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Stress analysis of adhesive in a cracked steel plate repaired with CFRP

Yu Zhang *, Kai Zhang, Haikun Zhao, Jianhang Xin, Menglan Duan

Institute for Ocean Engineering, China University of Petroleum, Beijing, No.18 of Fuxue Road, Changping, Beijing 102249, China

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ABSTRACT

To repair a cracked steel-plate with carbon fiber reinforced polymer (CFRR) is an effective and simple method to strengthen a cracked region in a steel structure, which can improve security and extend steel structure's lifetime. As the repaired structure is subjected to tension loads, initial damage usually occurs in the adhesive. In this paper, the stress distributions of adhesive in a cracked steel plate repaired with CFRP were obtained based on a theoretical method and the finite element method (FEM) with different crack lengths. The maximum shear stress and peel stress in the adhesive were obtained from products of stress ratios and stresses for the case of a through-wall crack. As stress ratios could be approximated as a curve independent of material combinations, and stresses for a repaired steel plate with a through crack have explicit expressions, we could simply predict adhesive failure or the maximum load using quadratic stress criteria.

1. Introduction

Carbon fiber reinforced polymer (CFRP) patch-repair technology has been used to strengthen steel structures and repair the surface defects of aircraft. [1,2] This technology has also been used to repair the surface defects of petroleum pipelines and offshore platforms due to its many advantages, such as requiring no welding and allowing for quick repairs [3–7]. Compared with traditional repair technology like welding and bolt fastening, CFRP patch-repair technology does not destroy the destruction of original structure and stress concentration. CFRP repair also offers corrosion-resistance and better fatigue properties than other methods [8].

There are many rules regarding the repair of pipeline defects in the oil and gas industry, including ASME PCC-2-2015, DNV-RP-F113, and ISO 24817-2015 [9–11]. These rules offer material parameters for CFRP used to repair pipeline defects like cracks and corrosion, including formulas for the necessary thickness and length of the CFRP layer. However, the initiation and propagation of fatigue cracks often occur in the service period of offshore platforms and boats, and no guidelines or rules existed for their repair until recently [12].

Many researchers have studied the model of a cracked plate repaired by CFRP or composite patches. Tsouvalis and Mirisiotis [13] analyzed patch strain and crack propagation rates under cyclic loading, using experimental and FE models to study the repair of cracked steel-plate. Albedah and Khan [14] confirmed that composite patches increase the fatigue life of cracked structures, but the level of improvement depends strongly on the adhesive layer, and adhesives greatly decrease the fatigue life of repaired structures. Nateche and Meliani [15] created a procedure to determine a patch-repairing index to measure the residual harm of a crack-like defect after repair. Okafor and Singh [16] performed linear and nonlinear static finite element analysis (FEA) of bonded composite patch repair, and the results indicated that the region of maximum skin stress shifts from the crack front to the patch edges. Klug and Sun [17] used large deflection theory to study the effect of different variables, including thermal residual stresses and host and repair plate thickness, on the stress of a single-sided repair model. Naboulsi and Mall [18,19] introduced an analytical procedure to characterize the stress intensity factor (SIF) in a panel repaired with a bonded composite patch. Rezgani and Madani [20] proved that repair by patch composite increases the rigidity of the damaged structure and retards crack propagation. Ramji and Srilakshmi [21] used six 3D FEMs to obtain an optimum composite patch shape for application to an inclined cracked panel. Chung [22] used experimental and FEM models to study the optimal patch length, whose results indicated that performance is better when the patch length is 1.5 times the panel length. Osnes [23] used experimental and theoretical methods to predict the failure loads of adhesively bonded lap-shear joints.

The distribution of the interface stress in cracked steel-plate repaired with CFRP can be similarly analyzed by a model of a double- or single-bonded joint. Tsai [24] proposed theoretical solutions for adhesively bonded lap joints based on the assumption of linear shear stress distributions through the thickness of the adherends. Zhang [25] analyzed the stresses of an adhesive joint under tension when taking the thickness of the adhesive layer into account. Deng [26] analyzed the interface stress of a beam reinforced with CFRP, and two conditions were considered in the theoretical and numerical calculation. Miller et al. [27] performed experimental and analytical studies to quantify the force transfer between CFRP and a steel substrate. The results showed

* Corresponding author.
E-mail address: zhangyu@cup.edu.cn (Y. Zhang).

