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Long-term Mechanical Behavior of CFRP-strengthened Steel Members for a Truss Tower

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Abstract

This research aimed to clarify the long-term mechanical performance of a steel truss member strengthened by a carbon fiber-reinforced polymer (CFRP) without protective coating through exposure testing. Strengthening and repair methods using CFRP have been developed in recent years; however, there is a lack of durability research for CFRP-strengthened members, especially mechanical performance investigation according to actual exposure testing. In this study, 10 CFRP-strengthening steel specimens were created in 2015, and elastic bending tests were conducted biannually. Eventually, although resin loss occurred due to environmental effects, the mechanical performance of CFRP-strengthened steel was not degraded, and we propose a calculation method of bending stiffness to evaluate the lower value of stiffness for design.

Keywords: Exposure test, Bending test, CFRP, Strengthening, Steel tower

1. Introduction

Many steel high-rise structures, e.g., power transmission towers and radio wave towers, have been built and support human activities and industrial work as well as the economy. However, it is reported that the corrosion of steel structural members occurs and results in the severe structural performance degradations (Budhe et al. 2019 and Alcántara et al. 2017). Furthermore, the collapse of steel towers has occurred several times due to heavy wind and typhoons. Steel bridges, buildings and marine structures should be repaired to maintain their mechanical performance and avoid degradation from corrosion. A gainst this background, a large number of repair and strengthening methods have been proposed using member replacement, additional steel members and reinforced polymer material (Zhao et al. 2007 and Linghoff et al. 2009). In the case of the use of reinforced polymer material, usually, adhesively bonded CFRP plates or hand-layup-molded CFRP using carbon fiber (CF) sheets are applied to the steel surface. CFRP plates have excellent mechanical properties, such as a high elastic modulus, strength, a quite stable mechanical character and speedy construction, but CFRP plates can only be applied to the planar surface. On the other hand, a hand-layup can be applied to various surface conditions, and we can design various fiber orientations depending on the design requirements. Thus, the CFRP strengthening method for steel members by hand-layup is a much-researched topic and is used in civil engineering fields (Zhao et al. 2007 and Nhut et al. 2020). Although the durability of CFRP material has been reported (Vistasp 2007, Ascione et al. 2008, Borrie et al. 2015, Mohsen et al. 2016 and 2017, Batuwitage et al. 2017, Liang et al. 2018 and Talikoti et al. 2019), a lack of durability research for CFRP-strengthened members has been presented, i.e. mechanical performance according to actual exposure testing (Nishizaki et al. 2015) is not clarified in detail. In this study, 10 CFRP-strengthened steel specimens were created in 2015, and elastic bending tests were conducted biannually including bare steel specimen to clarify their long-term mechanical performance. Then, the variations of the bending stiffness and stiffness evaluation methods of CFRP-strengthened steel were clarified.

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2. Specimens

The experimental study tested typical, slender, steel, circular hollow-section members under elastic three-point bending. All specimens consisted of galvanized steel with a diameter of 60.5 mm, thickness of 2.3 mm, length of 3,660 mm, and a slenderness ratio of 220. In total, 10 CFRP-strengthened specimens were made by the hand-layup molding method, as shown in Figure 1, in February 2015. Hand-layup molding does not require any special, heavy and electrical machines for molding, and so the method can be applied to an existing steel tower easily.

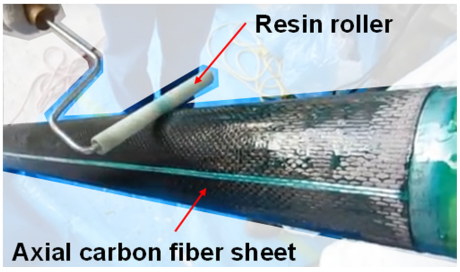


Figure 1. Hand-layup molding method.

