ANALYTICAL STUDY ON PERMANENT REPAIR OF FATIGUE CRACKS OF WELDED GUSSET JOINTS BY EXTERNALLY BONDED CARBON FIBER SHEETS

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1. INTRODUCTION

Vacuum assisted Resin Transfer Molding (VaRTM) as a composite fabricating technique can be used to install multiple layers of carbon fiber (CF) sheets on steel structures at a time (Fig. 1). The repair work has been proven to be very efficient and convenient with multiple layers of CF sheets and complex shapes of structure as studied in Thay *et al.* (2018). This paper deals with the analytical study and design of the number of layers of CF sheets required for permanent repair of fatigue crack of typical welded gusset joints in steel bridges by externally bonded CF sheets using VaRTM technique.

2. SPECIMEN AND STUDY CONDITIONS

2.1 Specimens

Fig. 2 shows the geometry and dimensions of the target specimen of welded gusset joint. The out-of-plane gusset plates ($L200\times W100\times t9$ mm) are attached to the both sides of the steel plate ($L600\times W150\times t9$ mm) by fillet welded joints with the leg length of approximately 6 mm. The grip sections at both sides are designed with the width of 90 mm due to the limitation of fatigue testing machine. Radius of 185 mm are designed at the change of cross section. In order to control and initiate the fatigue crack from only one side, the bead shape is treated and improved by the pencil grinder at another side of weld bead.

2.2 Initial crack length and repair method

For repair method, first, the specimen is supposed to be subjected to fatigue test until crack propagate to a=20 mm from the center of gusset plate as an initial crack. This is to ensure that the crack is completely penetrated through one side to another side. Then the specimen is repaired by externally-boned four sets of CF sheets ($L530\times W50\times t_f$ mm) at the distance of 15 mm to 65 mm from the center of gusset plate.

2.3 Number of CF sheet layers and reduction factor

Fig. 3 shows relationship between number of CF sheet layers and reduction factor of base plate strengthened by CF sheets. The reduction factor ξ_0 is given by Eq. (1) below, where E_f, E_s are elastic modulus of CF sheet and steel, and A_f, A_s are cross section of CF sheet and steel.

$$\xi_0 = E_s A_s / (E_s A_s + 2E_f A_f) \tag{1}$$

From the figure, the reduction factor rapidly decreases at low number of CF sheet layers, while the trend changes at large number of CF sheet layers. Base on this result and the construction operation condition of VaRTM technique, the number of CF sheet layers are considered to be limited to approximately 50 layers.

2.4 Threshold stress intensity factor range at crack tips

In this study, the number of CF sheet layers required for permanent repair (no growth of crack) of fatigue crack is designed to be based on threshold stress intensity factor (SIF) range ΔK_{th} given by the following Eq. (2) (JSSC (1993)). In case of applied stress ratio R (=$\sigma_{min}/\sigma_{max}$) = 0.1, the value of threshold SIF range is ΔK_{th}=4.80 MPa.m$^{0.5}$.

$$\Delta K_{th}(R) = \max\{(\Delta K_{th} + 4.0)\cdot(0.9 - R), \Delta K_{th}\} \tag{2}$$

Table 1 summarizes the design conditions in calculation process of number of CF sheet layers required for permanent repair.

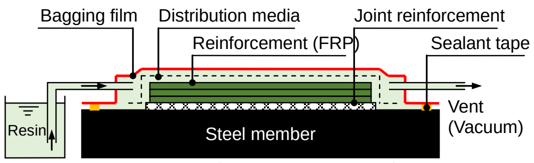
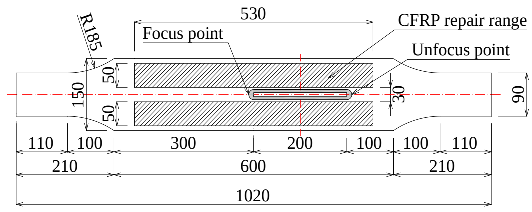
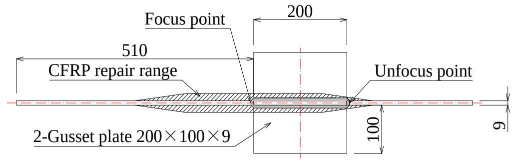


