REPAIR METHOD USING CFRP FOR CORRODED STEEL GIRDER ENDS

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ABSTRACT

This paper describes a study on a repair method using Carbon Fiber Reinforced Polymer (CFRP) sheets for corroded steel girder ends that have reduced load-carrying capacities in compression and shear. CFRP sheets are bonded on the corroded vertical stiffeners and/or webs using a low elastic modulus putty layer. This putty layer makes it possible to prevent delamination of the CFRP sheets when large deformations occur induced by buckling. A practical design method is proposed, and laboratory experiments for validation are described.

KEYWORDS

Carbon fiber reinforced polymer, steel bridge, repair, buckling, experiment, design.

INTRODUCTION

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

Figure 1. Repair method using steel plates for corroded girder ends
To overcome this problem, we focused on fiber reinforced polymers as repair material for corroded steel girder ends. Among them, carbon fiber reinforced polymer (CFRP) is especially promising due to its characteristics such as light weight, high elasticity, high strength and high durability. Repairs carried out to seismic retrofit concrete structures using CFRP have been widely done in our country. On the other hand, applications of CFRP to steel structures are comparatively rare; although CFRP has been applied to flanges in steel girder bridges or chord members in steel truss bridges. In general, these members are subjected to normal stress. But corrosion in steel bridges mostly 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. Ref.1) presents the test results on CFRP plate stiffened light steel beam under end-bearing loads. It revealed the CFRP strengthening significantly increases the web-buckling capacity. However, there was a case that did not know whether CFRP-stiffened beam reached the maximum load due to debonding. Moreover, this research does not address the repairing of corroded steel and the shear buckling. Therefore, this study focuses on the applicability of CFRP in repairing corroded webs and vertical stiffeners at the ends of the steel girders.

**REPAIR METHOD USING CFRP SHEETS**

When corroded vertical stiffeners or webs are at an ultimate state, local or shear buckling might occur under compression or shear, as shown in figure 2 and figure 3. So far it has not been reported that CFRP bonded on these members can adapt to large deformations and recover their initial performance. Therefore, we studied the constitution of the adhesion layer that will prevent delamination of CFRP caused by buckling. Our previous study confirmed that polyurea putty, which has low elastic modulus (55-75MPa) and high elongation (300-500%), inserted between the steel plate and CFRP sheet, can help prevent delamination under large deformations. Here, it is difficult to acquire material properties obtained from other than a tensile test because elongation at break is too high. And high modulus carbon fiber sheet, with Young’s modulus of 640GPa, had the best repair efficiency among the various FRP sheets tested. We, therefore, propose the repair method for corroded vertical stiffeners and webs at the steel girder ends using CFRP sheets, 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.
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 the application of CFRP sheets to the corroded support in order to recover the compressive strength. CFRP sheets are adhesively bonded on the corroded parts.

The number of CFRP layers is decided so that the layers add up to be thicker than the thickness reduced by corrosion, which is calculated using steel equivalent thickness of 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. And the orientation of the fiber is set to be in the vertical direction. With this method, the strength recovers when 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. The details on the bonding method of CFRP sheets on the corroded support are shown in figure 6.

To check the validity of this design method, we carried out 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 the other with CFRP bonded on the corroded part. The number of CFRP layers and other details were determined by the above mentioned method. And 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 CFRP bonded on the webs were anchored on the lower flanges to provide an R-shape as shown in figure 8.

Figure 5. Actual cross section on the support for reaction force

Figure 6. The details of bonding method of CFRP on the corroded support

Figure 7. The test girder for the uniaxial compression test
The relationship between load and vertical displacement at the loading point are shown in figure 9. Here, to confirm the expected recovery of strength in design, finite element analyses (FEA) were also conducted. The result revealed that load-carrying capacities in compression can recover as expected by using the proposed design method.