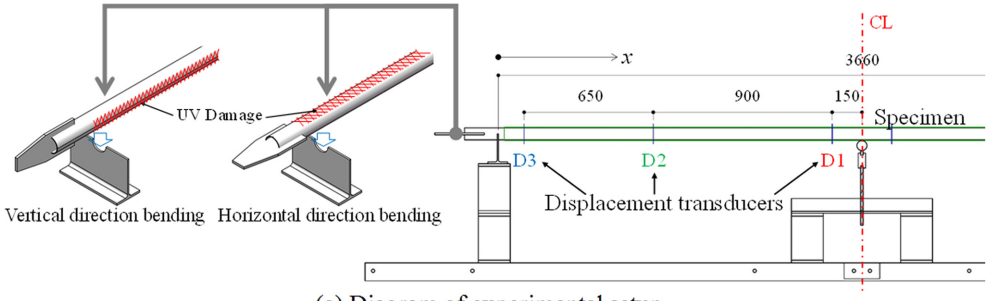
All specimens were molded on an actual steel tower to confirm the applicability of the method and evaluate the variation of mechanical properties, and painting (protective coating) was not applied to minimize the construction time and evaluate the environmental impact without a protective coating of the CFRP. In total, three plies of carbon fiber sheets (UM46-40G, Toray Industries, Japan) with a 440 GPa elastic modulus were used for the wrapping of CFRP-strengthened steel specimens to provide almost 75% increase in flexural stiffness. To mold and adhere a CFRP onto steel surface, we used primer resin (E810L, Konishi Co., Japan) on galvanized steel surface firstly, then impregnate the epoxy resin (E2500, Konishi Co., Japan) by hand-layup. After the preparation of CFRP-strengthened steel specimens, in total, five specimens were exposed outdoors and other five specimens indoors to evaluate the durability of the material and variation of CFRP strengthening effects. On the other hand, a bare steel specimen was also prepared to compare the CFRP strengthening effects and get a benchmark of bending stiffness. Figure 2 shows the outdoor exposure test conditions. CFRP-strengthened specimens were set up in a horizontal direction to the plane of gusset plates shown in Figure 2 to concentrate a damage by ultraviolet (UV). The value of the UV energy at the exposure position was 374MJ/m^2/year in 2015.

3. Experiment

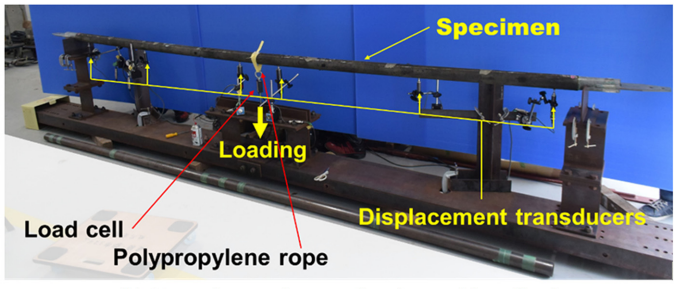
Figure 3 shows the experimental method and setup.



Figure 2. Exposure test condition.



(a) Diagram of experimental setup



(b) Experimental setup (horizontal bending)

Figure 3. Experimental method.

Loading was applied with a polypropylene rope to prevent damage to the CFRP surface. Boundary condition can be assumed to the simply supported condition because specimens were put on the semicircular cut-out plate as shown in Figure 3 (a). Figure 3 (a) also shows the UV-damaged surface corresponding to bending directions. Experiments were conducted biannually from February 2015 to September 2020. Two type of loading direction were adopted as shown in Figure 3 (a) - a horizontal and vertical direction to the plane of gusset plates - because the CFRP-strengthened specimens were horizontally set up in the exposure test as shown in Figure 2. Thus, variation of bending stiffness depended on gusset plate direction is expected because the resin of top surface in the exposure test was severely damaged by UV. The slenderness ratios (λ) of the specimens without and with CFRP strengthening were 220 and 160, respectively. Thus, the authors adopted an elastic bending test to investigate the mechanical performance of the compressive strength, because the compressive strength can be evaluated by the Euler buckling strength of specimens using the elastic modulus (E) and slenderness ratio (Architectural Institute of Japan 2005).