Fig. 1 Schematic view of VaRTM technique for repairing and strengthening



(a) Plan view



(b) Side view

Fig. 2 Target specimen

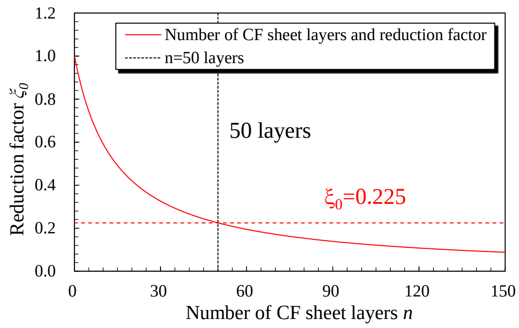


Fig. 3 Number of CF sheet layers and reduction factor

Table 1 Design conditions

Materials	Symbols	Units	Values	Notes
Initial crack half-length	a	mm	20	
Repair range	Δb	mm	50	15~65
Threshold SIF range	ΔK_{th}	MPa.m$^{0.5}$	4.80	
Nominal stress range	$\Delta\sigma_{sn}$	MPa	60~100	

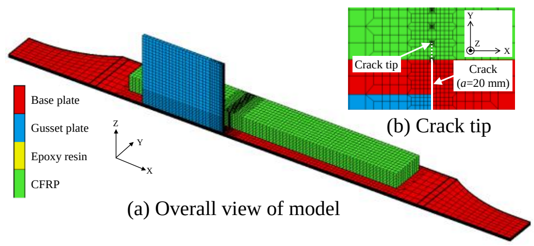


Fig. 4 Analytical model (repair with gusset plate)

Keywords: Permanent repair of fatigue crack, Welded gusset joint, Threshold SIF, CF sheet, VaRTM technique
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3. ANALYTICAL EVALUATION

3.1 Theoretical calculation

The SIF at crack tip is calculated using the following equation (Eq. (3)), where F_w and σ_{sR} is correction factor for SIF accounting for the effect of finite width and nominal stress at the nominal section of steel plate, given by Eq. (4) and (5), respectively (Liu *et al.* (2009)).

$$K_{sR} = F_w \sigma_{sR} \sqrt{\pi a} \tag{3}$$

$$F_w = (1 - 0.025\xi^2 + 0.06\xi^4)\sqrt{\sec(\pi\xi/2)}, \xi = 2a/b_s \tag{4}$$

$$\sigma_{sR} = \sigma_{sn} E_s t_s / (E_s t_s + 2E_f (b_f/(b_s - 2a)) t_f) \tag{5}$$

Here, b_s and b_f are width of steel plate and CF sheet, respectively.

3.2 Analytical method and model

The 3D finite element analysis (FEA) is conducted using MSC Marc 2018. Fig. 4 shows the analytical model of repair specimen. According to the symmetry, a quarter of specimen is modelled using solid element. The cracks are modelled using double nodes definition. The energy release rate is computed using the virtual crack closure technique (VCCT) and the stress intensity factor is calculated. Material properties of steel plate (SM400), CF sheet (CFRP) with high elastic modulus, and epoxy resin (Toray ACE AUP40) are descripted in Table 2. To verify the validity of analytical model, four kinds of models as follows: (a) non-repair model without gusset plate, (b) non-repair model with gusset plate (c) repair model without gusset plate and (d) repair model with gusset plate are considered. It should be noted that calculation of number of CF sheet layers is solely conducted in model (d).

3.3 Analytical results and discussions

Table 3 shows the comparison of analytical and theoretical value of SIF range in model (a) ~ (d). In non-repair model, SIF range is getting higher when gusset plate is considered. In repair model, although the same trend can be seen, the value tends to be smaller compare to theoretical value. This is due to the effect of adhesive considered in analytical model. However, the relative errors are below 10% in all case studies. Table 4 and Fig. 5 show the number of CF sheet layers required for permanent repair studied in analytical model (d) under applied nominal stress range of 60, 70, 80, 90 and 100 MPa. From the figure, linear relation between nominal stress range and number of CF sheet layers required for permanent repair can be verified. Under conditions studied in this paper, the number of CF sheet layers required for permanent repair can be obtained from linear equation (Eq. (6)). For reference, Eq. (7) is linear equation from theoretical calculation.

$$n_{ana} = 0.65\Delta\sigma_{sn} - 14.20, \quad R^2 = 0.9993 \tag{6}$$

$$n_{the} = 0.58\Delta\sigma_{sn} - 10.60, \quad R^2 = 1.0000 \tag{7}$$

3.4 Design of taper at CF sheet end

Reference to the evaluation studied in Thay *et al.* (2018), taper at CF sheet end with 51 layer of CF sheets is designed using theoretical calculation (JSCE ed. (2013)). The fixation length is 150 mm and taper length are limit to below 115 mm. Fig. 6 and 7 show the proposed design of taper at CF sheet end the analytical result of principal stress.

