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Repair method for corroded steel girder ends using CFRP sheet

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ABSTRACT: Loss of cross section owing to corrosion is a primary factor in the deterioration of steel bridges. Therefore, carbon fiber-reinforced plastic (CFRP) sheet has attracted attention as a material for repairing and reinforcing steel bridges because of its light weight, high strength, and superior durability. Although many studies have been published relating to this topic, previous studies have primarily focused on the application of CFRP to axial or bending members. However, most of the corrosion is found on the webs or columns at the ends of the main girders. Few investigations have examined repairing corroded webs or columns using CFRP sheet. In this research, a shear buckling test for steel girders and a uniaxial compression test for cruciform columns are conducted to develop a repair method for corroded steel girder ends using CFRP sheet. In this method, low elastic putty layers are inserted between steel and CFRP sheets to improve the performance of out-of-plane deformation.

1 INTRODUCTION

In Japan, most of the deterioration of steel structures stems from corrosion. In particular, steel girders are corroded at the ends owing to water leakage from expansion joints. Additionally, deicing salts used in winter worsen this situation. The usual repair work for such damage includes replacing corroded members with new ones or attaching new steel plates onto the corroded part using bolts or welding, as shown in Figure 1. However, these repairs lack workability because heavy machinery and welding devices are required, regardless of the scale. As a result, repair works have not progressed, despite the increasing number of corroded locations. This has become an issue. Therefore, a simple and effective repair method for corroded steel girder ends is urgently needed.

To overcome this problem, we focused on fiber-reinforced polymers as repair materials for corroded steel girder ends. Among them, carbon fiber-reinforced polymer (CFRP) is particularly promising owing to its light weight and superior elasticity, strength, and durability. Repairs to seismic retrofit concrete structures using CFRP have been extensive in Japan. However, applications of CFRP to steel structures are comparatively rare, although CFRP has been applied to flanges in steel girder bridges and chord members in steel truss bridges. In general, these members are subjected to normal stress. However, corrosion in steel bridges primarily occurs at webs or vertical stiffeners near supports. With these members, local buckling is of concern, yet there are few studies on the application of CFRP to these members. Okuyama et. al. (2012) presents the test results on CFRP plate-stiffened light steel beams under end-bearing loads. These tests revealed that CFRP strengthening significantly increases the web-buckling capacity. However, it was not known whether CFRP-stiffened beams reached the maximum load owing to debonding. Moreover, this research does not address shear buckling or the repair of corroded steel. Therefore, this study focuses on the applicability of CFRP in repairing corroded webs and vertical stiffeners at the ends of steel girders.

