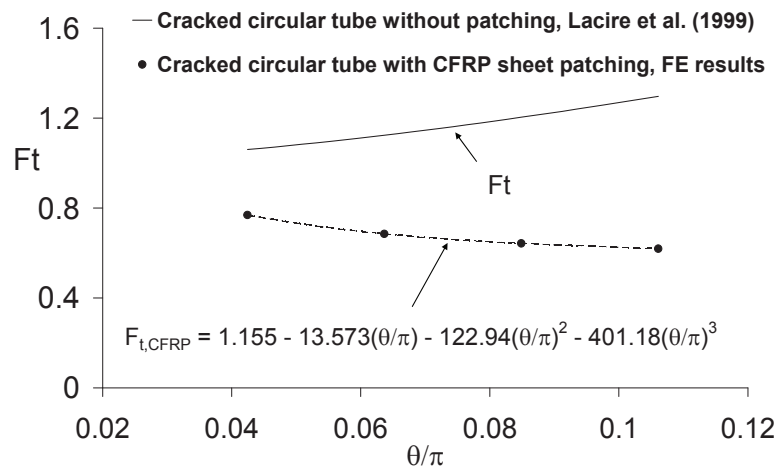


Figure 6 Geometrical factors of cracked steel circular tube with and without CFRP patching

Based on the finite element results, an equation of $F_{t,CFRP}$ to the third order with respect to θ/π is proposed as follows:

$$F_{t,CFRP} = 1.155 - 13.573 \left(\frac{\theta}{\pi} \right) - 122.94 \left(\frac{\theta}{\pi} \right)^2 - 401.18 \left(\frac{\theta}{\pi} \right)^3 \quad (5)$$

By modifying the opening stress and the geometry factor of Equation 3, the corresponding effective stress intensity factor range ($\Delta K_{CFRP,eff}$) for cracked circular tube with CFRP patching is proposed as follows:

$$\Delta K_{CFRP,eff} = (\sigma_{\max} - \sigma_{op}^p) F_{t,CFRP} \sqrt{\pi R_m \theta} \quad (6)$$

where σ_{op}^p is the opening stress for plate with CFRP patching. For member with FRP patching, as part of the loading is shared by the FRP patching, the far end stress which is needed to cause the crack to open should be larger. Therefore, the opening stress is modified according to the stiffness of patching and steel plate (Rose 1982). The modified equation of the opening stress for member with FRP patching is given as following.

$$\sigma_{op}^p = \left(\frac{E_s t_s + E_{frp} t_{frp}}{E_s t_s} \right) \sigma_{op} \quad (7)$$

In this study, the maximum stress was assigned as 283 MPa and it was according to the high stress range spectrum defined in the fatigue test program carried out by Roach and Rackow (2005). The initial and final half crack lengths were taken as 25.4 mm and 63.5 mm respectively and the C and m were taken as 8.88×10^{-12} m/cycle and 3.03 according to the material constant of G40.12 350WT steel (Yin et al 2006). The prediction of the fatigue life of cracked steel circular tube with and without CFRP patching is shown in Figure 7. It is shown from the figure that the numbers of cycles of loading of cracked steel circular tube without and with CFRP patching are 23262 and 503441, respectively. This numerical study showed that the number of cycles of loading is increased about 21.6 times for the cracked steel circular tube with CFRP sheet patching.

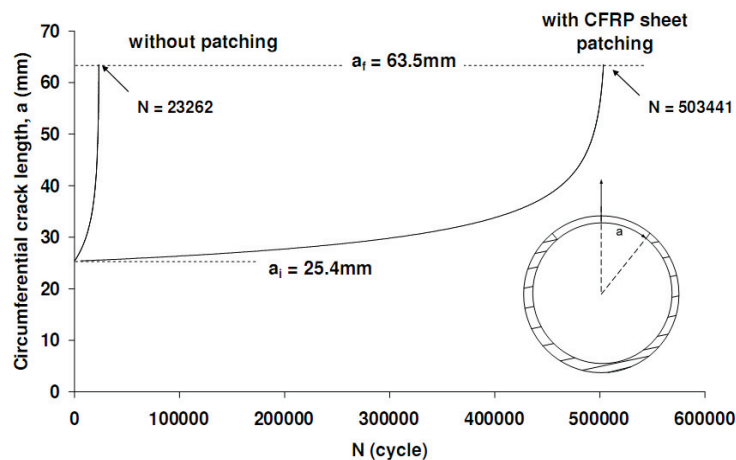


Figure 7 Comparison of fatigue life of cracked steel circular tube with and without CFRP patching

5. Summary And Conclusions

Finite element study of the reduction of SIF of cracked steel circular tube repaired with CFRP patching is presented. The cracked steel circular tube was modeled by using 3-D brick elements and the adhesive and CFRP patching were modeled by using shell elements. In order to verify the finite element results of cracked steel circular tube without CFRP patching, the SIF of models with half circumferential crack length equals to 25.4 mm, 38.1 mm, 50.8 mm and 63.5 mm were compared with the predictions proposed by Lacire et al. (1999). Then, SIF of models with CFRP patching was predicted by means of finite element method. Comparison of the SIF of cracked steel circular tube with and without CFRP

patching shows that the SIF is reduced significantly for model with CFRP patching and the maximum reduction is about 54%. Based on the finite element results of the SIF, fatigue life of the welded steel circular tubes with and without CFRP patching is predicted according to the Paris equation. Comparing to the model without CFRP patching, it is shown that the increase of number of cycles of loading is about 21.6 times for the model with CFRP patching when the circumference half crack length grows from 25.4 mm to 63.5 mm.

Acknowledgments

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