Study on Repair Method using CFRP for Corroded Steel Girder Ends

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Abstract

This paper describes a study on repair methods using carbon fiber reinforced polymer (CFRP) sheets for corroded steel girder ends. It was confirmed from experiments that although corrosion at girder ends reduced load-carrying capacities in compression and shear, bonding CFRP sheets onto the corroded parts through a low elastic putty layer could revive their initial performance, preventing delamination under large deformation. A practical design method for this repair method is also proposed.

Introduction

In Japan, most deterioration in steel structures stems from corrosion. In particular, steel girders are corroded at the ends due to water leakage from expansion joints. Deicing salts in winter make this situation worse. The usual repair works 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 Fig.1. However, these repair works lack in applicability because heavy machinery and welding facilities are required regardless of the scale of required work. As a result, repair works have not progressed in contrast to the increasing number of corrosion issues. Therefore, a simple and effective repair method for the corroded steel girder ends is urgently needed.

To counter this problem, we focus on fiber reinforced polymers as repair material for corroded steel girder ends. Among them, carbon fiber reinforced polymer (CFRP) is especially promising due to characteristics such as its light weight, high elasticity, high strength and high durability as shown in Table. 1 and Fig.2.

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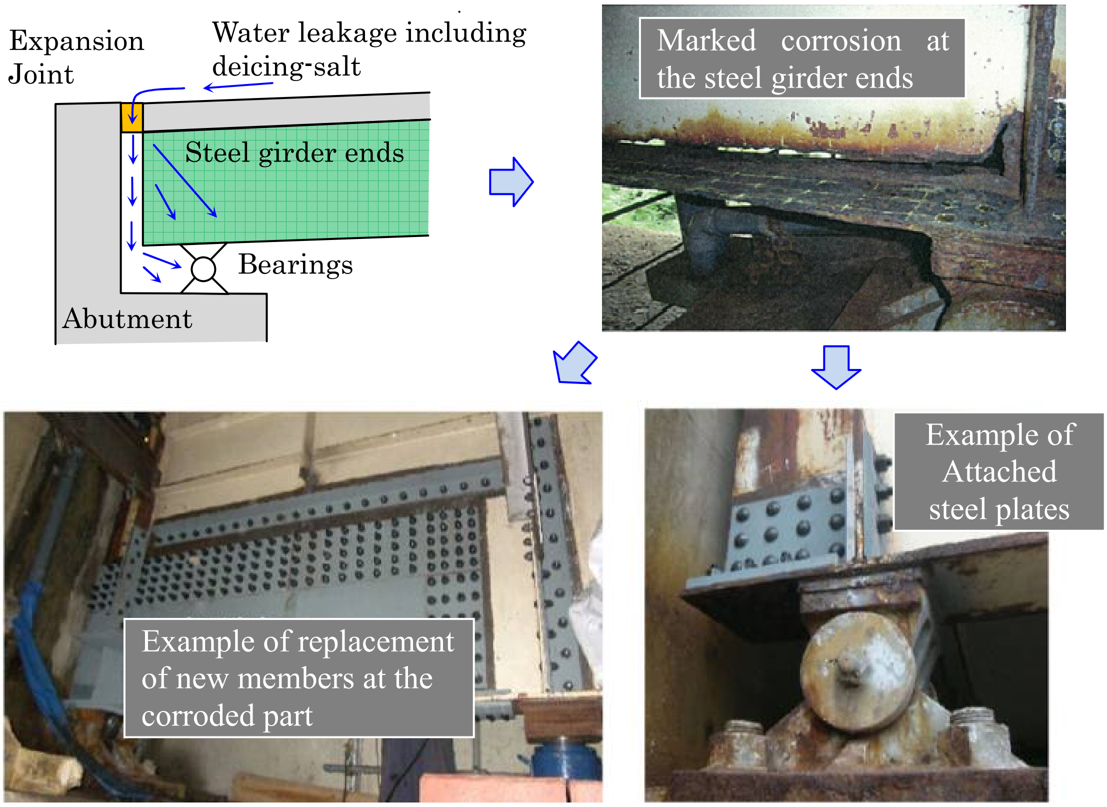


