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Bonding characteristics and flexural stiffening effect of CFRP strand sheets bonded to steel beams

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Abstract

Corrosion of steel structures is unavoidable and the structural performance decreases dramatically due to the corrosion. As a repairing method for corroded steel members, bonding carbon fiber sheets with resin had been developed. In this study, in order to clarify the stiffening effect and debonding characteristics of CFRP (Carbon Fiber Reinforcement Polymer) strand sheets, the flexural tests using high strength steel reinforced by CFRP strand sheets were performed. As a result, it was clarified that CFRP strand sheets have stiffening effect equivalent to the theoretical value and its debonding property is practically high enough when FRP sheets have an appropriate bonding length.

Keywords: CFRP strand sheets; corrosion; debonding; flexural strengthening; steel members

1. Introduction

Corrosion of steel structures is unavoidable and the structural performance decreases due to the corrosion. As a repairing method for corroded steel members of which cross-sectional area is reduced, a method to bond the carbon fiber sheet with resin to steel members has been studied [1]. This method is known as an efficient and economical method for repairing because no heavy equipment is necessary at work site. As for common reinforcing method, the continuous fiber sheet [2] and the FRP (Fiber Reinforcement Polymer) strip [3] are being used. However, there exist some demerits on employing these materials. When using continuous fiber sheets, adhesion defects may be caused by poor impregnation of resin. When also using FRP strips, debonding may occur at lower load because of interfacial shearing stress concentrated between steel and FRP at its tips [4].

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In recent years, to solve these problems, the FRP strand sheet (Fig. 1) which consists of bunch of individually hardened continuous fiber strands was developed [4]. It is expected that no defects occur by using the FRP strand sheets because it is impregnated with resin and hardened at factory beforehand. Furthermore, the FRP strand sheet can reduce necessary layers of a sheet compared to continuous fiber sheets because of its high mass per unit area.

The purpose of this study is to propose the flexural strengthening method for steel members by using CFRP (Carbon Fiber Reinforcement Polymer) strand sheets. In order to clarify the stiffening effect and debonding characteristics of CFRP strand sheets and to optimize the strengthening design specifications, the flexural tests using high tension steel beams strengthened with CFRP strand sheets are performed. Two cases of experiment are carried out; Experiment 1 & 2. In Experiment 1, the result from previous research [4] is reflected in the strengthening design. Moreover in Experiment 2, the debonding characteristics obtained from Experiment 1 are reflected. In this study, the effects of the overlap splice joint (Fig. 2) of CFRP strand sheets are also examined.

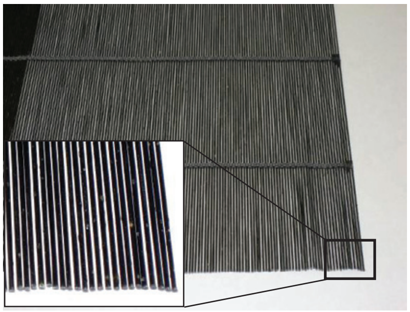

Fig. 1. CFRP Strand sheets

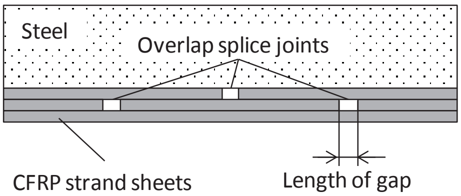

Fig. 2. Schematic drawing of overlap splice joint

2. Experiment 1

2.1. Materials

As a base metal, SBHS700 (JIS G3128: High yield strength steel plates for welded structure) steel is used. Its yield stress is 836 MPa and elastic modulus is 200 GPa. The reason for using the high yield strength steel is to observe the debonding characteristics under large strain. CFRP strand sheets are used for reinforcements. The material properties of CFRP strand sheets are listed in Table 1.