Table 1. Bending stiffness calculated by theory

	D1 (N/mm)	D2 (N/mm)	D3 (N/mm)
Bare steel	36.1	59.5	335.8
CF-sheet evaluation	61.5	101.4	572.6
CFRP evaluation	65.0	107.1	604.8

Table 2. Sectional coefficients of specimens

	Moment of inertia (mm^4)	Elastic modulus (GPa)	EI_{CFRP} ($kN{\cdot}mm^2$)
CF-sheet evaluation	585×10^2	440	257×10^5
CFRP evaluation	332×10^3	88	292×10^5

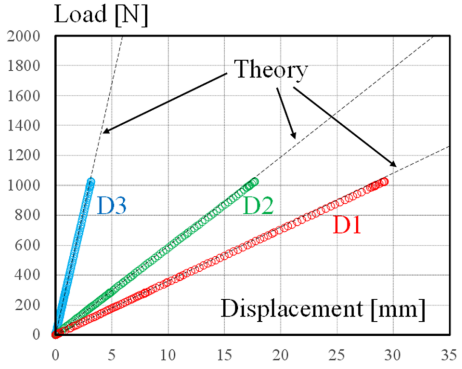


Figure 4. Load - displacement relations for bare steel specimen.

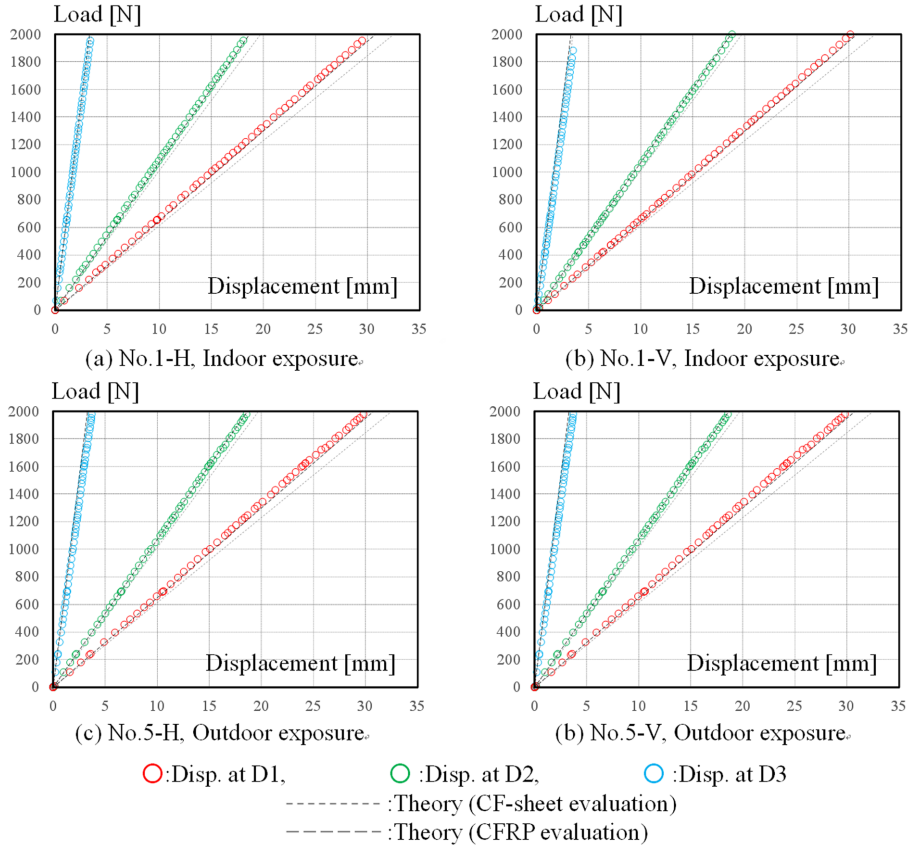


Figure 5. Load - displacement relations for CFRP-strengthened specimens (February 2015).

