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Strengthening Effect of CFRP Bonded Steel Plate with Insufficient Bond Length

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ABSTRACT: As a repair and strengthening method for steel structures, a method of bonding CFRP with resin has been applied. Generally, in CFRP bonding method, since the steel and CFRP are designed on the premise of behaving as a complete composite in section, the bonding lengths for transmitting loads are required on both sides of CFRP. However in some cases, it is difficult to secure required bonding lengths on both sides of the section to be reinforced. In this research, the tensile tests were conducted on the test specimens in which CFRP adhered to a steel plate with insufficient bond length, and the influence of insufficient bond length on strengthening effect was investigated. In addition, the experimental results were compared with the theoretical value and a design method of the reinforcement with insufficient bond length was proposed.

1 INTRODUCTION

In recent years, a method of bonding CFRP with resin has been applied as a repair method of deteriorated steel structures because CFRP is light in weight and excellent in high strength, high elastic modulus, and corrosion resistance (Wakabayashi et al.,2015). Generally, in CFRP bonding method, since the steel and CFRP are designed on the premise of behaving as a complete composite in section, the bond length for transmitting loads are required on both sides of CFRP. In some cases, the required bond length becomes longer due to the rigidity of the CFRP layer, the thickness and the shear modulus of elasticity of the adhesive layers. In addition, the corrosion of steel bridges often occurs in narrow parts and complicated shapes. In some other cases, it is difficult to secure required bond length on both sides of the section to be reinforced.

In this research, the authors focused on the case which the bond length of CFRP cannot be satisfied with the required bond length for complete composite in section. The tensile tests were conducted on the test specimens in which CFRP was bonded to both sides of a steel plate with insufficient bond length, and the influence of insufficient bond length on strengthening effect was investigated. In addition, the experimental results were compared with the theoretical ones which proposed the design method of the amount of reinforcement with insufficient bond length.

2 STRENGTHENING EFFECT WITH INSUFFICIENT BOND LENGTH

In the model that CFRP is bonded on both sides of the steel plate shown in Figure 1, the required bond length l_n for steel and CFRP to be a composite cross section is given as follows

$$l_n \geq \frac{1}{c}\cosh^{-1}\left(\frac{1}{\eta-1}\cdot\frac{1-\xi_0}{\xi_0}\right) \tag{1}$$

Where,

$$c = \sqrt{\frac{b_f G_e}{h_e}\cdot\frac{2}{1-\xi_0}\cdot\frac{1}{E_s A_s}} \tag{2}$$

$$\xi_0 = \frac{1}{1+(2E_f A_f)/(E_s A_s)} \tag{3}$$

$$G_e = \frac{E_e}{2(1+\nu_e)} \tag{4}$$

l_n : Requiered bond length for composite cross section
E_s, A_s : Elastic modulus and cross sectional area of steel plate
E_f, A_f : Elastic modulus and cross sectional area of CFRP
η : Convergence degree of steel plate stress (1.01)
b_f : Width of CFRP
G_e, h_e : Shere modulus and thickness of adhesive layer
E_e, ν_e : Elastic modulus and Poisson's ratio of adhesive layer

In order to reconcile the convergence degree η and the value of the composite cross section completely (η=1.0), the required bond length l_n becomes infinite.. Ishikawa et al.(2010) proposed to calculate the required bond length to be a composite cross section of steel and CFRP with convergence degree $\eta = 1.01$. When the bond length l is l_n or more ($l \geq l_n$) as shown in Figure 2 (a), the strain of the steel plate and CFRP at the center are corresponding with that of the calculated as a composite cross-section.

However, when the bond length is insufficient ($l < l_n$), as shown in Figure 2 (b), the strain of the steel plate is larger than that of CFRP and calculated as a composite cross-section even in the center of CFRP bonded. This is because the CFRP does not bear enough load. The strengthening effect cannot be obtained as designed by composite cross section.