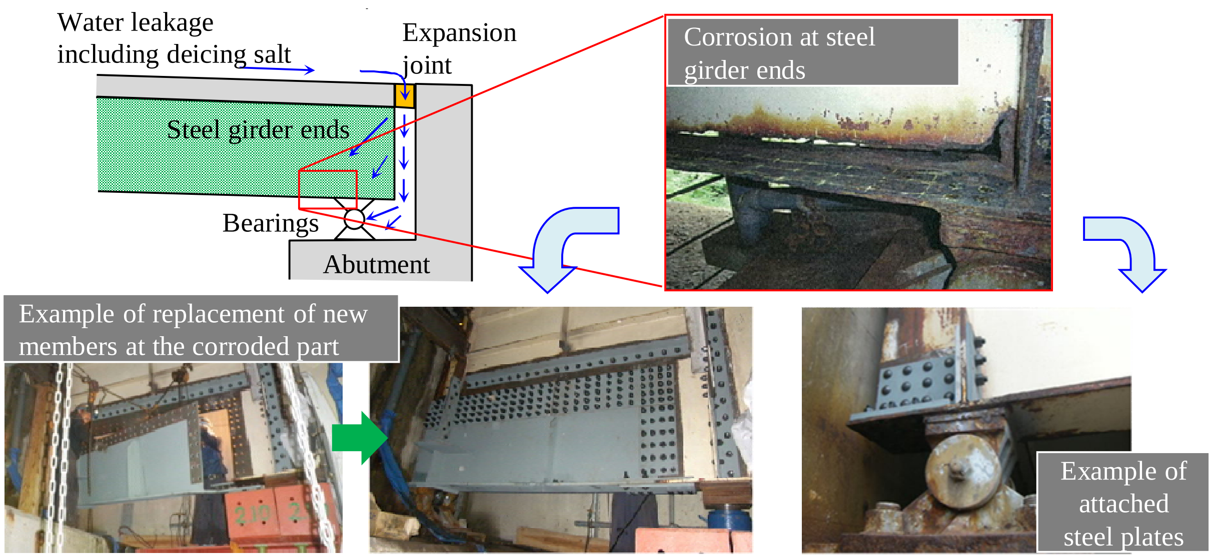

Figure 1. Repair Method Using Steel Plates for Corroded Girder Ends

2 REPAIR METHOD USING CFRP SHEET

When corroded vertical stiffeners or webs are in an ultimate state, local or shear buckling might occur under compression or shear, as shown in Figure 2 and Figure 3. Thus far, it has not been reported whether CFRP bonded on these members can adapt to large deformations and recover the initial performance of the members. Therefore, we studied the constitution of the adhesion layer that will prevent the delamination of CFRP caused by buckling. Our previous study confirmed that inserting polyurea putty, which has a low elastic modulus (55–75 MPa) and high elongation (300–500%), between the steel plate and CFRP sheet can help prevent delamination under large deformations. In this study, it is difficult to acquire material properties from non-tensile tests because elongation at the break is excessively high. A high modulus carbon fiber sheet, with Young's modulus of 640 GPa, displayed the best repair efficiency among the various FRP sheets tested. Therefore, we propose a repair method for corroded vertical stiffeners and webs at steel girder ends using CFRP sheets, as shown in Figure 4. In the following sections, we will report on the practical design method and the results of experiments conducted to confirm its validity.

Figure 2. Local Buckling at Vertical Stiffener

Figure 3. Shear Buckling at Webs

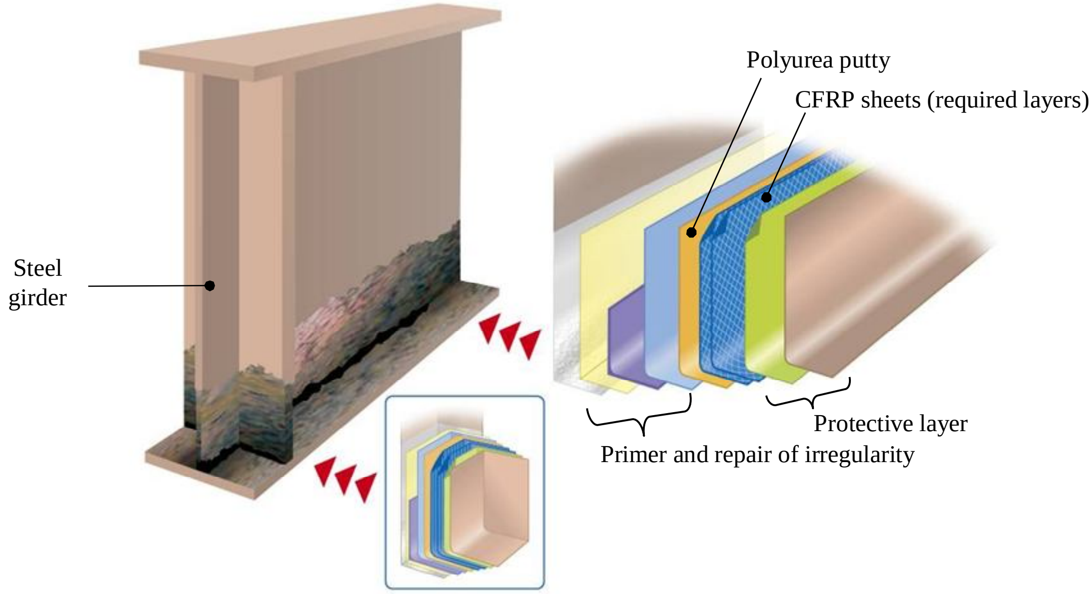

Figure 4. Proposed Repair Method Using CFRP Sheets for Steel Girder Ends

3 DESIGN METHOD FOR CORRODED SUPPORTS

The reaction force on the support is resisted by a cross section consisting of vertical stiffeners and webs, as shown in Figure 5. When some parts of the support are corroded, load-carrying capacity in compression suddenly decreases by induced local buckling. Herein, we considered applying CFRP sheets to the corroded support to recover its compressive strength. CFRP sheets are adhesively bonded to the corroded parts.

