(34) PERMANENT REPAIR OF FATIGUE CRACKS OF WELDED GUSSET JOINTS BY EXTERNALLY BONDED CARBON FIBER SHEETS USING VARTM TECHNIQUE

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Vacuum assisted Resin Transfer Molding (VaRTM) as a composite fabricating technique can be used to apply carbon fiber (CF) sheets on cracked steel structures. The repaired operation work has been proven to be very efficient and convenient even on complex shapes of structures due to the flexibility of this method. This paper deals with the permanent repair of fatigue crack of typical welded gusset joints in steel bridges by externally bonded CF sheets using VaRTM technique, experimentally and analytically. The number of layers of CF sheets is determined analytically based on value of threshold stress intensity factor (SIF) range from safest design curve by JSSC, verifying by theoretical calculation. In order to prevent the debonding of adhesive at CF sheet end, taper is designed under condition of fatigue limit of adhesive using theoretical calculation. The target specimens of welded gusset plates were fabricated and subjected to cyclic load. The fatigue tests of two types of specimens, non-repaired and repaired specimen using VaRTM technique in the parameters of nominal stress ranges and number of layers of CF sheets, have been conducted and repaired effects have been evaluated under applied stress ranges. Based on the analytical study under repair condition studied, 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. Experimental results provide the possibility of permanent repair of fatigue crack, showing that fatigue crack of welded gusset joints can be permanently prevented from growing and fatigue life can be extended to fatigue limit (zero-crack propagation under 10 million times cyclic load or over) under applied nominal stress range of 60~120 MPa with specimen strengthened by 25 layers of CF sheets alone.

Key Words : *permanent repair of fatigue crack, welded gusset joint, threshold SIF, CF sheet, VaRTM technique*

1. INTRODUCTION

In urban highway steel bridges, fatigue damage has occurred with rapid increase in traffic and the passage of overloaded vehicles. This has raised the need for the appropriate and effective maintenance method in order to rehabilitate and maintain the steel bridges in service under healthy condition[1]. Existing repair and strengthening methods such as stop-hole method or high-strength bolt joint method have the disadvantage in cross sectional loss of structures and demand heavy specialized equipment and special technique in order to operate it. On the other hand, repair of fatigue cracks by externally bonded carbon fiber reinforced plastic (CFRP) has been investigated and proven to be very effective for the practical use as seen in several reports[2~4]. However, the repair work are getting inconvenient when high rigidity of CFRP patch plates are required.

Recently, in mechanical engineering fields, structural members of aircraft and wind turbine blades for instance have been often fabricated by VaRTM (Vacuum assisted Resin Transfer Molding) technique as described in technical review of Ref. 5). VaRTM technique is a low cost composite fabrication process, which able to fabricate large FRP structures easily and efficiently or to install multiple layers of carbon fiber (CF) sheets on steel structures at a time. The VaRTM technique has been applied to strengthen concrete structures[6)], to repair and strengthen steel structures, mainly on girder end with and without sectional loss as conducted in several studies[7~9)], and to enhance fatigue durability in welded gusset joints[10)]. **Fig.1** shows schematic view of VaRTM technique.

In the purpose of extend widely the application method of VaRTM technique in practical use, this paper deals with the analytical and experimental study in design of the number of layers of CF sheets required for permanent repair of fatigue cracks of typical welded gusset joints in steel bridges by externally bonded CF sheets using VaRTM technique. Moreover, design of taper at the ends of CF sheets in the purpose of preventing the debonding of adhesive layer are conducted and proposed.

2. SPECIMEN AND DESIGN CONDITIONS

(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 general section of steel plate are designed with the width of 150 mm. The applied maximum nominal stress range is approximately 145 MPa, equivalent to nominal stress range of approximately 130 MPa in case of stress ratio R=0.1. 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 supposed to be treated and improved by the pencil grinder at unfocused weld bead. The focused bead has been treated by not pencil grinder and but bristle blaster. (**Fig.3**)