4. CONCLUSIONS

Based on the analytical study under condition above, number of layers of CF sheets required for permanent repair of fatigue crack of welded gusset joints are proposed and number of CF sheet layer is between 25 and 51 layers under applied nominal stress range of 60~100 MPa. Future work will deal with the fatigue test to verify and evaluate the durability of repair specimen using VaRTM technique.

Table 2 Material properties

Materials	Items	Symbols	Units	Values
Steel plate	Elastic modulus	E_s	MPa	205,000
	Width	b_s	mm	150
	Thickness	t_s	mm	9
CF sheet	Elastic modulus	E_{cf}	MPa	440,000
	Design thickness	t_{cf}	mm	0.217
	Volume fraction	v_f	%	50
CFRP	Elastic modulus	E_f	MPa	220,000
	Width	b_f	mm	50
	Thickness	t_f	mm	n×2×0.217
Epoxy resin	Elastic modulus	E_e	MPa	3,430
	Poisson's ratio	ν_e	–	0.39
	Thickness	t_e	mm	0.5

Table 3 Comparison of analytical and theoretical calculation

Analytical models (a=20 mm, n=51 layers, $\Delta\sigma_{sn}$=100 MPa)	Analytical SIF range ΔK_{ana} (MPa.m$^{0.5}$)	Theoretical SIF range ΔK_{the} (MPa.m$^{0.5}$)	Relative error (%)
Non-repair without gusset plate	26.48	26.19	1.11
Non-repair with gusset plate	28.47	26.19	8.02
Repair without gusset plate	4.22	4.52	7.02
Repair with gusset plate	4.76	4.52	5.03

Table 4 Number of CF sheet layers required for permanent repair in parameter of applied nominal stress range

Nominal stress range $\Delta\sigma_{sn}$ (MPa)	Analytical SIF range ΔK_{ana}(MPa.m$^{0.5}$)		Number of CF sheet layers n	Thickness of CFRP t_f (mm)
	Non-repair	Repair		
60	17.08	4.73	25	10.9
70	19.93	4.78	31	13.5
80	22.77	4.73	38	16.5
90	25.62	4.70	44	19.1
100	28.47	4.76	51	22.1

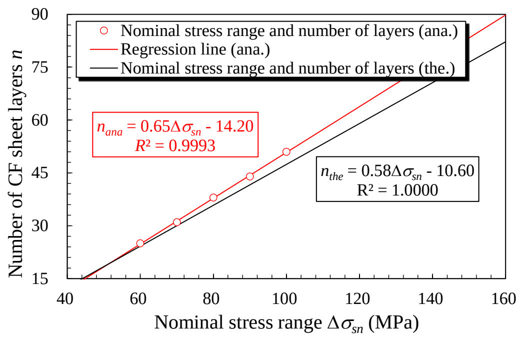

Fig. 5 Nominal stress range and number of CF sheet layers

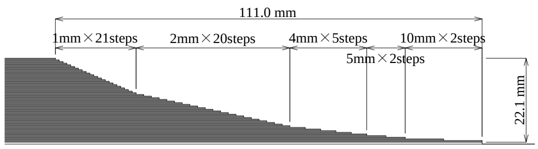

Fig. 6 Design of taper at CF sheet end (n=51 layers)

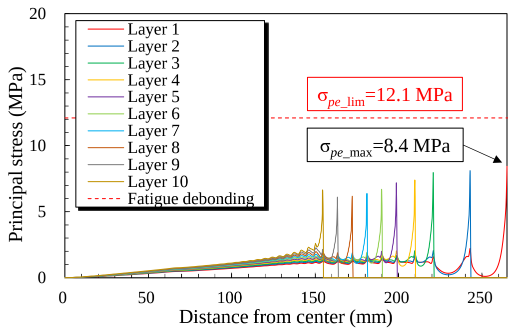

Fig. 7 Adhesive principal stress at taper end ($\Delta\sigma_{sn}$=100 MPa)

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