The number of CFRP layers is determined so that the layers add up to be thicker than the thickness reduced by corrosion, which is calculated by using the steel equivalent thickness of the CFRP sheet; the thickness of a CFRP sheet is converted to that of steel using the ratio of Young's modulus for CFRP to steel. This design concept is consistently adopted in this paper. The fiber is oriented in the vertical direction. With this method, the strength recovers when the CFRP is bonded to coincide with the direction of load transfer. This leads to increased flexural stiffness, which is proportional to the critical buckling load. Details of the bonding method of CFRP sheets on the corroded support are shown in Figure 6.

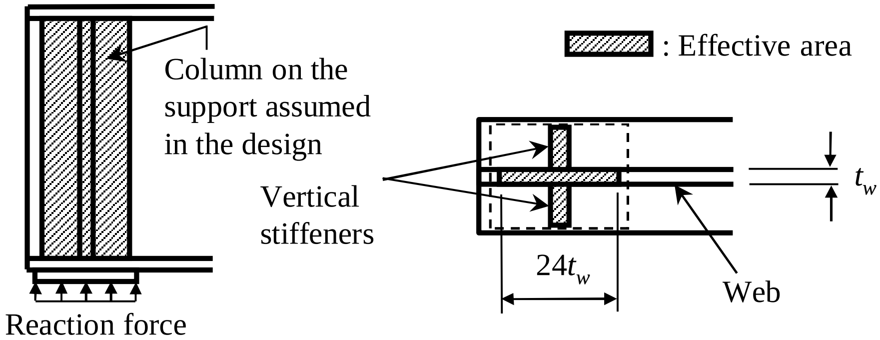

Figure 5. Actual Cross Section on Support for Reaction Force

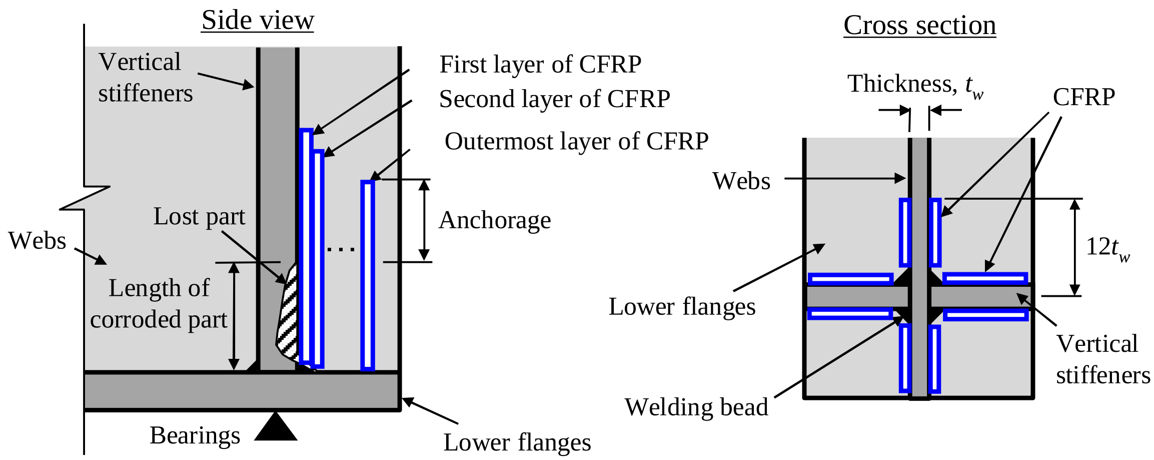

Figure 6. Details of Bonding Method of CFRP on Corroded Support

To verify the validity of this design method, we conducted uniaxial compression tests on girders with the thickness at the bottom reduced to simulate actual corrosion conditions, as shown in Figure 7. Two types of tests were conducted: one without CFRP and one with CFRP bonded on the corroded part. The number of CFRP layers and other details were determined by the above-mentioned method. As stated, the CFRP sheets were bonded on vertical stiffeners and webs to match the amount of loss in each part. The bottom ends of the CFRP bonded on the webs were anchored on the lower flanges to create an R-shape, as shown in Figure 8. The relationships between load and vertical displacement at the loading point are shown in Figure 9. Additionally, to confirm the expected recovery of strength in design, finite-element analysis (FEA) was conducted. The results revealed that load-carrying capacities in compression can recover as expected by using the proposed design method.