Since the strain of the steel plate at the center of the CFRP bonded when the bond length is insufficient calculated using the strain calculated as the composite cross-section and the convergence degree η, in this research, strengthening effect was calculated by multiplying the convergence degree η by the strengthening effect ξ_0. For the model shown in Figure 1, the convergence degree η is given by the following equation, e.g. Ishikawa et al. (2010).

$$\eta = 1 + \frac{1}{\cosh(cl)}\cdot\frac{1-\xi_0}{\xi_0} \tag{5}$$

Where,
l : Half bond length of CFRP （$l < l_n$）

Equations (1) and (5) are applicable when a single layer of CFRP as shown in Figure 1, however in actual repair, it is often laminated in multiple layers. It is also targeted when multiple layers are bonded. Although the convergence degree in the case of multiple layers is proposed by Miyashita et al. (2011), the proposed method needs the analytical program and computationally complicated. Therefore, in this research, in order to propose a simple design method, all layers were regarded as a single layer, as shown in Figure 3. In this method, Eq. (5) is applied by the method of integrating all adhesive layers into the first adhesive layer, and the convergence degree η is calculated.

On the other hand, it is known that a debonding prevention effect can be expected by using a poly-urea putty with low elasticity and high elongation properties(Wakabayashi et al.,2015). By using a poly-urea putty, the required bond length for the steel and CFRP might become so long because the putty has low elasticity. Therefore, in order to consider the method proposed effective for the design of CFRP bonding repair with poly-urea putty, the cases of poly-urea putty were also considered.

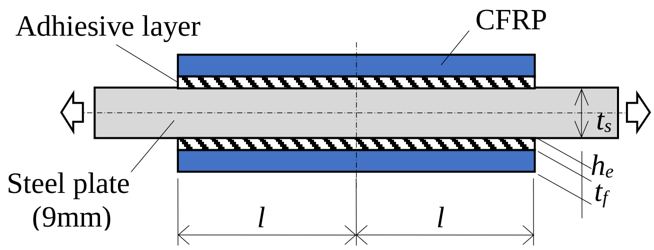


Figure 1. CFRP bonded steel model.

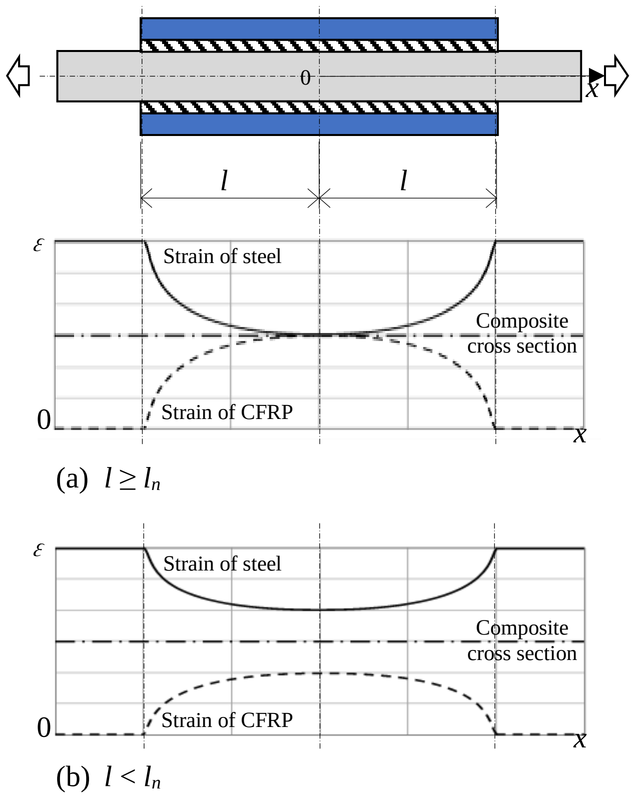


Figure 2. Strain transfer of CFRP bonded steel model.

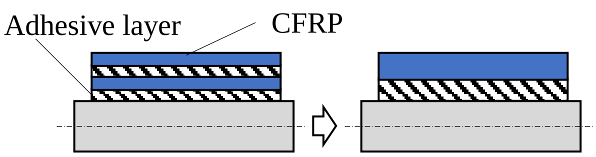


Figure 3. Thickness of Adhesive layer in the case of multi-layers.

3 EXPERIMENTAL PROCEDURE

3.1 *Materials*

The mechanical properties of each material used in the experiments and calculations are shown in Tables 1 to 3. For structural steel, the rolled steel for general structure (SS400) was used, and for CFRP, a high elasticity type carbon fiber sheet, which is the standard for steel reinforcement (Wakabayashi et al.,2015) was used.

