ENHANCEMENT OF FATIGUE DURABILITY IN CRUCIFORM WELDED JOINTS BY CARBON FIBER SHEETS USING VARTM TECHNIQUE

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1. INTRODUCTION

Carbon fiber (CF) sheets have been applied to repair and strengthening steel structures due to their excellent properties. However, difficulty in quantitative evaluation of enhancement of fatigue durability due to the complex bead shapes leads to the lack of study. Vacuum assisted Resin Transfer Molding (VaRTM) technique (Fig. 1), a low-cost fabrication process widely used in mechanical engineering can adhere multiple CF sheet layer to uneven surfaces with liquid resin. This paper deals with the enhancement of fatigue durability in the typical non-load-carrying cruciform welded joints by CF sheets using VaRTM technique.

2. SPECIMEN AND STRENGTHENING METHOD

2.1 Development length

Fig. 2 shows the outline of target specimen for strengthening specimen. The development length required for bonded 5 layers of CF sheets is theoretical calculated (JSCE ed. 2018) and the value equals to 37 mm. Table 1 shows the material properties used in the calculation.

2.2 Taper design

In this study, to prevent the debonding of adhesive, the taper at CF sheet end is designed with step of 10 mm for each layer. The design is based on the criteria of fatigue durability of adhesive which states 30% of static strength (principal stress) equals to fatigue limit (Thay *et al.* 2018). Principal stress is theoretically (Thay *et al.* 2018) and analytically (finite element analysis (FEA) conducted by MSC Marc 2018) calculated. From the experiment value of adhesive (Toray ACE AUP40), the fatigue limit of AUP40 is σ_{pe_lim}=24.3 MPa. From Fig. 3, the debonding of adhesive is prevented in case of fatigue test below nominal stress of σ_{sn_lim}=255 MPa (considering $\sigma_{pe\_\mathrm{lim}}/\sigma_{sn\_\mathrm{lim}}$=0.095).

2.3 Strengthening method

The procedures of CF sheet strengthening using VaRTM technique are as follows: pencil grinder treatment, resin coating, injection of epoxy resin in vacuum condition and treatment after VaRTM. In order to control and prevent initiation of fatigue cracks from the weld toes, the bead shapes are treated by the pencil grinder for 10 mm from both sides of the edges. After surface preparation, it is coated using high viscosity type of adhesive Konishi E258R (200 g/m^2). The adhesive E258R is added to weld toe with radius of 20 mm to prevent the unimpregnated resin at weld toe due to any possibility of poor construction procedures and to improve the quantitative evaluation at weld toe. The experiments are conducted using electro-hydraulic servo type material strength testing machine (Shimadzu Servo Pulser EV200kN).

3. REDUCTION OF STRESS CONCENTRATION

3.1 Test conditions

In order to verify the strengthening effect of bonded CF sheets by VaRTM technique, the specimens of non-strengthening (CWN) and strengthening (CWC) are prepared and the tensile tests are conducted under nominal stress of 150 to 255 MPa. Strain gauges are attached at the position of 1 mm (location nearest to weld toe) and 86 mm (general location which is not affected by weld toe) from weld toe.

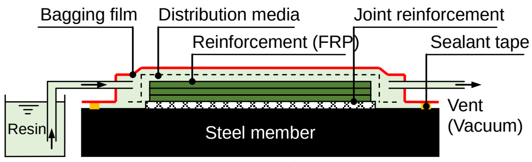
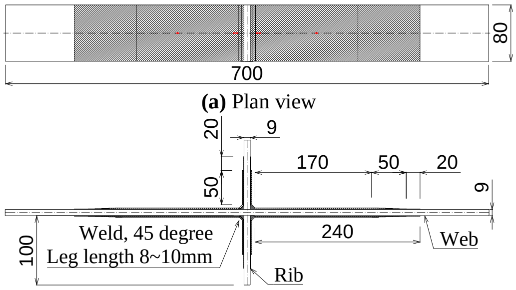