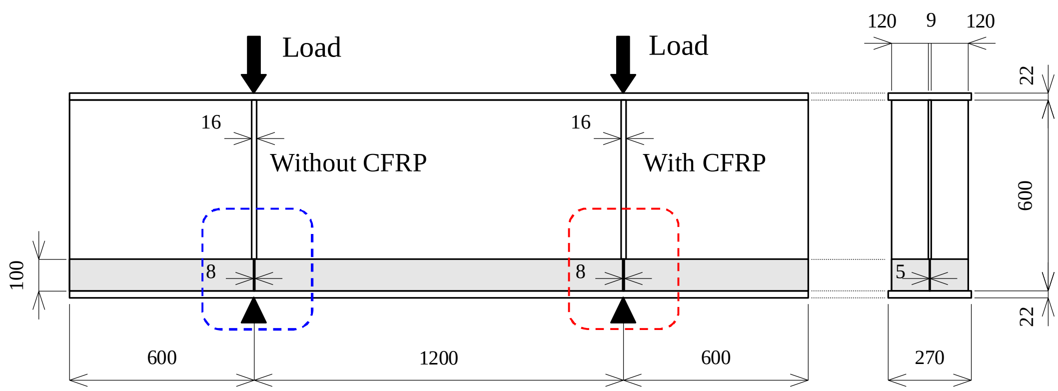

Figure 7. Test Girder for Uniaxial Compression Test

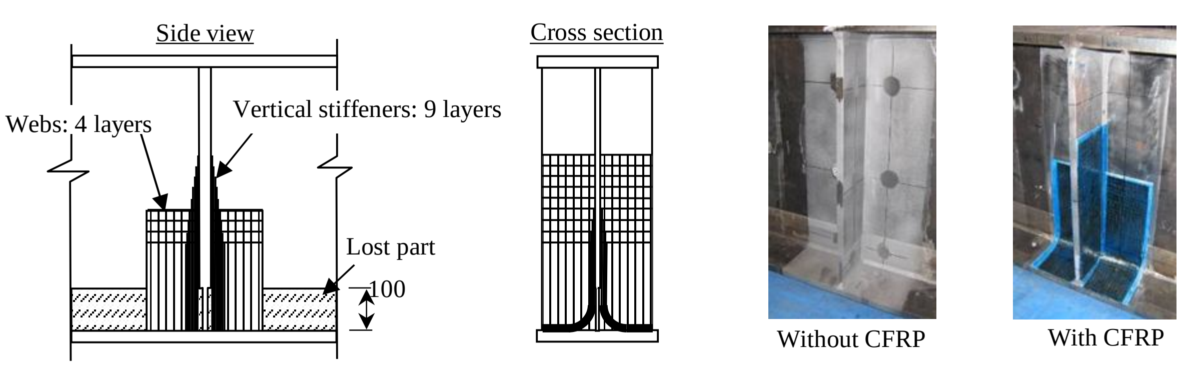

Figure 8. Details of Bonded CFRP on Specimen

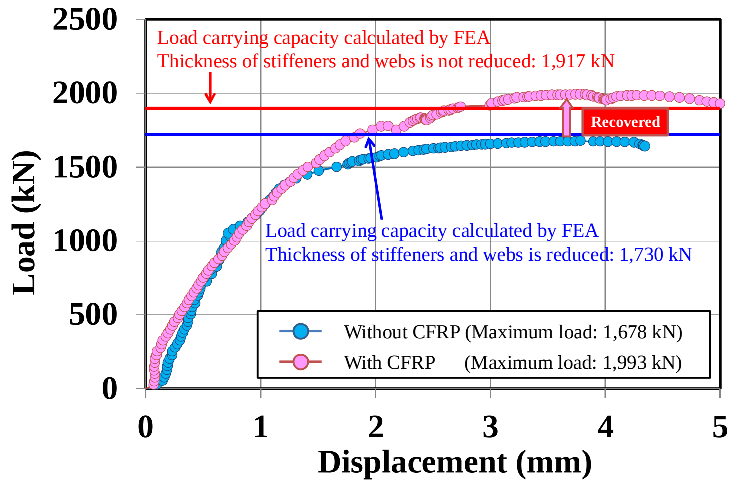

Figure 9. Load-Displacement Curve

4 DESIGN METHOD FOR CORRODED SUPPORTS

Corrosion in a steel girder often develops not only at flanges and vertical stiffeners near supports but also at end web panels. In this case, because the load-carrying capacity of the girder decreases under shear owing to corrosion, repairing of corroded webs is necessary to recover their initial performance. For this purpose, we considered applying CFRP sheets to repair corroded webs. The design method determining the number of CFRP sheets was the same as that mentioned in the previous section; the thickness of CFRP sheets was converted to that of steel by using the ratio of Young's modulus for both. The orientations of carbon fiber were set at ±45° considering the direction of the principal stress under