SHEAR BUCKLING TEST FOR STEEL GIRDER BONDED CFRP ON ITS WEB

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Abstract
Loss of cross section due to corrosion is a main factor in deterioration of steel bridges. Therefore, carbon fiber reinforced plastic (CFRP) is paid to attentions for repairing and reinforcing the steel bridges since CFRP is light weight, high strength and high durability. Although many researches relating to this topic have been reported so far, previous researches mainly focused on the application of CFRP to axial or bending members. On the other hand, most of the corrosion is found on web at the end of main girders. Investigations on repairing and reinforcing corroded web using CFRP have been reported few. In this research, shear buckling test for steel girder bonded by CFRP sheets on web is carried out. Low elastic putty layers are inserted between steel and CFRP sheets in order to improve the performance of out-of-plane deformation. An evaluation method of shear strength of the girder is also proposed.

Keywords: Carbon Fiber Reinforced Plastic (CFRP), steel girder bridges, corrosion, shear buckling, repair, reinforcement

1. Introduction
Recently, corrosion of steel bridge girders became a common problem in many countries. In Japan, the number of aging bridges steadily increases in the near future. The breakings of members in two steel truss bridges have already been found. Therefore, maintenance of existing bridges is important issue.

Loss of cross section due to corrosion is a main factor in deterioration of steel bridges. As the conventional repairing and reinforcing method, steel plates have been attached on corroded members. However, this method is restricted under service time because attachment works require heavy machineries. Therefore, efficient and rational method for repairing and
reinforcing damaged steel bridges is strongly needed.

In this situation, Carbon Fiber Reinforced Plastic (CFRP) has been paid to attention because it is light weight, high strength and high durability. Many researches relating to the application of CFRP to steel structures have been reported [1] - [3]. Previous researches mainly focused on the members subjected to normal stress, flanges in steel girder bridges and chord members in steel truss bridges.

In general, corrosion is mostly found on web at the ends of the steel girders where out-of-plane deformation is dominant under shear force at the ultimate state. Although debonding of CFRP under large deformation becomes a problem, investigations on this countermeasure are few.

Therefore, the objective of this study is to investigate the reinforcement effect and debonding behaviours of CFRP bonded on web in a steel girder. For this purpose, shear buckling test is carried out. Based on the test results, an evaluation method of ultimate strength is proposed.

2. Outline of Experiment

2.1 Test girder

Shear buckling tests for seven specimens were performed. Two types of steel girders that are different aspect ratios of a web are tested. Aspect ratios of the webs are 1.0 and 1.5. The former and latter girders are called G1 and G2 respectively. Dimensions of the girders are shown in Figure 1. In the case G1, the length, the height and the web thickness of girders are respectively 2700mm, 800mm and 6mm, whereas in the case G2, they are respectively 4600mm, 1000mm and 6mm. Table 1 shows experimental cases.
2.2 CFRP sheets and bonding form

Figure 2 shows the bonding form of CFRP sheets. Two kinds of CFRP sheet are used. Their properties are shown in Table 2. These CFRP sheets are bonded on both sides of web as shown in Figure 1. In all cases, two CFRP layers are laminated on one side of the web.

The fiber orientation angles in G1-2 are tensile and compressive directions in the first and second layers respectively. In contrast, the fiber orientation angles in G1-3 are the opposites of G1-2 in order to investigate the effect of the fiber orientation angles on the reinforcement.

The fiber orientation angles in G2 are the same as G1-3. The objective of G2-2 and G2-3 is to investigate the effect of fiber orientation angles on the reinforcement. In G2-4, the area bonded CFRP is minimized to cover the diagonal tension field assumed in the Basler’s equation [4].

Low elastic putty layers are inserted between steel and CFRP sheets in order to improve the performance of out-of-plane deformation in all cases.

3. Results and discussions

3.1 Reinforcement effect

Table 3 shows the results of shear buckling tests. In this table, $P_u$ and $P_{max}$ represent shear...
strength calculated from the Basler’s equation [4] and the maximum load in experiment respectively. Reinforcement effect $R_e$ is defined as follows.

$$R_e = \frac{P_{\text{max}} - P_{\text{max,n}}}{P_{\text{max,n}}} \times 100\%$$

(1)

Where, $P_{\text{max,n}}$ is the maximum load of the specimen without CFRP sheets in experiment.

To compare with G1-1, the reinforcement effect of G1-2 and G1-3 are 6.2% and 12.4% respectively. To compare with G2-1, the reinforcement effect of G2-2, G2-3 and G2-4 are 27.8%, 29.2% and 26.6%, respectively. Shear strength of the specimens with CFRP sheets became greater than the specimens without CFRP sheets. It is confirmed that the CFRP sheet improves shear strength.