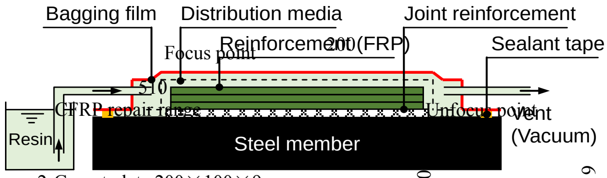
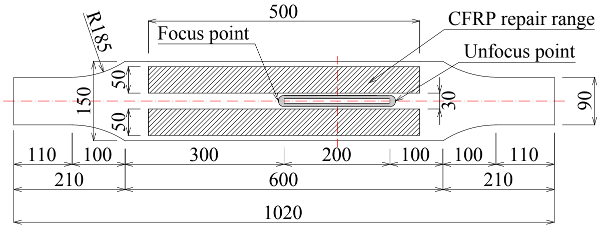
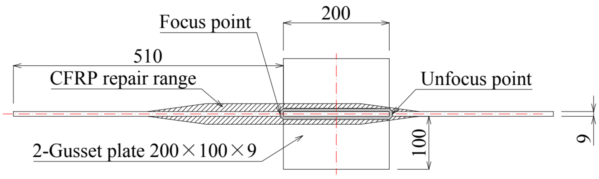


Fig.1 Schematic view of VaRTM technique for repair and strengthening

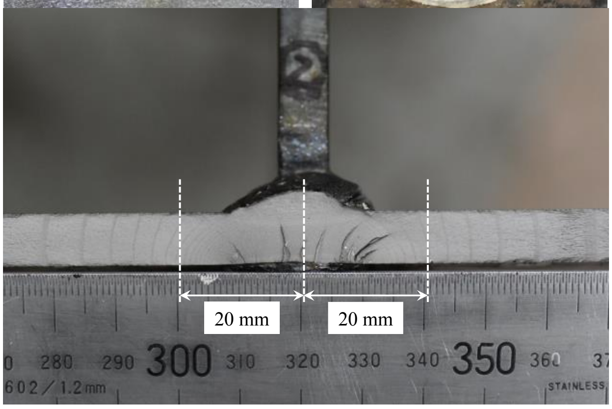


(a) Plane view



(b) Side view

Fig.2 Target specimen



(2) Initial crack length and repair range

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 (crack half-length) as an initial crack. This is to ensure that the crack is completely penetrated through one side to another side. **Fig.4** shows an example of cross section failure with crack propagation by beach marks. Then the specimen is repaired by four sets of externally-boned CF sheets ($L500\times W50\times t_f$ mm) at the distance of 15 mm to 65 mm from the center of gusset plate. This is due to the convenience of VaRTM process and to avoid bonding the CF sheets over the weld beads.

(3) Number of CF sheet layer and reduction factor

Fig.5 shows relationship between number of CF sheet layers and reduction factor of base plate strengthened by CF sheets (medium-elasticity type). The reduction factor ξ_0 is given by **Eq.(1)** below.

$$\xi_0 = \frac{E_s A_s}{E_s A_s + 2E_f A_f} \tag{1}$$

Here,

E_s, E_f: Elastic modulus of steel and CF sheet (MPa)

A_s, A_f: Cross-section area of steel and CF sheet (mm^2)

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. Based on this result and the construction condition of VaRTM technique, the number of CF sheet layers are considered to be limited to approximately 50 layers. From the figure, with 50 layers of CF sheet, the reduction factor ξ_0 is 0.225.

(4) Threshold stress intensity factor range

In this study, the number of CF sheet layers required for permanent repair (no growth of crack propagation) of fatigue crack is designed to be based on threshold stress intensity factor (SIF) range at crack tips in the function of applied stress ratio $\Delta K_{th}(R)$ given by the following **Eq.(2)**, recommended by Japanese Society of Steel Construction (JSSC)[11]. The value of SIF range ΔK_{th} varies to the applied stress ratio R, which is supposed to be R=0.1 in this study. SIF range ΔK_{th} is the value at R=1.0, which equals to 2.0 $MPa.m^{0.5}$.

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

Here,

σ_{min} : Minimum applied nominal stress (MPa)

σ_{max} : Maximum applied nominal stress (MPa)

From the equation, in case of applied stress ratio R=0.1, the value of threshold stress intensity factor range is $\Delta K_{th}(0.1)$=4.80 $MPa.m^{0.5}$.

Table 1 summarizes the design conditions in calculation process of number of CF sheet layers required for permanent repair. The analytical study is conducted under applied nominal stress range at general section of steel plate in the range of 60~100 MPa.

(5) Theoretical calculation

The stress intensity factor 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 **Eq.(5)**, respectively[12].