shear. The same number of CFRP sheets was bonded on both sides of the web in the directions of compression and tension. The details are shown in Figure 10. The bottom ends of CFRP on the webs were anchored on the lower flanges in an R-shape.

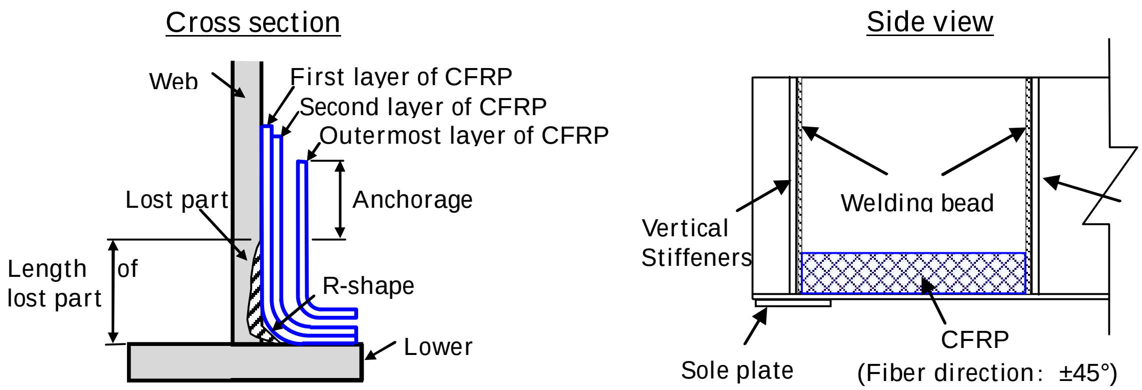

Figure 10. Details of CFRP Bonding Method on Corroded Webs

To verify the validity of this design method, an extreme situation in an existing bridge was considered and shear buckling tests were conducted for full-scale steel girders with simulated corrosion at the bottom of the web panel. Figure 11 shows the schematic view of the tested girders. Three cases were tested: (1) a sound girder (G1), (2) a corroded girder (G2) with a through-hole opened in the test web panel to simulate the corrosion, and (3) a repaired girder (G3) with the through-hole repaired by the proposed CFRP bonding method. The number of CFRP layers was 18 (nine layers in each orientation) per side. The same number of layers was bonded on both sides of the web.