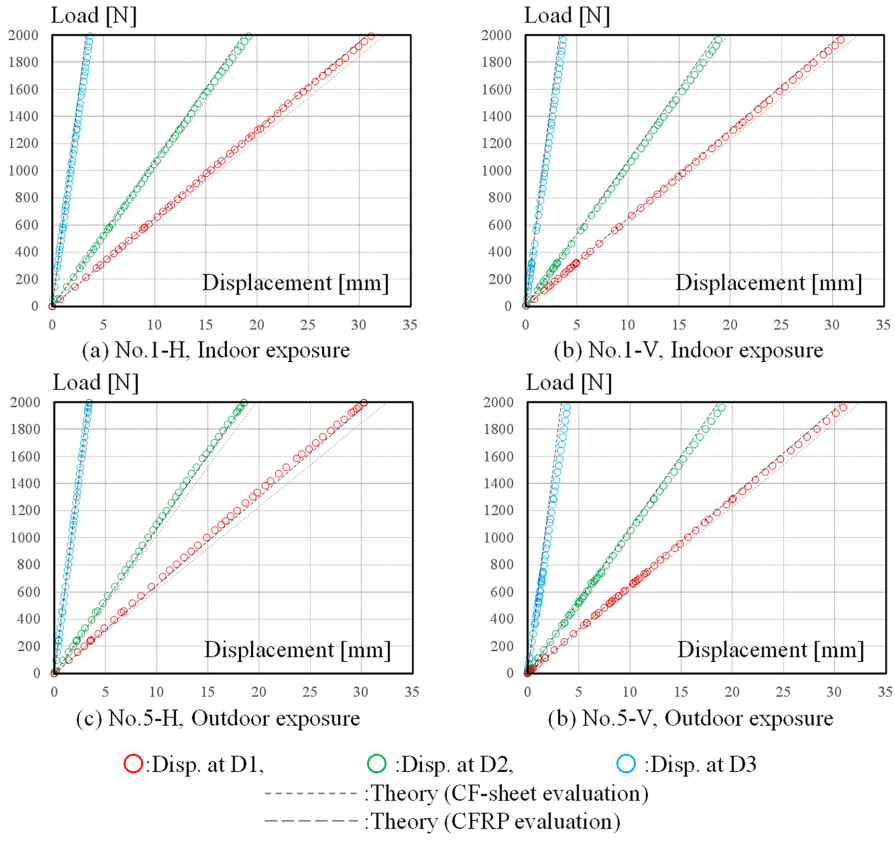


Figure 6. Load - displacement relations for CFRP-strengthened specimens (February 2018).