The resin materials used were the epoxy primer and impregnation epoxy resin without poly-urea specimens, and the urethane primer, poly-urea putty and impregnation epoxy resin with poly-urea specimens. The detailed bonding procedures and resin application are described in the next section.

3.2 *Bonding procedure*

The bonding procedures with and without poly-urea are shown below. After the steel surface was treated by the grinder to remove paint and rust, the primer was applied to the steel surface, and then poly-urea was applied only for the poly-urea putty specimen. After all CFRP sheets were bonded with impregnation epoxy resin, the total thickness of the steel plate with CFRP was measured using a caliper.

Table 1. Mechanical properties of steel

Steels	Elastic modulus E_s (kN/mm^2)	Yield stress (N/mm^2)	Dimension b_s×t_s×l_s (mm)
SS400	200	341	25×6×600

Table 2. Mechanical properties of CFRP (carbon fiber sheet)

CFRP	Elastic modulus E_f (kN/mm^2)	Width b_f (mm)	Thickness t_{cf} (mm)
FTS-C8-30	684	23	0.143

Table 3. Mechanical properties of resin

Resins	Elastic modulus E_e (N/mm^2)	Poisson's ratio ν_e	Layers
FP-N9	2821	0.4	Epoxy primer
FP-E9P	2821	0.4	Impregnation epoxy resin
FP-UL1	－※	－※	Urethane primer
FU-Z	58.3	0.49	Poly-urea putty

※Unable to measure due to solvent system

3.2.1 Without poly-urea putty

The bonding procedure for the specimen without ply-urea putty is the surface treatment with the grinder → epoxy primer coating (amount: 150 g/m^2) → more than 12 hours and within 1 week curing → CFRP bonding required a number of layers (the amount of resin per each layer: 600 g/m^2) → Curing for more than a week until the resting.

3.2.2 With poly-urea putty

The bonding procedure for the specimen with ply-urea putty is the surface treatment with grinder → urethane primer coating (150 g/m^2) → more than 3 hours and within 1 week curing → poly-urea putty coating (1000 g/m^2) → more than 12 hours and within 1 week curing → CFRP bonding required number of layers (the amount of resin per each layer: 600 g/m^2) → Curing for more than a week until the resting.

3.3 *Tensile tests*

The non-strengthening sections at both ends of the test specimen were held between the chucks of the testing machine. The uniaxial monotonic tensile tests were carried out at a speed of 2 mm/min using Instron-type universal testing machine. During the test, the applied load, vertical displacement, and axial strain at the center of the steel and CFRP were measured.

4 RESULTS AND DISSCUSSION

4.1 *Thickness of adhesive layer*

Table 4 shows a list of test specimens and the measured thickness of each bonding process. The half bond length of each specimen is not enough for the composite cross section of steel and CFRP at the center of the specimen. From these measured thicknesses in each procedure, the adhesive layer thickness h_e, which required the calculation of the convergence degree of each specimen, is determined. Without poly-urea putty specimen, the adhesive layer thickness is given by the following equation.

$$h_e = \frac{t_p - t_s}{2} + \frac{t_c - t_p}{2} - nt_{cf} \tag{6}$$

Where,

t_p, t_c : Thickness of specimen after primer coating and after CFRP bonding

t_{cf} : Thickness of carbon fiber in CFRP

n : Number of layers of CFRP

With poly-urea putty specimen, the elastic modulus of poly-urea putty is as small as about one-fiftyth of that of impregnation epoxy resin. Furtherthe degree of stress transfer influence is sufficiently larger than the influence of only poly-urea layer. Therefore, the adhesive layer thickness for the calculation of the convergence degree is given by the following equation.

$$h_e = \frac{t_u - t_p}{2} \tag{7}$$

Where,

t_u : Thickness of specimen after poly-urea putty coating

4.2 *Comparison of experimental and theoretical value*

The strain at the center of the steel obtained from the tensile test is compared with that at the center of the steel calculated from the strengthening effect considering the convergence degree. The steel center strain considering the convergence degree is calculated by multiplying the non-strengthening steel strain ε_{sn} by $\eta\xi_0$.