### 3.2 Load-displacement curves

Figure 3 shows load versus displacement curves for each specimen. The horizontal axis is the displacement on the lower flange under the loading point. For all of specimens, displacements progressed linearly until the maximum load. After reaching the maximum load, load decreased gradually due to the breaking of CFRP sheets for the specimens with CFRP sheets. It is confirmed that the CFRP sheet improves the performance of out-of-plane deformation.

### 3.3 Failure modes

After shear buckling test, the tension field action was observed in test panels for each specimen regardless of the reinforcement. For the specimens with CFRP sheets, breaking of CFRP sheets progressed along the fiber orientation angles. As a representative example, failure modes of specimen G2-2 and G2-3 are shown in Figure 4.
4. Evaluation method of ultimate strength

4.1 Basler’s equation

The Basler's equation, which calculates shear load-carrying capacity of a steel girder, is represented as the following equation [4].

\[
\frac{Q_u}{Q_y} = \frac{\tau_{cr}}{\tau_y} + \frac{\sqrt{3}}{2} \frac{1 - \tau_{cr}/\tau_y}{\sqrt{1 + \alpha^2}}
\]  

(2)

Where, \(Q_u\), \(Q_y\), \(\tau_{cr}\), \(\tau_y\), \(\sigma_y\) and \(\alpha\) represent respectively ultimate shear strength, yield shear strength, elastic shear buckling stress, yield shear stress (= \(\sigma_y/\sqrt{3}\)), yield stress and aspect ratio of test panel web (= width \(b\) / height \(h\)). In this equation, the first term is the strength contributed by elastic buckling, and the second term is the contribution from post-buckling strength. It is assumed when shear strength reached \(Q_u\) the tension field action occurs. Using eq.2, shear capacity of a steel girder can be predicted.

4.2 Elastic buckling stress

(1) Steel girder

Elastic shear buckling stress \(\tau_{cr}\) of web of steel girder in eq.(2) is calculated as the simply supported plate under pure shear. It can be expressed as follows.

\[
\tau_{cr} = k_s \frac{\pi^2 E_s}{12(1 - \nu_s^2)} \left( \frac{t_s}{h} \right)^2 = k_s D_s \frac{\pi^2}{t_s h^2}
\]  

(3)

Where, \(E_s\), \(\nu_s\), \(t_s\), \(h\), \(D_s\) and \(k_s\) represent Young’s modulus of steel, poisson’s ratio of steel, thickness of web, height of web, flexural rigidity and coefficient of buckling depending on aspect ratio, respectively. Shear buckling coefficient \(k_s\) is represented as follows.

\[
k_s = \begin{cases} 
5.34 + 4.00 / \alpha^2 & (\alpha \geq 1.0) \\
4.00 + 5.34 / \alpha^2 & (\alpha < 1.0)
\end{cases}
\]  

(4)

(2) Steel girder reinforced by CFRP sheets

As shown in Figure 5, two layers of CFRP sheets are laminated on both sides of web through lower elastic putty layers. Herein, in order to derive the elastic shear buckling stress of composite section, it is assumed that steel plate, putty layers and CFRP sheet layers contribute
to elastic buckling stress. Following eq.(3), elastic shear buckling stress \( \tau_{crv} \) of steel plate reinforced by CFRP sheets can be obtained as follows.

\[
\tau_{crv} = k_yD_y \frac{\pi^2}{h^2(t_s + 2t_{f0} + 2t_{f1} + 2t_{f2})}
\]  
(5)

Where, \( t_{f0} \) is thickness of putty layer, \( t_{fi} \) are thickness in layer \( i \) of CFRP \((i = 1, 2)\). \( D_y \) is flexural rigidity of steel plate bonded CFRP sheets, which is given as

\[
D_y = \int_{-\ell_y/2}^{\ell_y/2} \frac{E_F}{1-v_F^2} z^2 dz + 2\int_{-\ell_y/2}^{\ell_y/2} \frac{E_F}{1-v_F^2} \frac{E_{fi}}{1-v_{fi}^2} z^2 dz + 2\int_{-\ell_y/2}^{\ell_y/2} \frac{E_F}{1-v_F^2} \frac{E_{fi}}{1-v_{fi}^2} z^2 dz
\]

\[
= \frac{E_F t_s^3}{12(1-v_s^2)} + \frac{2E_{fi}}{3(1-v_{fi}^2)} \left( \frac{t_{fi}}{2} + t_{f0} \right)^3 - \left( \frac{t_{fi}}{2} \right)^3 + \frac{2E_{fi}}{3(1-v_{fi}^2)} \left( \frac{t_{fi}}{2} + t_{f0} + t_{f1} \right)^3 - \left( \frac{t_{fi}}{2} + t_{f0} \right)^3
\]

\[
+ \frac{2E_{fi}}{3(1-v_{fi}^2)} \left( \frac{t_{fi}}{2} + t_{f0} + t_{f1} + t_{f2} \right)^3 - \left( \frac{t_{fi}}{2} + t_{f0} + t_{f1} \right)^3
\]