Fig. 1 Schematic view of VaRTM technique



(a) Plan view

(b) Side view

Fig. 2 Target specimen

Table 1 Material properties

Materials	Items	Symbols	Units	Values
Steel plate	Elastic modulus	E_s	MPa	205,000
(SM400)	Thickness	t_s	mm	9
CF sheet	Elastic modulus	E_{cf}	MPa	245,000
(High-	Design thickness	t_{cf}	mm	0.167
Strength)	Volume fraction	v_f	%	50
Epoxy resin	Elastic modulus	E_e	MPa	3,430
(AUP40)	Thickness	t_e	mm	0.4
Glass fiber	Elastic modulus	E_{csm}	MPa	18,750
(CSM)	Thickness	t_{csm}	mm	0.143

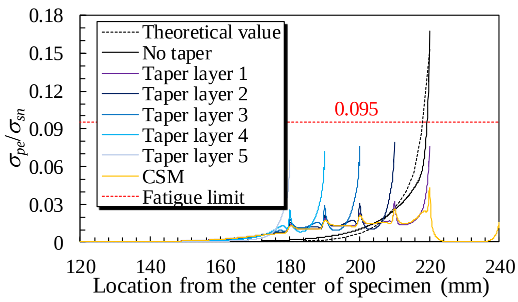
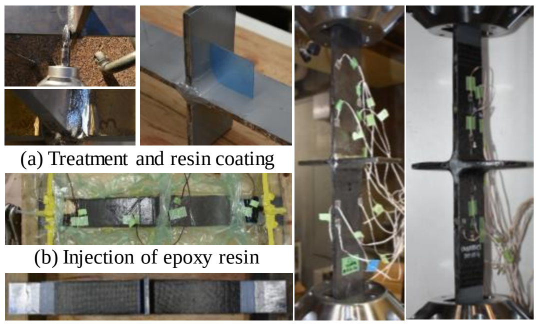


Fig. 3 Principal stress distribution



(a) Treatment and resin coating

(b) Injection of epoxy resin

(c) Treatment after VaRTM (d) CWN (e) CWC

Fig. 4 Adhesion procedures by VaRTM and test setup

Keywords: Fatigue durability, Cruciform welded joints, CF sheet, VaRTM technique, Stress concentration
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3.2 Modelling of weld toe

In Fig. 5, bead shapes are simulated using photo image data of actual bead taken at 360 degree (approximately 100 photos) with digital single-lens reflex camera (Nikon D7200) with general-purpose image analysis software (Autodesk Recap Photo and Autodesk Meshmixer). Finite element analysis (FEA) is conducted using MSC Marc 2018 with four-node quadrilateral plan strain elements. A quarter of the specimen is modelled due to the symmetry of the test specimen. The minimum element size at weld toe is 0.01 mm, while the other parts are 0.2 mm.

3.3 Verification of stress reduction

Fig. 6 shows the comparison of stress value obtained from experiment (σ_{exp}) and all modelled specimens (σ_{ana}). Good agreement can be confirmed with the variation in the range of ±5%. The experimental and analytical relative error of stress value at general part (86 mm) compared to theoretical value are 3.26% and 0.82%, respectively, which verified the stress reduction by bonded CF sheets.

4. FATIGUE DURABILITY

4.1 Test conditions

Table 2 shows the fatigue test series and conditions. Fatigue tests are conducted by test machine using in static test with the applied stress ratio R of 0.1 in all cases and the frequency f of 10 or 15 Hz. 5 cases (applied nominal stress range $\Delta\sigma_{sn}$=150~230 MPa) of CWN and 3 cases ($\Delta\sigma_{sn}$=180~230 MPa) of CWC are conducted. Beach mark method are adopted in order to measure crack propagation speed.

4.2 Fatigue test results

Fig. 7 shows the relationship between nominal stress range ($\Delta\sigma_{sn}$) and number of cycles from start of test to failure of specimen (N_f). Considering on the fatigue strength, the number of cycles of strengthening specimen bonded with 5 layers of CF sheets reaches 10 million cycles without initiation of fatigue crack (defines as fatigue limit) under nominal stress range of 180 MPa. Considering on the prolongation of fatigue life, the number of cycles extends from 0.57 to 2.55 million cycles (approximately 5 times) under nominal stress range of 200 MPa and from 0.40 to 4.96 million cycles (approximately 12 times) under nominal stress range of 230 MPa.