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

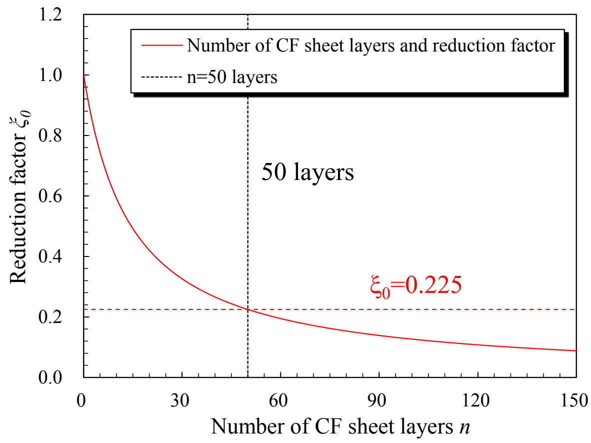
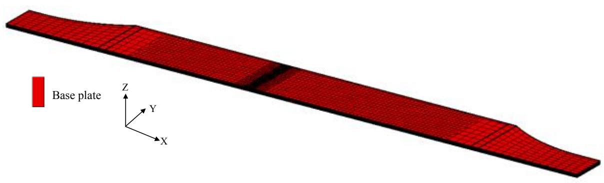


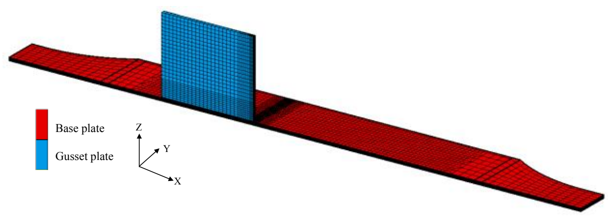
Fig.5 Number of CF sheet layers and reduction factor

Table 1 Design conditions

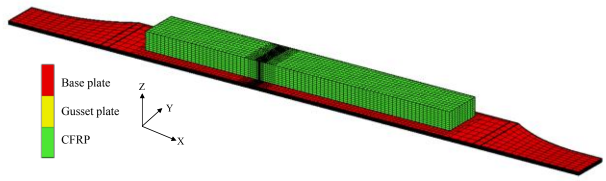
Items	Symbols	Units	Values	Notes
Initial crack half-length	a	mm	20	
Repair range	Δb	mm	50	15~65
Number of CF sheet layer	n	–	<50	Approx.
Threshold SIF range	$\Delta K_{th}(0.1)$	$MPa.m^{0.5}$	4.80	
Stress ratio	R	–	0.1	
Nominal stress range	$\Delta\sigma_{sn}$	MPa	60~100	



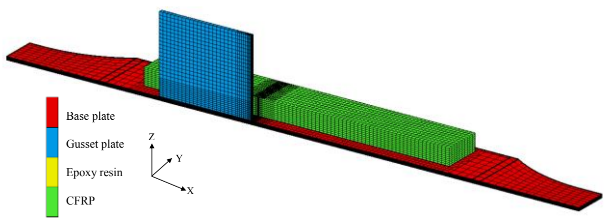
(a) Non-repair model without gusset plate



(b) Non-repair with gusset plate



(c) Repair without gusset plate



(d) Repair with gusset plate

Fig.6 Analytical model

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

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

Here,

a : Initial crack half-length (mm)
b_s, b_f : Width of steel and CF sheet (mm)
t_s, t_f : Thickness of steel and CF sheet (mm)

(6) Analytical method and model

The 3D finite element analysis (FEA) is conducted using general-purpose analysis program, MSC Marc 2018, with elastic analysis. **Fig.6** shows the analytical model of specimens. According to the symmetry, a quarter of specimen is modelled using solid element. To verify the validity of analytical model, four kinds of models as follows: (a) non-repair model without gusset plate (**Fig.6(a)**), (b) non-repair model with gusset plate (**Fig.6(b)**) (c) repair model without gusset plate (**Fig.6(c)**) and (d) repair model with gusset plate (**Fig.6(d)**) are considered. It should be noted that calculation of number of CF sheet layers is solely conducted in model (d). The modelling of weld bead are neglect since the analytical study mainly focus on the analytical result after occurrence of initial crack (a=20 mm).

The patch plate of CF sheet are modelled as one body of CFRP, which is the combination of CF sheet and epoxy resin (Toray ACE AUP40). The thin layer of adhesive (Toray ACE AUP40, thickness t_e=0.5 mm) between steel plate and CFRP are modelled with solid elements as shown in **Fig.7(a)**. There are no any consideration of interface between steel plate and adhesive and between adhesive and CFRP. With the sufficiency of development length of CFRP, modelling of taper end, which will be discussed in **Chapter 3**, is not considered.