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Nomenclature

a	crack length
b	width of steel-plate
F	Longitudinal load
t_s	thickness of steel-plate
t_f	thickness of CFRP
t_a	thickness of adhesive
L_s	length of steel-plate
L_f	length of CFRP
L_a	length of adhesive
τ	shear stress
σ	peel stress
Ns, Nf	longitudinal tension of steel-plate and CFRP, respectively
Qs, Qf	shear force of steel-plate and CFRP, respectively
Ms, Mf	bending moment of steel-plate and CFRP, respectively
τ_s	shear stress at the steel-plate
τ_f	shear stress at the CFRP layer
u_f^T	longitudinal displacement functions for CFRP
u_s^T	longitudinal displacement functions for steel-plate
u_{1f}^T	displacement at the top surface of CFRP
u_{1s}^T	displacement at the surface of adhesion-steel
u_{2f}^T	displacement at the surface of adhesive-CFRP
σ_s	longitudinal stresses at the steel-plate and CFRP
σ_f	longitudinal stresses at CFRP
γ_a	adhesive shear strain
u_f	total displacements at the interfaces of adhesive-CFRP
u_s	total displacements at the interfaces of adhesive-steel
u_{2f}^M	displacements caused by moment at the surface of adhesive-CFRP
u_{1s}^M	displacements caused by moment at the surface of adhesive-steel
τ_{max}^b	maximum shear stresses obtained by the theoretical method
τ_{FE-max}^b	maximum shear stresses obtained by FE method
σ_{max}^b	maximum peel stresses obtained by the theoretical method
σ_{FE-max}^b	maximum peel stresses obtained by FE method

that approximately 98% of the total force transfer occurs within the first 100 mm from the end of the CFRP plate. M. Ramji et al. [28] used three approaches to investigate the mechanical behavior of a beam reinforced with CFRP. Their research showed that increasing the reinforcement length could increase the failure loads in the repaired model as the interfacial stress peak was reduced.

This paper analyzes the stress distribution of edge cracks in steel-plates repaired with CFRP (the cracked steel-plate in a platform can be seen in Fig. 1). The theoretical method and FEM analyses were used to calculate the stresses in the repaired model under some rational assumptions, with good consistency. The relationships of the maximum shear stress and peel stress with the crack length were obtained, and these can be used to predict the adhesive failure in the repair model based on quadratic stress criteria.

2. Theoretical analysis of a cracked steel-plate repaired by CFRP

The right of Fig. 1 shows a steel-plate in a platform with an edge crack. The CFRP repair model can be assumed to be shown in Fig. 2(a), the CFRP double-patch model of a steel plate with an edge crack, which consists of steel-plate, adhesive, and CFRP. The longitudinal tension force at the end of the steel-plate will partly be transferred from the adhesive layer to the CFRP layer.

In this paper, the limiting case when the crack runs through the steel-plate [as shown in Fig.2(b)] was studied first with the theoretical method. The following assumptions were made to simplify the stress analysis in the CFRP double-patch model: (1) The shear and peel stresses in the adhesive layer do not vary through the thickness of the adhesive layer as it is very small. The longitudinal tension of the adhesive layer is neglected. (2) The shear stress in the steel and CFRP layer varies linearly with thickness. (3) The displacement function at the steel-adhesive, and CFRP -adhesive interfaces is continuous. As the 3D model [Fig. 2(b)] was symmetric along the longitudinal direction, it was simplified to the 2D model shown in Fig. 3.

Fig. 4 shows an infinitesimal element of the 2D model. In the figure, τ and σ are respectively the shear stress and peel stress at the adhesion layer, and N, Q, and M are the longitudinal tension, shear force, and bending moment, respectively, at the CFRP and steel-plate.

Based on Fig. 4, the longitudinal, transverse, and moment equilibria can be respectively described as:

$$\frac{dN_s}{dx} - 2\tau b = 0 \qquad \frac{dN_f}{dx} + \tau b = 0 \tag{1}$$

$$dQ_s = 0 \qquad \frac{dQ_f}{dx} - \sigma b = 0 \tag{2}$$

$$\frac{dM_s}{dx} - Q_s = 0 \qquad \frac{dM_f}{dx} - Q_f + \tau b \frac{t_f}{2} = 0 \tag{3}$$

The longitudinal force equilibrium of the repaired model can be described as:

$$F = N_s + 2N_f \tag{4}$$

2.1. Shear stress distribution in the CFRP layer and steel-plate

Based on Fig. 5, the linear distribution of shear stress at the CFRP layer and steel-plate can be described by Eqs. (5a) and (5b). τ_s and τ_f are the shear stress at the steel-plate and CFRP layer, respectively. The shear stress in the free surface of the CFRP layer and the symmetry

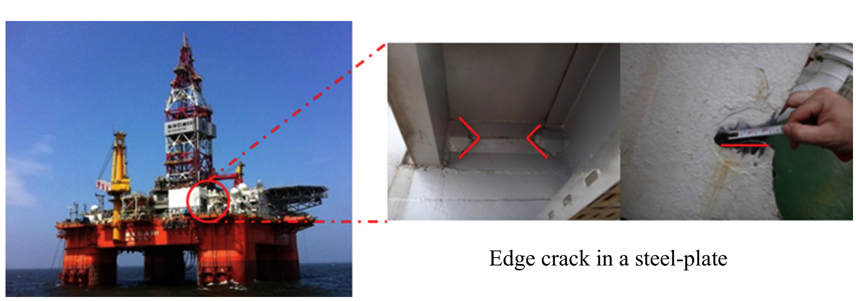

Fig. 1. Edge crack at an offshore platform.