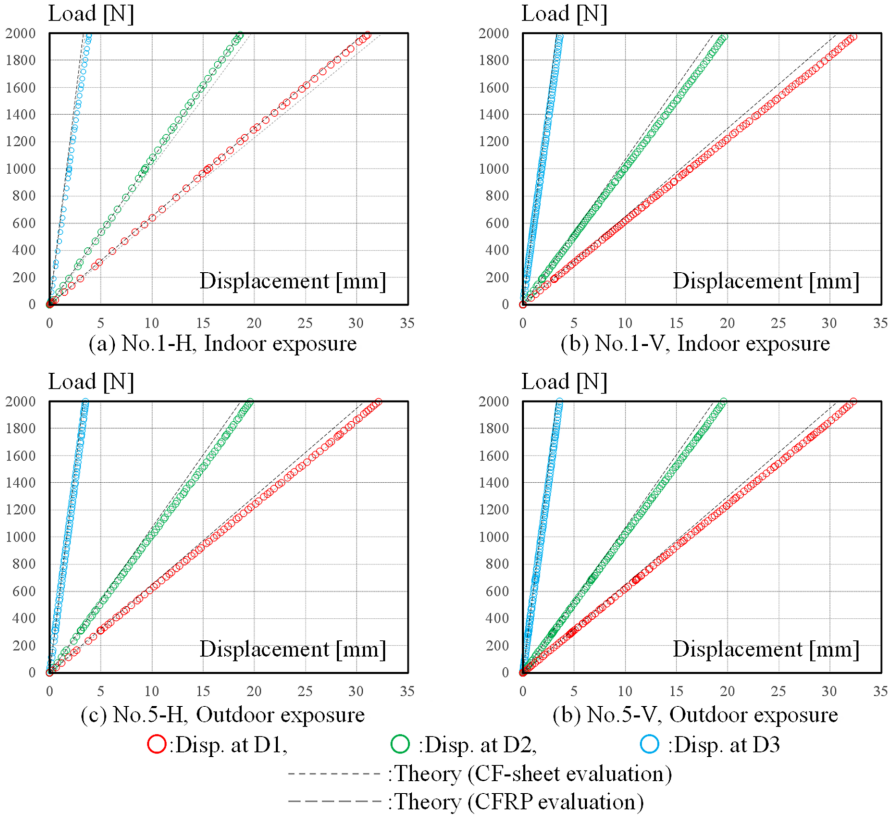


Figure 7. Load - displacement relations for CFRP-strengthened specimens (September 2020).

4. Exprimental Results and Discussions

Table 1 shows the evaluated bending stiffness according to Bernoulli-Euler theory. The theoretical stiffness is obtained by the following equation:

$$\delta=\frac{P}{48(E_sI_s+EI_{CFRP})}(6xL^2-4x^3) \quad (1)$$

where P represents central loading, E_s is the elastic modulus of steel (E_s = 205 GPa (Architectural Institute of Japan 2005)), I_s is the moment of inertia of steel (I_s = 178,000 mm^4 (Japanese Industrial Standards, 2015)), EI_{CFRP} is the bending stiffness of CFRP, L is the span and x is the position of displacement transducers, e.g., position of displacement transducer D1 corresponds to x=1,680 mm. In this study, two types of bending stiffness were assumed for CFRP-strengthened specimens, as shown in Table 2. CF-sheet evaluation means that the bending stiffness was calculated by the mechanical properties of the carbon fiber with 100% volume content, and CFRP evaluation was calculated by the composite law using the mechanical properties of carbon fiber and resin with a 20% volume content of fiber, as shown in equation (2). In both evaluation method –CF-sheet evaluation and CFRP evaluation–, the elastic modulus of resin is not considered because of its minuscule effect.

$$EI_{CFRP}=\begin{cases}E_{CF}\dfrac{\pi}{64}\{(60.5+2\times3t_{CF})^4-60.5^4\} & \text{: CF-sheet evaluation}\\ \dfrac{E_{CF}}{5}\dfrac{\pi}{64}\{(60.5+2\times5\times3t_{CF})^4-60.5^4\} & \text{: CFRP evaluation}\end{cases} \quad (2)$$

Figure 4 shows the load-displacement relations obtained by bending tests and theoretical relations for a bare steel specimen. Furthermore, Figure 5 shows the load-displacement relations for the CFRP-strengthened specimen. The theoretical relations in Figure 4 and 5 are calculated by equations (1) and (2). Load–displacement relations correspond to theory with only 3% errors, and so it can be confirmed that the adopted experimental method shown in Figure 3 can successfully evaluate the bending stiffness. Figure 5 (a)-(d) shows that all experimental results correspond to the theory; in particular, it can be seen that CFRP evaluation provides a good evaluation for the experiment, and a linear elastic behavior can be found. Figure 6 shows the results in February 2018, with three-year exposure results, and Figure 7 shows the results in September 2020, after 5.5 years. We cannot find significant differences between the initial results conducted in February 2015 and the results in September 2020. Figure 8 shows the variation of bending stiffness evaluated from load-displacement relations in Figures 5-7. There is a