The cracks are modelled using double nodes definition (**Fig.7(b)**). The minimum size of elements at crack tip is 0.1 mm. The energy release rate (ERR) in mode I (opening mode) (g_I) is computed using the virtual crack closure technique (VCCT) function[13] and the stress intensity factor in mode I (K_I) is calculated using the following equation (**Eq.(7)**).

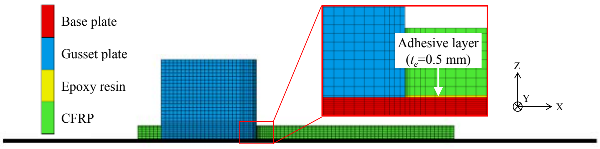
$$K_I = \sqrt{g_I E_s} \tag{6}$$

Here,

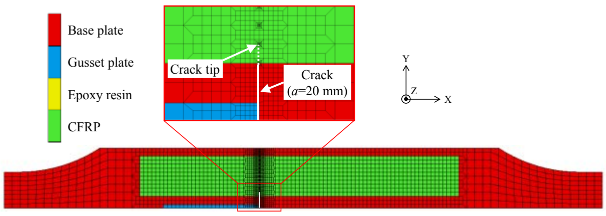
K_I : Stress intensity factor in mode I (N/mm$^{3/2}$)
g_I : Energy release rate in mode I (N/mm)
E_s : Elastic modulus of steel plate (N/mm^2)

It should be noted that mode I is the most critical mode and dominant over mode II (sliding mode) and mode III (tearing mode) in this analytical model. The basic modes of crack extension are shown in **Fig.8**. **Fig.9** shows an example of crack deformation mode and contour band of energy release rate in mode I at crack tip in steel plate thickness direction.

Material properties of steel plate (SM400), CF sheet, CFRP (CF sheet and epoxy resin) and epoxy

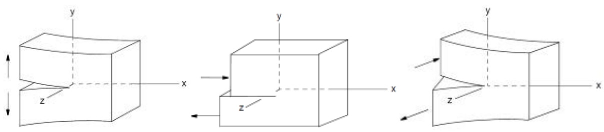


(a) Adhesive layer



(b) Crack tips

Fig.7 Analytical model details



(a) Mode I: opening **(b)** Mode II: sliding **(c)** Mode II: tearing

Fig.8 Basic modes of crack extension[13]

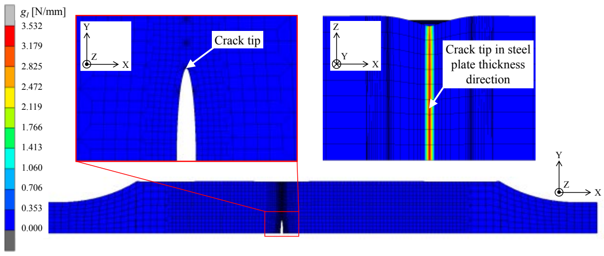


Fig.9 Deformation of crack and contour band of energy release rate in mode I (model (a), $\Delta\sigma_{sn}$=100 MPa, a=20 mm)

Table 2 Material properties

Materials	Items	Symbols	Units	Values
Steel plate (SM400)	Elastic modulus	E_s	MPa	205,000
	Poisson's ratio	ν_s	–	0.3
	Width	b_s	mm	150
	Thickness	t_s	mm	9
CF sheet (medium-elasticity type)	Elastic modulus	E_{cf}	MPa	440,000
	Poisson's ratio	ν_{cf}	–	0.3
	Design thickness	t_{cf}	mm	0.217
	Volume fraction	ν_f	%	50
CFRP (CF sheet+ epoxy resin)	Elastic modulus	E_f	MPa	220,000
	Poisson's ratio	ν_f	–	0.3
	Width	b_f	mm	50
	Thickness	t_f	mm	n×2×0.217
Epoxy resin (Toray ACE AUP40)	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

resin are descripted in **Table 2**. The unidirectional CF sheets (medium-elasticity type) are installed in longitudinal direction of the specimen and the isotropic material properties of CFRP is input. Toray ACE AUP40, cold hardening type epoxy resin with low-viscosity, is selected as the adhesive.