(6)

Where, \( E_F \) is young's modulus of putty, \( v_F \) is poisson's ratio of putty, \( t_{f0} \) is the thickness of the patty. \( E_{fi} \) and \( v_{fi} \) are young's modulus and poisson's ratio of CFRP in layer \( i \) \((i = 1, 2)\), respectively.

### 4.3 Evaluation of shear strength

In order to evaluate shear strength of steel girder bonded CFRP on its web, an evaluation method is proposed based on the Basler’s equation. Three equations are derived according to how post-buckling strength is incorporated in composite section. Each equation is validated from the comparison between the maximum loads in experiment and evaluated values.

**a) Evaluation method A**

Referred to Basler’s works, the shear strength \( \mathcal{A}Q_u \) (eq.(7a)) can be obtained by substituting eq.(5) to eq.(2).

\[
\frac{\mathcal{A}Q_u}{Q_y} = \frac{\tau_{crv}}{\tau_y} + \frac{\sqrt{3} 1 - \tau_{crv}/\tau_y}{2 \sqrt{1 + \alpha^2}}
\]  
(7a)

**b) Evaluation method B**

The post-buckling strength is added to the terms which CFRP sheets contribute until steel became yielded. The shear strength \( \mathcal{B}Q_u \) is expressed as follows.
Where, \( E_L \) is young’s modulus of main direction of CFRP and \( c_t \) is total thickness of CFRP of tensile direction (=2\( t_{cf} \)).

**c) Evaluation method C**

The post-buckling strength is added to the terms which CFRP sheets contribute until the breaking of fiber. The shear strength \( cQ_B \) is expressed as follows.

\[
\frac{cQ_B}{Q_y} = \frac{\tau_{crv}}{\tau_y} + \frac{\sqrt{3}}{2} \frac{1 - \tau_{crv}/\tau_y}{\sqrt{1 + \alpha^2}} \left( 1 + \frac{E_L\bar{t}_c}{E_s t_s} \right)
\]  

(7b)

Where, \( E_L \) is young’s modulus of main direction of CFRP and \( \bar{t}_c \) is total thickness of CFRP of tensile direction (=2\( t_{cf} \)).

**4.4 Material properties**

The material properties of fiber sheets, Epoxy resin and CFRP sheets are shown in Table 4. Young's modulus \( E_p \) and poisson's ratio \( \nu_p \) and the thickness of putty are respectively 66MPa, 0.3 and 0.8mm. Young's modulus \( E_s \), poisson's ratio \( \nu_s \) and the thickness of web are respectively 200GPa, 0.3 and 6mm.

**4.5 Results**

Table 5 shows the comparison between the maximum loads obtained from the test and shear strength calculated by the proposed three methods. For all of specimens, it can be seen that evaluation method B has a reasonable accuracy, in which the contribution of CFRP sheets are considered until the steel plate became yielded. CFRP sheets bonded on the both sides of web can increase the flexural rigidity of web, and have the contribution to elastic shear buckling stress. The CFRP sheets bonded on the area where steel yielded did not debond for the sake of lower elastic putty layers, while deformation proceeded. After exceeding the maximum loads,
the CFRP sheets can not take charge of load.

5. Conclusions

In order to clarify the reinforcement effect of CFRP bonded on web of a steel girder, shear buckling test were carried out for seven specimens. Experimental parameters are aspect ratio of web, the type of CFRP sheets and the fiber orientation angles. Referring to the Basler’s works, three evaluation methods of shear strength were proposed. The validity of proposed methods was discussed through the comparison. The findings of this research are summarized as follows.

1) In the case G1, the reinforcement effect of G1-2 that bi-axial sheets are bonded on web is 7%, whereas that of G1-3 that uni-axial sheets are bonded is 13%. Their difference of reinforcement effect results from the amount of bonded carbon fiber.

2) In the case G2, all reinforcement effects are almost same because the amounts of bonded carbon fiber are almost same.

3) Low elastic putty layers can prevent the debonding of CFRP although the breaking of CFRP progresses during the loading.

4) Evaluation method B which CFRP sheets contribute before yielding of steel shows good agreement with test results. The prediction error is from -6.3% to 2.2%.

6. References