Table 1. Material properties of CFRP strand sheets

	Sheet	Mass per unit area	Design thickness	Guaranteed value		Measured value	
				Elastic modulus	Tensile strength	Elastic modulus	Tensile strength
		g/m^2	mm	kN/mm^2	N/mm^2	kN/mm^2	N/mm^2
Experiment 1	SSHM900	900	0.429	640	1900	695	2670
Experiment 2	SSHM900	900	0.429	640	1900	721	2970

2.2. Outline of tests

Two H-shaped steel girders are used to conduct flexural tests. CFRP strand sheets are bonded to lower flanges. The three-point loading tests are performed until yield load of steel (1020 kN) or until debonding of CFRPs occur. Measured values are deflection and strain in CFRP/steel. Debonding of CFRP is also observed.

The experimental parameters are the bonding length of each layer and the presence or absence of overlap splice joint as listed in Table 2. The specimens are shown in Fig. 3. F10B has 4 overlap splice joints from 1st layer to 3rd layer as shown in Fig. 3. The numbers of ply of CFRP strand sheets is basically 10 layers. Specimen F10B has 11 layers because there are few one-layer at overlap splice joint parts. Therefore, the stiffening effect of F10A and F10B should be the same.

Table 2. Parameters of Experiment 1

Specimen	Number of ply	Length of 1st layer mm	Length of overmost layer mm	Length of step mm	Number of joints	Length of gap mm
F10A	10	2360	920	80	0	-
F10B	10+1	3900	900	150	4	0

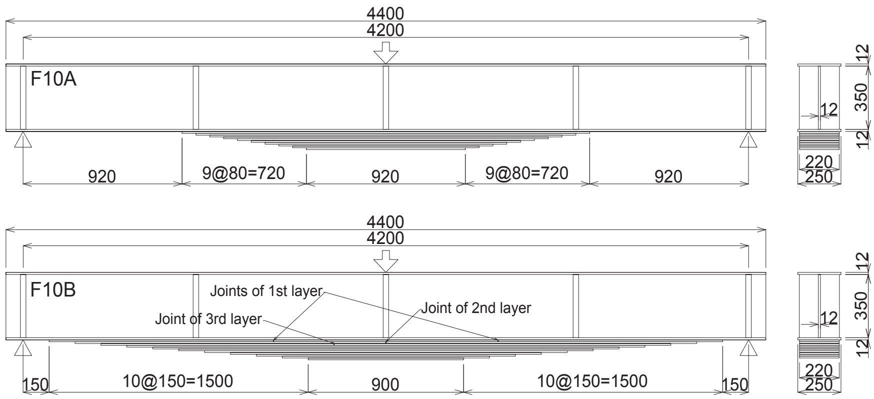

Fig. 3. Specimens of Experiment 1

2.3. Design method

The minimum bonding length of each layer for obtaining the theoretical stiffening effect can be calculated by following equations.

$$I_i = I_s + \frac{E_{cf}}{E_s}\left(I_{cf} + A_{cf} \cdot e_{cf}^{\,2}\right) \tag{1}$$

$$x_i = \frac{2\sigma_m I_{i-1}}{y_{i-1} P_y} \tag{2}$$

The explanation of function is as follows;

- E_s, E_{cf} : elastic modulus of steel and CFRP
- I_i : geometrical moment of inertia of composite cross-section at *i*_th layer
- I_s, I_{cf} : geometrical moment of inertia of steel and CFRP
- A_{cf} : cross-sectional area of CFRP
- y_i : distance from neutral axis to optional location
- e_{cf} : distance from neutral axis to centroid of CFRP
- x_i : position of tip of *i*_th layer of CFRP from the supporting point
- σ_m : stress of steel at the tip of *i*_th layer of CFRP
- P_y : flexural load at center

In this study, P_y is 1020 kN which is the yield load of unreinforced steel, and σ_m is 460 MPa which is the stress of reinforced steel at 1020 kN. Substituting these values into eq. (2) yields the minimum bonding length of each layer. Normally, the load transfer length is necessary when bonding the CFRP to the structure. In previous research [4], that length was more than 100 mm. In this study, 200 mm is adopted as load transfer length. Therefore, the bonding length is further extended to 200 mm on one side.