3. ANALYTICAL EVALUTION

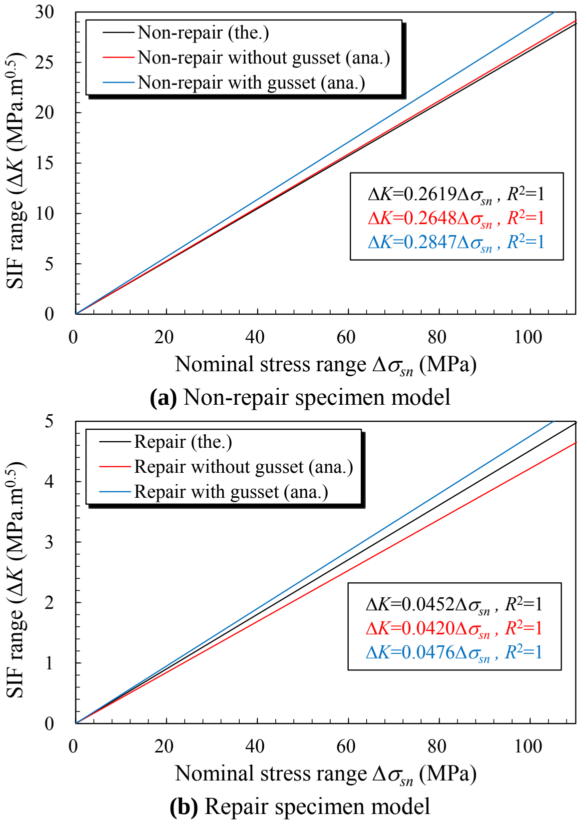
(1) Validity of analytical model

Table 3 and **Fig.10** show the comparison of analytical and theoretical value of SIF range in model (a) ~ (d). **Table 4** shows the comparison of analytical value of SIF range between specimen model with and without gusset plate in model (a) ~ (d). For the repair models, CFRP equivalent to 51 layers of CF sheet are conducted. It should be noted that in theoretical calculation, existing of gusset are neglected and epoxy resin are not considered (perfect bonding of CFRP).

From **Fig.10(a)**, good agreement between analytical and theoretical calculation of non-repair specimen model without gusset plate can be verified (relative error of 1.11%). In consideration of gusset plate, the difference between specimen models with and without gusset plate can be confirmed (relative error of 7.51%). From **Fig.10(b)**, the same trend of the influence of specimen with gusset plate (relative error of 12.69%) can be seen in repair specimen. However, good agreement between analytical and theoretical calculation of repair specimen model without gusset plate cannot be verified (relative error of 7.02%). This is due to the effect of adhesive layer considered in analytical model, which reduce the value of SIF range. Overall in both cases, repair and non-repair specimen, the value of SIF range is getting higher when gusset plate is considered. Influence of gusset plate and epoxy resin is two parameters that should not be neglected in this study. Therefore, analytical model of repair specimen with gusset plate (analytical model (d)) is selected to calculate the number of CF sheet layers required for permanent repair under design condition summarized in **Table 1**.

(2) Number of CF sheet layers

Table 5 and **Fig.11** 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 design conditions studied in this paper, the number of CF sheet layers required for permanent repair can be obtained from linear equation (**Eq.(7)**). For reference, **Eq.(8)** is linear equation from theoretical calculation.



(a) Non-repair specimen model

(b) Repair specimen model

Fig.10 Comparison of analytical and theoretical calculation

Table 4 Comparison of analytical calculation between specimen model with and without gusset

Analytical models (a=20 mm, n=51 layers, $\Delta\sigma_{sn}$=100 MPa)	Analytical SIF range ΔK_{ana} (MPa.m$^{0.5}$)		Relative error (%)
	Without gusset	With gusset	
Non-repair	26.48	28.47	7.51
Repair	4.22	4.76	12.69

Table 5 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

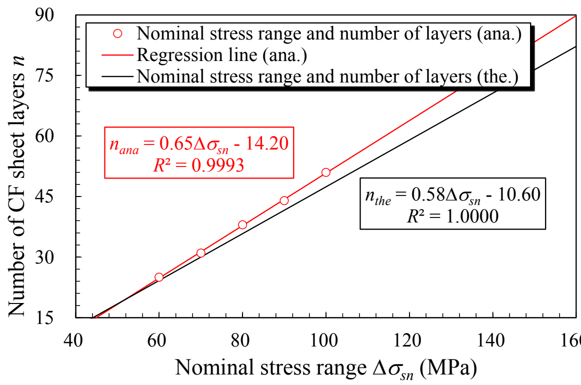


Fig.11 Nominal stress range and number of CF sheet layers

$$n_{ana} = 0.65\Delta\sigma_{sn} - 14.20, \quad R^2 = 0.9993 \tag{7}$$

$$n_{the} = 0.58\Delta\sigma_{sn} - 10.60, \quad R^2 = 1.0000 \tag{8}$$

3. DESIGN OF TAPER AT CF SHEET END

In this study, the evaluation of adhesive strength by maximum principal stress was adopted by first investigate the debonding strength of adhesively debonding joints of the same epoxy resin (Toray ACE AUP40) and then design the taper at CF sheet end using theoretical calculation.