Figure 4 shows the experimental and calculated results for E40-4 (without poly-urea, 4 layers of CFRP, half bond length l = 40 mm) and P100-4 (with poly-urea, 4 layers of CFRP, half bond length l = 100 mm). The relationship between stress and strains of the strengthening and non-strengthening steel are shown in the figure. In this figure, the experimental value of the strain at the center of the steel is shown in open circles. The theoretical value of the composite cross section is shown in dot-dashed line, and the theoretical value considering the convergence

Table 4. List of test specimens and measured thickness of each procedure

ID	Poly-urea putty	Number of ply n	Half bond length l (mm)	Measured thickness (mm)				Adhesive layer thickness* h_e (mm)
				After grinding t_s	After primer t_p	After poly-urea t_u	After CFRP t_c	
E25-2	without	2	25	5.70	6.39	-	9.23	1.479
E25-4		4	25	5.71	6.14	-	11.22	2.183
E25-6		6	25	5.72	6.15	-	12.78	2.672
E40-3		3	40	5.71	6.36	-	10.82	2.126
E40-4		4	40	5.73	6.11	-	11.13	2.128
E40-5		6	40	5.74	6.11	-	11.87	2.207
P50-3	with	3	50	5.72	5.76	7.48	12.18	0.860
P50-5		5	50	5.70	5.74	7.50	14.41	0.880
P100-3		3	100	5.70	5.74	7.44	12.36	0.850
P100-4		4	100	5.68	5.72	7.43	13.64	0.855
P150-2		2	150	5.69	5.73	7.40	11.93	0.835
P200-3		3	200	5.70	5.74	7.40	12.51	0.830

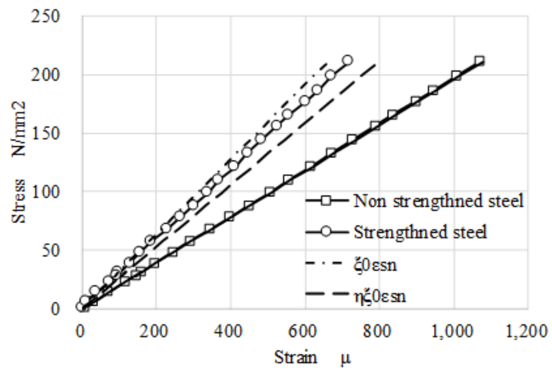
* The adhesion layer thickness with poly-urea is the application thickness of poly-urea only.

degree η is shown in dashed line. For both E40-4 and P100-4, the experimental values are plotted between the theoretical value ξ_0 of the composite cross-section and the theoretical value $\eta\xi_0$ considering the convergence degree. Additionally the strengthening effect can be evaluated on the safety side by the proposed method ($\eta\xi_0$). The difference between the experimental and the theoretical results considering the convergence degree is 12.6% for E40-4 and 6.35% for P100-4. It is found that the error is larger in the case without poly-urea putty specimen.

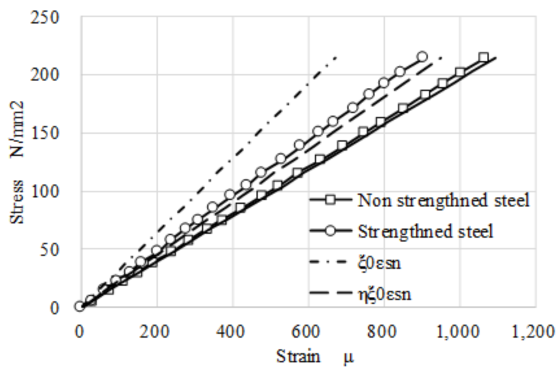
Table 5 shows a list of comparisons between the experimental and the theoretical values $\eta\xi_0$ considering the convergence degree η for all test specimens. The error between $\eta\xi_0$ and the experimental value is 3.62% to 22.60% without poly-urea, 0.86% to 6.97% with poly-urea. Therefore, it is clarified that the experimental and theoretical values agree well with poly-urea compared with the specimen without poly-urea. In addition, focusing on the difference in the number of layers under the same conditions, it is found that the error increases as the number of layers increases. This is because, as described above, without poly-urea, the effect of the resin of all the adhesive layers is concentrated to the first adhesive layer, and the difference of effect of the adhesive layer resin cannot be ignored when the number of layers increases.