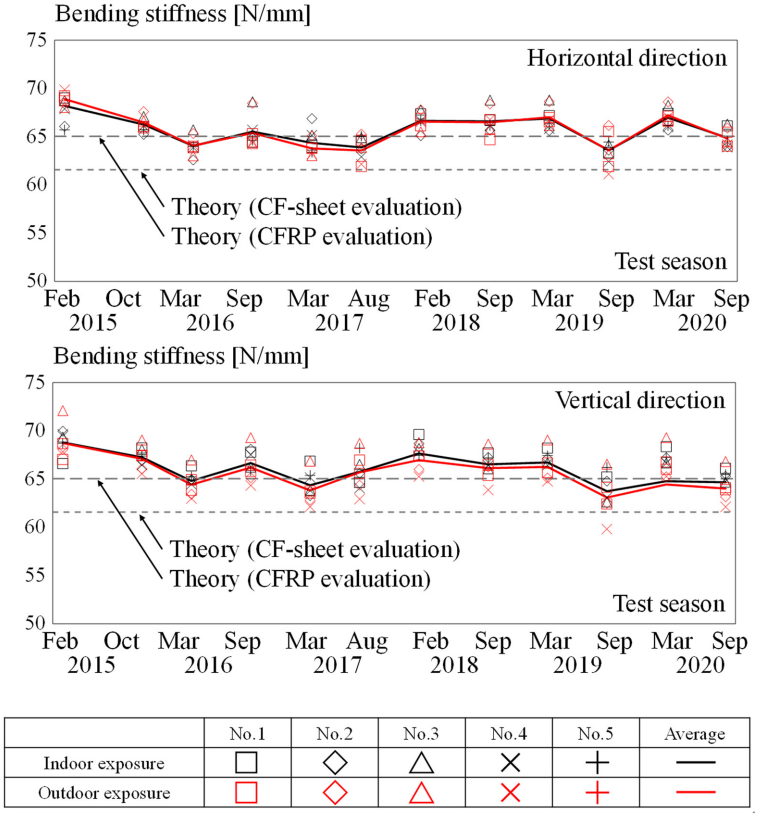


Figure 8. Variation of bending stiffness for CFRP-strengthened specimens.



(a) Indoor exposure specimen (b) Outdoor exposure specimen

Figure 9. CFRP surface in September 2020.

small amount of variability in each test, but we consider that an almost stable elastic bending test could be conducted because the variation coefficient of each specimen is 1.6-3.7%. The bending stiffness of outdoor-exposure specimens was slightly lower than those indoors; this is because a loss of the outer matrix resin occurred due to UV effects. However, the lower bound of bending stiffness can be evaluated for CF-sheets, as shown in Figure 8, because the CF-sheet evaluation assumes minimum effects of CFRP strengthening. Figure 9 shows the surface condition of CFRP-strengthened specimens in September 2020. In the case of indoor-exposure specimens, they resembled fairly new specimens despite being made in 5.5 years prior to observation. On the other hand, it can be found that outer epoxy resin of the upper side was almost removed and the CF reaches the outside. However, a CF layer can stop UV light from transferring inside the CFRP, and so it is estimated that the material degradation will be stopped and damage will not increase sustainably.

5. Conclusions

In this paper, the long-term mechanical performance of CFRP-strengthened steel pipes without protective coating was evaluated through exposure and bending tests. We confirmed that the bending stiffness was not decreased significantly in 5 years, even if coating was not applied to prevent the damage of the resin by UV. Furthermore, bending stiffness could be evaluated by the fully composite beam theory. Although resin loss occurred due to environmental effects, the mechanical performance of CFRP could be reasonably calculated by the CF-sheet evaluation. This means that the use of CFRP to strengthen degraded steel does not require a protective coating, allowing a reduction of the construction time.

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