(1) Debonding strength of epoxy resin

The specimen is double lap joints between base plate (steel plate: $L600\times W50\times t9$ mm) and patch plate (steel plate: $L300\times W50\times t16$ mm) adhered by the same epoxy resin Toray ACE AUP40 using VaRTM technique (**Fig.12**). Specimen preparation is shown in **Fig.13** (surface preparation by alumina blast, setting of glass fiber chopped strand mat (CSM), VaRTM and edge preparation after VaRTM). Insertion of CSM is to facilitate the impregnation of the epoxy resin and to prevent the corrosion due to electrochemical action.

Fig.14 shows the experimental setup of the static test. The below end of the patch plates are fixed by fixture in order to control and observe the debonding at the upper end of the patch plates. The debonding load of adhesive is observed by digital microscope and the change of load and shear stress obtained from strain value near the end of patch plates[15]. The results of tensile tests of epoxy resin Toray ACE AUP40 is shown in **Table 6**. From the table, the average maximum principal stress is 40.2 MPa. From the fatigue limit evaluation criteria of adhesives which proposes and states that "30% of static debonding strength equals to fatigue limit"[14], the fatigue limit of Toray ACE AUP40 is considered to be at principal stress of 12.1 MPa.

(2) Design of taper at CF sheet end

From evaluation of failure criteria and test results mentioned above, taper at CF sheet end was designed under condition of fatigue limit below 12.1 MPa using theoretical calculation recommended by Japan Society of Civil Engineers (JSCE)[3]. The most critical condition of 51 layers of CF sheet is selected to design. The development length is 150 mm[3] and taper length are limited to below 115 mm. Material properties of steel plate, CF sheet and epoxy resin are described in **Table 2** above.

Fig.15 shows the proposed designed of taper at CF sheet end. The adhesive thickness between each 51 layers of CF sheets is taken into account in this study. The results are plotted in **Fig.16**. From the figure, the

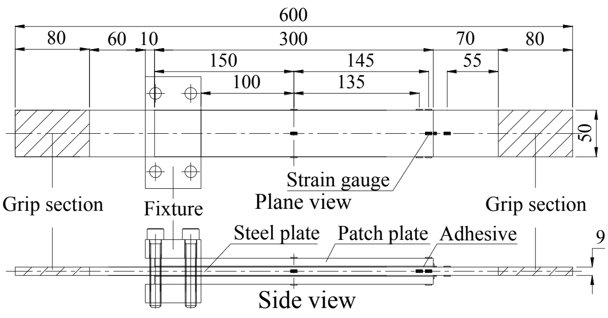
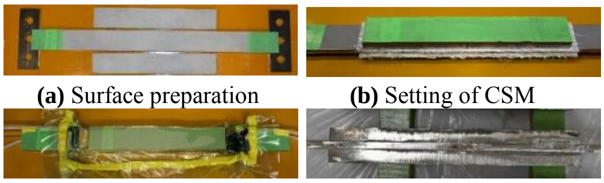


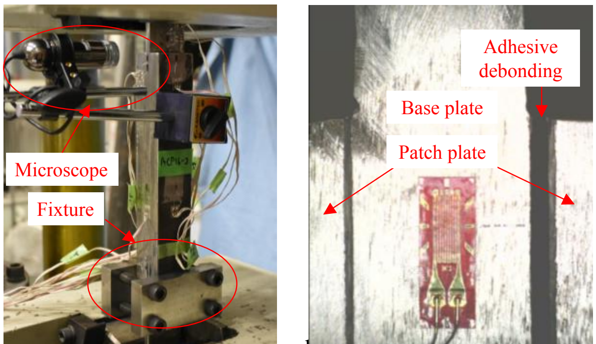
Fig.12 Double lap joint specimen



(a) Surface preparation **(b)** Setting of CSM

(c) VaRTM **(d)** Edge preparation after VaRTM

Fig.13 Procedures of VaRTM



and

Table 6 Experimental result of epoxy resin AUP40 tensile tests

Specimens	Debonding load P_{db} (kN)	Debonding principal stress σ_{pe_db} (MPa)	Fatigue limit of principal stress $\sigma_{pe\_db\_lim}$ (MPa)
ACP16-1	59.6	49.1	14.7
ACP16-2	46.3	39.8	11.9
ACP16-3	37.3	31.7	9.5
Average	48.8	40.2	12.1