DESIGN METHOD FOR CORRODED WEB

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 in shear due to corrosion, it is necessary to repair corroded webs to recover their initial performance. For this purpose, we considered the application of CFRP sheets to repair corroded webs. The design method determining the number of CFRP sheets was the same as mentioned in the previous section; the thickness of CFRP sheets was converted to that of steel using the ratio of Young’s modulus for both. The orientations of carbon fiber were set at ±45 degrees considering the direction of the principle 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 providing an R-shape.
To check the validity of this design method, considering an extreme situation in an existing bridge as shown in figure 11(a), shear buckling tests were carried out for full-scale steel girders with simulated corrosion at the bottom of the web panel as shown in figure 11(b). Figure 12 shows the schematic view of the tested girders. Three cases were tested. The first case was sound girder (G1). The second case was corroded girder (G2), with a through-hole opened in the test web panel to simulate the corrosion. The last case was repaired girder (G3); the through-hole was repaired by the proposed CFRP bonding method. The number of CFRP layer was 18 (9 layers in each orientation) per one side. The same number of layers was bonded on both sides of the web.

Figure 13 shows the relationship between load and vertical displacement under loading point that resulted from the shear buckling test. Table 1 lists the maximum loads in each case. It was found that the maximum loads in case G2, which was the corroded case, decreased about 16% compared with the sound case G1. On the other hand, the initial performance was recovered in case G3 by bonding CFRP on the through-hole in the web. Therefore, even when severe corrosion as through-hole occurs on end web panels, load-carrying capacity in shear is recovered by appropriately bonding CFRP sheets on the corroded webs using the proposed method.

![Figure 11 Example of corrosion and test girder](image1)

![Figure 12. The full-scale test girder for the shear buckling test](image2)

![Figure 13. Load-displacement curve](image3)
Figure 14 shows the residual deformation of the girders after loading tests. In case G2, the angle of the diagonal tension field induced by shear buckling is not equal to the diagonal direction of the web panel due to the through-hole. On the other hand, in case G3, the angle is equal to the diagonal direction of the web panel. It can be said that the corroded web panel has completely recovered by bonding CFRP sheets, leading to improved load-carrying capacity of the web.

<table>
<thead>
<tr>
<th>Case</th>
<th>Reduced thickness at the bottom of web panel</th>
<th>W or W/O CFRP sheet</th>
<th>Maximum Load (kN)</th>
<th>Ratio of maximum load to G1</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>None</td>
<td>Without</td>
<td>1,389</td>
<td>100%</td>
</tr>
<tr>
<td>G2</td>
<td>100% (Through-hole)</td>
<td>Without</td>
<td>1,166</td>
<td>83.9%</td>
</tr>
<tr>
<td>G3</td>
<td>100% (Through-hole)</td>
<td>With</td>
<td>1,479</td>
<td>106.5%</td>
</tr>
</tbody>
</table>

CONCLUSION

The objective of this study was to establish a repair method using Carbon Fiber Reinforced Polymer (CFRP) sheets for corroded steel girder ends that have reduced load-carrying capacities in compression and shear. The conclusions can be summarized as follows.

1. CFRP sheets were adhesively bonded on corroded vertical stiffeners and/or webs near supports using a low elastic modulus putty layer. This putty layer makes it possible to prevent delamination of CFRP sheets when large deformations occur induced by buckling. The number of CFRP layer was decided so that the layers were thicker than the thickness reduced by corrosion, calculated using steel equivalent thickness of CFRP sheet; the thickness of CFRP sheet was converted to that of steel using the ratio of Young’s modulus for CFRP to steel.

2. First, we carried out uniaxial compression tests of girder in order to confirm the applicability of the proposed method to corroded supports which 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 carried out to confirm the applicability of the proposed method to corroded webs near the support which have reduced load-carrying capacity in shear. Test girders were full-scale models, and corrosion was simulated by creating a through-hole reflecting the extreme condition of the girders. The orientations of carbon fiber were set at ±45 degrees considering the direction of principle stress under shear. The same number of CFRP sheets was bonded on both sides of the web in the orientations of compression and tension. Results of the experiments showed that even when severing corrosion created a through-hole on end web panels, load-carrying capacity in shear can be recovered by appropriately bonding CFRP sheets on the corroded webs using the proposed method.

REFERENCE