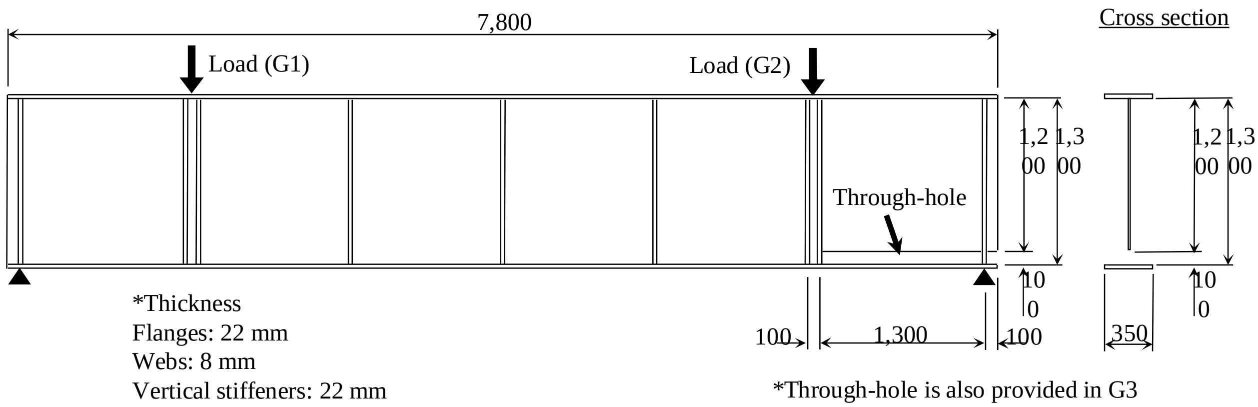

Figure 11. Full-Scale Test Girder for the Shear Buckling Test

Figure 12 shows the relationship between load and vertical displacement under the loading point resulting from the shear buckling test. The maximum loads in case G2 (corroded case) decreased by approximately 16% compared with case G1 (sound case). On the other hand, the initial performance was recovered in case G3 by bonding CFRP to the through-hole in the web. Therefore, even when severe corrosion in the form of through-holes occurs on end web panels, the load-carrying capacity under shear is recovered by using the proposed method to appropriately bond CFRP sheets on the corroded webs.

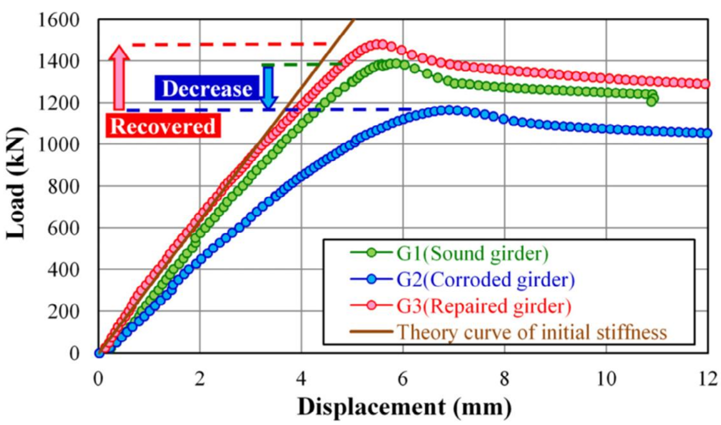

Figure 12. Load-Displacement Curve

5 CONCLUSIONS

The objective of this study was to establish a repair method using CFRP sheets for corroded steel girder ends that have reduced load-carrying capacities in compression and shear. (1) CFRP sheets were adhesively bonded on corroded vertical stiffeners and/or webs near supports by using a putty layer with low elastic modulus. This putty layer prevents delamination of CFRP sheets when large deformations are induced by buckling. (2) First, we conducted uniaxial compression tests of girders to confirm the applicability of the proposed method to corroded supports that have reduced load-carrying capacity in compression. The thickness of the bottom of the girders was reduced to simulate corrosion. Results of the experiments revealed that initial performance can be recovered by adhesively bonding CFRP sheets. (3) Next, shear buckling tests were conducted to confirm the applicability of the proposed method to corroded webs near supports with reduced load-carrying capacity under shear. Test girders were full-scale models and corrosion was simulated by creating a through-hole, reflecting the extreme condition of the girders. Results of the experiments showed that even when severing corrosion created a through-hole on the end web panels, load-carrying capacity under shear can be recovered by using the proposed method to appropriately bond CFRP sheets on the corroded webs.

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