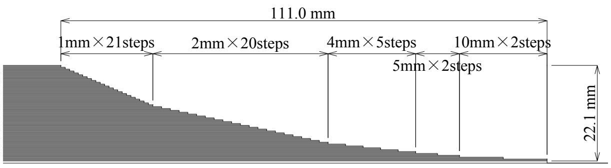


Fig.15 Design of taper at CF sheet end (n=51 layers)

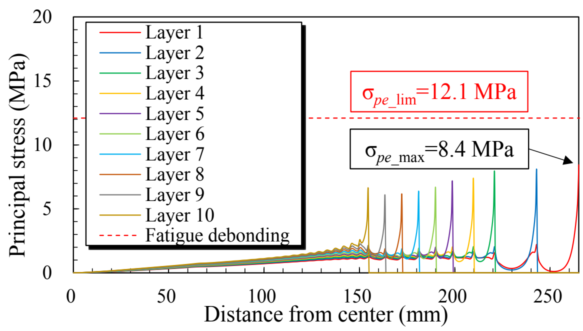


Fig.16 Adhesive principal stress at taper end ($\Delta\sigma_{sn}$=100 MPa)

Table 7 Number of CF sheet layers required for permanent repair in parameter of applied nominal stress range

Specimens	Number of layers	Stress range $\Delta\sigma_{sn}$ (MPa)	Number of cycles N_p (cycles)	Failure modes	Number of specimens
Non-repair	0	60	276,017	Weld toe crack	3
	0	80	128,232	Weld toe crack	
	0	100	72,195	Weld toe crack	
Repair	25	60	>10,000,000	Fatigue limit	1
		60→80	>10,000,000	Fatigue limit	
		80→100	>20,000,000	Fatigue limit	
		100→120	>10,000,000	Fatigue limit	

maximum principal stress of first layer is 8.4 MPa, which is below the average fatigue limit of 12.1 MPa, as well as below the lowest fatigue limit of 9.5 MPa (specimen of ACP16-3). It should be noted that this detailed design varies from 10 mm to 1 mm of taper is due the limit condition of the target specimen. In practical use, the sufficient length for taper design can be ensured.

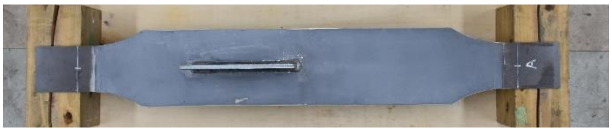
4. FATIGUE DURABILITY

(1) Repair method

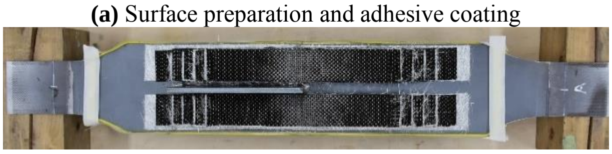
Fig.17 and **Fig.18** shows the procedures of CF sheet repairing using VaRTM technique and test setup. Coating and mill scale are removed using bristle blaster and then the surface are cleaned by acetone before coating by adhesive (Konishi E258R). Unidirectional CF sheets are installed in longitudinal direction of the specimen. To facilitate the impregnation of the epoxy resin, one layer of glass fiber chopped strand mat (CSM) is inserted every five layers of CF sheets. Then secondary materials such as one layer peel ply (to remove secondary materials after hardening), 3 layers of distribution media (to secure the fluidity of resin), etc. are set and enclosed in bagging film. The system is operated by vacuum pump in resin impregnation process. Cold hardening type epoxy resin with low-viscosity (Toray ACE AUP40T1) is selected as the adhesive. The viscosity of resin is 8–10 dPa·s. The impregnation time is within the pot life of resin (approximately 1 hour) and it is cured at 40 °C for 24 hours. Last, secondary materials are removed. It should be noted that Toray ACE AUP40T1 has a similar material properties to Toray ACE AUP40.