When strengthening steel members with CFRP, debonding of CFRP is the great concern. Normally, the debonding occurs between steel and the 1st layer of CFRP. Therefore, one needs to consider debonding in designing the length of the 1st layer. In previous research [4], steel stress at tip of the 1st layer of the CFRP strand sheet is 280 MPa when debonding occurs. Therefore, substitution of 280 MPa into eq. (2) as σ_m yields the debonding load of 1st layer of CFRP. In the case of F10A, the debonding of 1st layer of CFRP would occur at 780 kN. In the case of F10B, the debonding would not occur because the length of 1st layer is extended to near supporting points where the bending moment is nearly zero. The step lengths of each layer of F10A and F10B are the same.

2.4. Results and discussion

2.4.1. Stiffening effect

The load-strain curves of F10A and F10B are shown in Fig. 4. From this figure, it is found that the strain of steel and CFRP agrees well with the theoretical value in both specimens. Table 3 presents the experimental flexural rigidity (EI_{exp}), theoretical flexural rigidity (EI_{cal}) and achievement ratio (EI_{exp}/EI_{cal}), and the fracture state at each load. The theoretical flexural rigidities are calculated using eq. (1). In this table, the achievement ratios of flexural rigidities are almost 100% in spite of presence or absence of overlap splice joint. It means that the proposed design method regarding stiffening effect is correct.

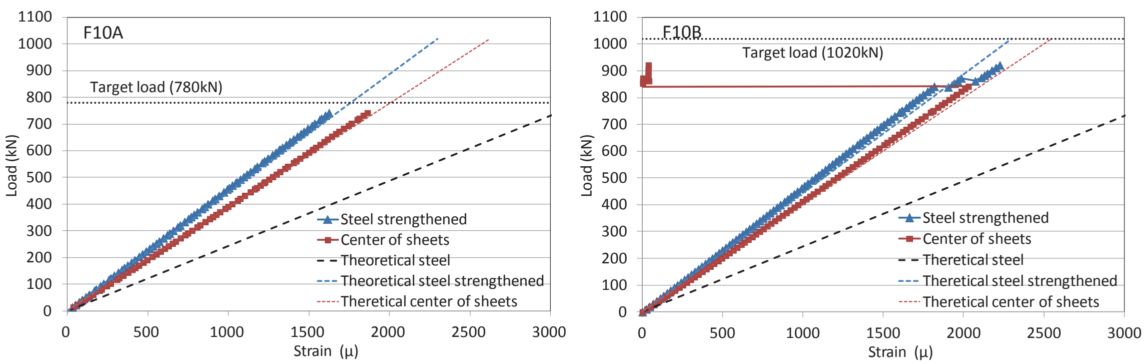

Fig. 4. The load-strain curves of F10A and F10B

Table 3. The results of Experiment 1

Specimen	Flexural rigidity kNmm²			Load	Fracture state	State
	EI_{exp}	EI_{cal}	Achievement %	kN		No.
F10A	67809	65672	103.3	742	Debonding from 3rd layer	A1
				881	Tensile rupture at center	A2
F10B	68752	65672	104.7	842	Debonding of 11th layer	B1
				873	Debonding of 10th layer	B2
				922	Tensile rupture at center	B3

2.4.2. Debonding property

From Table 3, it is observed that the proposed design method regarding debonding property is not correct. In the case of F10A, the debonding occurred between the 2nd and the 3rd layer of CFRP strand sheet, although the debonding load almost agrees with that of designed value. In F10B, debonding also occurred in between the 11th layer and the 10th layer. These results mean that the debonding at interlayer of CFRP needs to be considered in the design.

Table 4 presents calculated value of the stresses and strains of steel and the CFRP strand sheet at each fracture state. In this table, values of state A1, B1, and B2 regarding the debonding are theoretical value at tip of each layer are given, as well as values of state A2 and B3 regarding the tensile rupture of CFRP strand sheets are theoretical value at the center of span. The steel stress of state B1 agrees with that of state B2. The steel stress of state A1 should agree as well. However, the result shows that it is lower than those of B1 and B2. In F10A, the rapid load transfer occurs near the vertical stiffening plate. This causes the occurrence of debonding at lower stress in F10A. It should be noted that the debonding of CFRP is likely to occur near the stiffening plate. The results from F10B reveal that the steel stress is about 310 MPa when debonding occurs at interlayer of CFRP.