Table 5. Strengthening effect and comparison between experimental and calculated values

ID	h_e mm	A_s mm^2	A_f mm^2	ξ_0	c	η	$\eta\xi_0$	$\varepsilon_{exp}/(\varepsilon_{cal}\eta\xi_0)$ (%)
E25-2	1.479	142.5	6.58	0.760	0.068	1.112	0.845	3.62
E25-4	2.183	142.8	13.16	0.613	0.044	1.379	0.846	16.95
E25-6	2.672	143.0	19.73	0.514	0.035	1.666	0.857	22.60
E40-3	2.126	142.8	9.87	0.679	0.049	1.132	0.768	4.30
E40-4	2.128	143.3	13.16	0.614	0.044	1.207	0.741	12.60
E40-5	2.207	143.5	19.73	0.515	0.039	1.381	0.711	10.51
P50-3	0.860	143.0	9.87	0.679	0.077	1.020	0.693	3.75
P50-5	0.880	142.5	16.45	0.559	0.065	1.062	0.593	6.97
P100-3	0.850	142.5	9.87	0.679	0.077	1.000	0.679	6.65
P100-4	0.855	142.0	13.16	0.612	0.070	1.001	0.613	6.35
P150-2	0.835	142.3	6.58	0.760	0.090	1.000	0.760	0.86
P200-3	0.830	142.5	9.87	0.679	0.078	1.000	0.679	2.77



(a) E40-4



(b) P100-4

Figure 4. Relationship between stress and strain of E40-4 and P100-4.

Therefore, the adhesive layer thickness without poly-urea having large error is corrected. The adhesive thickness considering the influence of matrix resin of CFRP plate was proposed (Shirai et al.,2015). In the proposed method, by adding 1/3 of the thickness of the matrix resin in the CFRP plate to the adhesive thickness by multiplying the shear stiffness ratio of the matrix resin and the adhesive, it is possible to consider the shear deformation of the matrix resin.

In this research, the adhesive layer is the epoxy primer and impregnation epoxy resin, and the adhesive layer thickness is corrected by the same method as Shirai et al (2015). In this research, since the shear stiffness of the epoxy primer and the impregnation epoxy resin is the same, the modified adhesive layer thickness h_e' is given by the following equation.

$$h_e' = \frac{t_p - t_s}{2} + \frac{1}{3}\left(\frac{t_c - t_p}{2} - nt_{cf}\right) \tag{11}$$

Table 6 shows a comparison of the theoretical and experimental values calculated using the adhesive layer thickness h_e', the same procedure was applied to specimens without poly-urea layer. Although E25-4 and E25-6 have errors of 3.09% and 5.14%, the errors of all specimens are significantly improved, and it is clear that the experimental values and the theoretical values are almost the same by using the modified adhesive layer thickness h_e'.

Table 6. Strengthening effect and comparison between experimental and calculated values without poly-urea putty by using modified adhesive layer thickness

ID	h_e'	c'	η'	$\eta'\,\xi_0$	$\varepsilon_{exp}/(\varepsilon_{cal}\eta'\xi_0)$ (%)
E25-2	0.723	0.097	1.056	0.802	-1.62
E25-4	0.871	0.069	1.216	0.746	3.09
E25-6	1.034	0.057	1.431	0.736	5.14
E40-3	0.925	0.074	1.049	0.712	-2.84
E40-4	0.836	0.071	1.074	0.659	-0.39
E40-5	0.859	0.062	1.155	0.595	-7.76

5 CONCLUSION

When the bond length is insufficient and steel and CFRP do not become a composite cross-section at the center of CFRP bonded, an evaluation method considering the convergence degree is proposed and compared with the experimental results. The main conclusions obtained from this study are as follows.

- In the case of without poly-urea putty, it is possible to evaluate the strain of steel on the safe side by multiplying the strengthening effect by the convergence degree, which was calculated by adding the impregnation resin of each layer to the first layer.
- When the number of the ply of CFRP increases, the error between theoretical value considering the convergence degree and the experimental value obtained from the tensile tests becomes larger. However, by adding 1/3 of the total thickness of the impregnation resin to the primer, the experimental value and the theoretical value almost matched.
- In the case of with poly-urea putty, the rigidity of the poly-urea putty and the impregnation epoxy resin differ greatly; therefore, the experimental value and theoretical value almost agreed, by using the convergence degree, which was calculated by using only the thickness of the poly-urea putty as adhesive layer.

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