4.3 Prediction of crack propagation life

Fig. 8 shows the relationship between nominal stress range ($\Delta\sigma_{sn}$) and number of cycles from start of test to crack length of 1 mm (initial fatigue life N_i) and from crack length of 1 mm to failure of specimen (crack propagation life N_p) (N_f=N_i+N_p). The crack propagation life is computed by crack propagation analysis using the extrapolation of the average value of stress intensity factor based on linear fracture mechanics from each beach marks of specimens. From the figure, the crack propagation life N_p is the same regardless of the presence or absence of bonded CF sheets, which meant there is no strengthening effect in N_p. On the other hand, the initial fatigue life can be highly expected due to closure of crack at surface by bonded CF sheets when the crack length is small enough. It should be noted that the variation in initial fatigue life is due to stress concentration at weld toe.

5. CONCLUSIONS

In conclusion, the enhancement of fatigue strength by stress reduction and the prolongation of fatigue life in early stage of crack initiation in non-load-carrying cruciform welded joints by CF sheets using VaRTM technique can be confirmed.

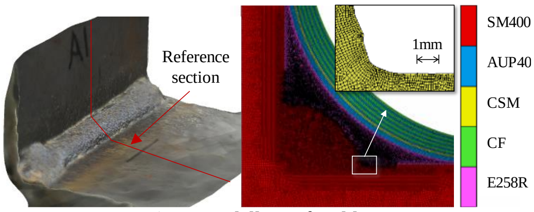

Fig. 5 Modelling of weld toe

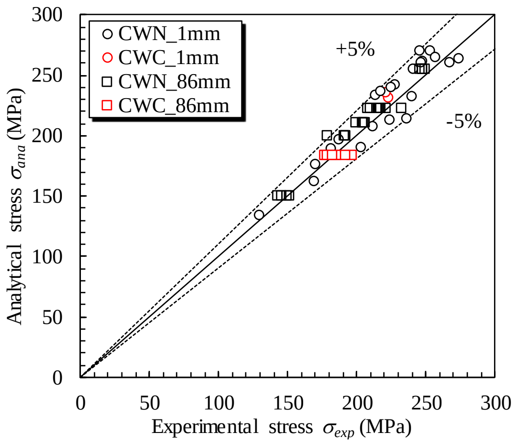

Fig. 6 Comparison of stress value (experiment and analysis)

Table 2 Fatigue test series and conditions

Specimens	$\Delta\sigma_{sn}$ (MPa)	R	f (Hz)	Number of specimens
CWN	150, 180, 190, 200, 230	0.1	10	4
CWC	180, 230, 200	0.1	10, 15	2

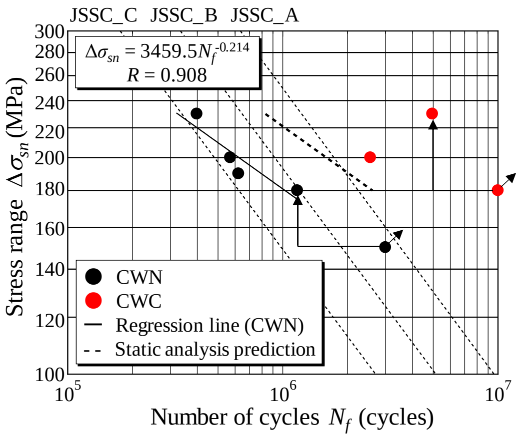

Fig. 7 Evaluation of fatigue durability ($\Delta\sigma_{sn}$ and N_f)

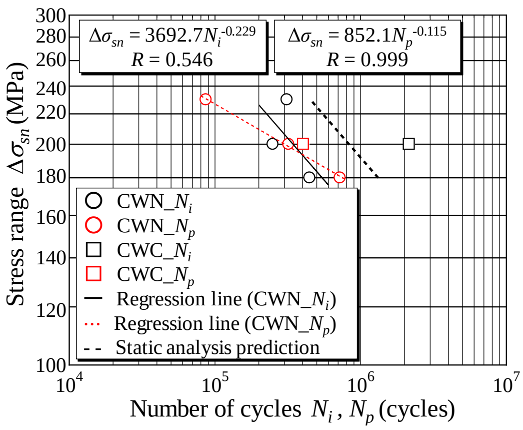

Fig. 8 Evaluation of fatigue durability ($\Delta\sigma_{sn}$ and N_i, N_p)

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