(2) Experimental results and discussions

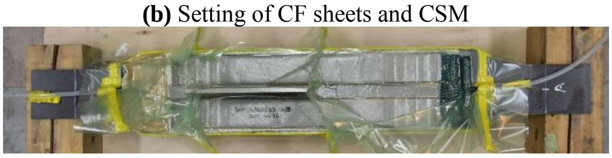
Table 7 shows the experimental series and results of non-repair and repair specimens of each fatigue tests. Three non-repair specimens are conducted under nominal stress range of 60, 80 and 100 MPa. One repair specimen strengthened with 25 layers of CF sheets are conducted to under nominal stress range of 60 MPa. Due to no sign of failure or crack propagation of specimen after more than 10 million cycles,



(a) Surface preparation and adhesive coating



(b) Setting of CF sheets and CSM



(c) Setting of secondary materials and VaRTM

(d) After VaRTM

Fig.17 Procedures of VaRTM

(a) Non-repair specimen **(b)** Repair sepcimen

Fig.18 Fatigue test setup

the same specimen is reconducted under nominal stress range of 80, 100 and 120 MPa. The fatigue testing machine used in the experiments is electro-hydraulic servo type material strength testing machine (Shimadzu Servo Pulser EV200kN). The applied stress ratio R is set to 0.1 in all cases. The specimens are subjected to cyclic load with the frequency of f=10 Hz. Beach mark method and disconnection detection method with enameled copper wires (ϕ=0.025 mm) are adopted in order to measure crack propagation speed. It should be noted that the enameled copper wires are attached at distance of 20 mm to both sides from the gusset center in order to define the initial crack. **Fig.19** shows the relationship between nominal stress range and number of cycles N_p (a=20 mm to failure of specimen). From the figure, the prolongation of fatigue life for the specimen repaired with 25 layers of CF sheet under nominal stress range of 60, 80, 100 and 120 MPa reached over 10 million cycles without any sign of crack propagation (defined as fatigue limit). The overestimates are mainly due to the safest design value of threshold SIF range ΔK_{th} (4.80 MPa.m$^{0.5}$). Future work will deal with the exact value of ΔK_{th} from the actual specimens to verify and properly evaluate the fatigue durability of repair specimens.

3. CONCLUSIONS

In conclusion, the findings in design of the number of layers of CF sheets required for permanent repair of fatigue cracks studied in the paper are summarized as follows:

(1) The validity of the proposed analytical is verified and the influence of gusset plate and epoxy resin is two parameters that should not be neglected.

(2) Under repair condition studied, the number of layers of CF sheets required for permanent repair of fatigue crack of welded gusset joints are proposed and it is between 25 and 51 layers under applied stress range of 60~100 MPa.

(3) The taper of the most critical condition of 51 layers of CF sheet is designed and proposed under fatigue limit based on failure criteria of adhesives. There are no debonding of adhesive at CF sheet end found during the fatigue test.

(4) Experimental results provide the possibility of permanent repair of fatigue crack, showing that fatigue crack of welded gusset joints can be permanently prevented from growing and fatigue life can be extended to fatigue limit under applied nominal stress range of 60~120 MPa with specimen strengthened by 25 layers of CF sheets alone.

Further work on actual threshold SIF range of specimen is required to be studied in order to properly evaluate the fatigue durability of repair specimen.

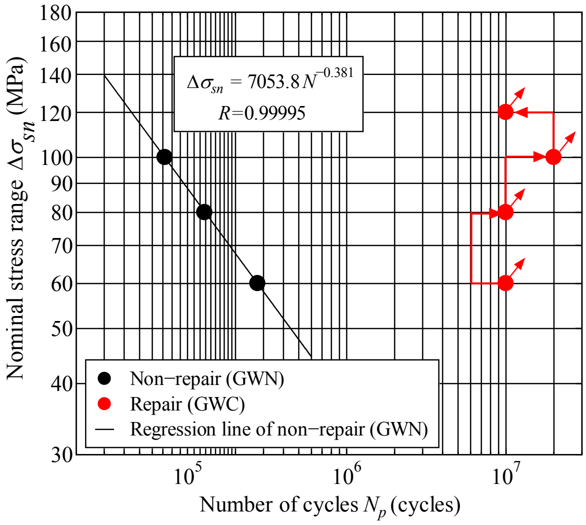


Fig.19 Evaluation of fatigue durability

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