In Table 4 is found that the CFRP stress of state B3 is lower than that of A2. The tensile strength in F10B is lower than guaranteed tensile strength of CFRP although the tensile strength in F10A is higher than that of CFRP. It can be considered that the reason of tensile strength reduction is the stress concentration at the overlap splice joint. Therefore, several millimeters gap between the CFRP strand sheets is required at overlap splice joint in order to reduce the stress concentration.

Table 4. Calculated value of stress and strain in each fracture state

Specimen	State No.	Load kN	Xi mm	Moment kNmm	Stress of steel N/mm^2	Strain of steel με	Stress of sheet N/mm^2	Strain of sheet με
F10A	A1	742	1080	400583	269	1347	958	1378
	A2	881	2100	925029	622	3111	2211	3182
F10B	B1	842	1650	694502	313	1563	1221	1757
	B2	873	1500	654615	309	1547	1191	1714
	B3	922	2100	967806	458	2288	1761	2534

3. Experiment 2

3.1. Outline of tests

The findings from Experiment 1 are as follows;

- In previous research, the steel stress at tip of 1st layer of which debonding of CFRP strand sheet occurred was 280 MPa.
- The steel stress when debonding occurred at interlayer of CFRP was around 310 MPa.
- Several millimeters gap between the CFRP strand sheets is required at overlap splice joint.

In Experiment 2, these findings are reflected to the design method. The steel stress, when debonding occurs at interlayer of CFRP, is decided as 300 MPa. The gap length between the CFRP strand sheets is also decided as 20mm, which takes into consideration of the construction error. The experimental parameters are listed in Table 6. F10D has 5 overlap splice joints from the 1st layer to the 4th layer. In the case of F10C, the length of the 1st layer is designed upon the assumption that debonding would occur at 650 kN, and the other layer is designed upon the assumption that debonding would not occur until 650 kN. In the case of F10D, no fracture would occur until 1020 kN.

Table 6. Parameters of Experiment 2

Specimen	Number of ply	Length of 1st layer mm	Length of overmost layer mm	Length of step mm	Number of joints	Length of gap mm
F10C	10	2000	740	70	0	-
F10D	10+1	3900	1600	115	5	20

3.2. Results and discussion

Table 7 presents the experimental flexural rigidity, the theoretical flexural rigidity, the achievement ratio, and the fracture state. The theoretical flexural rigidities are calculated using eq. (1). In this table, the achievement ratios of flexural rigidities are almost 100 %. From Table 7 is found that the fracture mode of F10C and F10D agree with the assumption based on the proposed design method. The debonding load of F10C is 815 kN, which is higher than designed value. The steel stress at tip of the 1st layer of which debonding of CFRP strand sheet occurred is 350 MPa. This value is higher than that of previous research. However, in this study, the steel stress when the debonding occurs at tip of the 1st layer of CFRP strand sheet is decided as 280 MPa in consideration of safety. In the case of F10D, the debonding at interlayer of CFRP strand sheet and the rupture of strand sheet at joint did not occur until 1020 kN. It means that the proposed design methods regarding debonding at interlayer of CFRP and gap between strand sheets at joint are correct.

Table 7. Results of Experiment 2

Specimen	Flexural rigidity kNmm2			Load	Fracture state
	EI_{exp}	EI_{cal}	Achievement %	kN	
F10C	66700	66171	100.8	815	Debonding from the 1st layer
F10D	68594	66171	103.7	-	No fracture

4. Conclusion

In order to clarify the stiffening effect and debonding characteristics of CFRP strand sheets and to optimize the strengthening design specifications, the flexural tests, using high strength steel beams strengthened with CFRP strand sheets, were performed. The results obtained from this research are summarized as follows;

- The steel beam strengthened with CFRP strand sheets can be designed as composite cross section.
- The steel stress at the tip of the 1st layer of which debonding of CFRP strand sheet occurred was 280 MPa.
- The steel stress when the debonding occurred at interlayer of CFRP strand sheet was 310 MPa.
- 20 mm gap between the CFRP strand sheets is required at overlap splice joint.

The flexural test results of the specimens, which were designed based on the above findings, exactly agreed with the designed value. Hence, in order to establish the optimal flexural design method for steel members using CFRP strand sheets, it is important consider and reflect in design of these results.

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