Fig.1 Repair method using steel plates for corroded girder ends

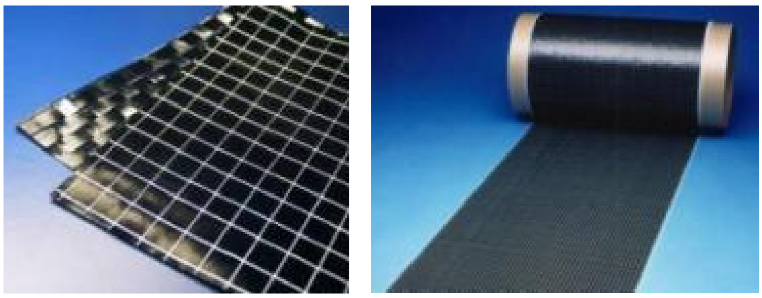


Fig.2 CFRP sheet

Table 1 Comparative Properties of CFRP and Steel

Type of materials	**Tensile strength (N/mm^2)**	**Young's modulus (kN/mm^2)**
High-strength carbon fiber	3400	245
Intermediate-modulus carbon fiber	2400-2900	390-450
High-modulus carbon fiber	1900	540-640
Steel	400-570	200

Widespread repairs, particular for seismic retrofits, using CFRP have been done for concrete structures, in our country. On the other hand, application of CFRP to steel structures are comparatively rare: some flanges in a steel girder bridge or chord members in a steel truss bridge as shown in Fig.3. In general, these members are subjected to normal stress. However, corrosion in steel bridges mostly occurs at webs or vertical stiffeners near supports. At these members, the occurrence of local buckling is of concern, yet there are few studies on the application of CFRP to these members. Therefore, this study focuses on the applicability of CFRP to repairing the corroded webs and vertical stiffeners at the ends of the steel girders.

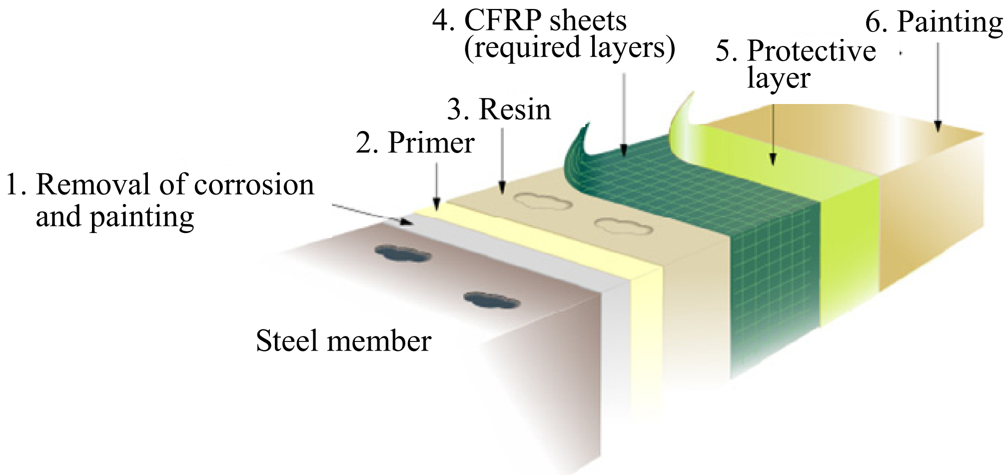


Fig.3 Application of CFRP sheet to steel member subjected to normal stress

Research flow

At the ultimate state of corroded vertical stiffeners or webs, local or shear buckling might occur under compressive or shear forces as shown in Fig.4 and Fig.5. So far it has not been reported whether CFRP bonded on these members can follow large deformation together with steel member under buckling and recover their initial performance. Therefore, we carry out the following experiments to establish appropriate repair methods for corroded vertical stiffeners or webs at the steel girder ends using CFRP sheets.

Fig.4 Example of local buckling at the vertical stiffener

Fig.5 Example of shear buckling at the webs

1) Uniaxial compression test of plate: to choose FRP sheet and resin materials following large deformations under buckling without delamination.
2) Uniaxial compression test of column: to confirm the improvement effect of load-carrying capacity in compression using CFRP sheets for corroded vertical stiffener.
3) Shear buckling test of girder: to confirm the improvement effect of load-carrying capacity in shear using CFRP sheets for corroded webs.

Furthermore, we investigate appropriate bonding patterns for CFRP sheets to steel girder ends.

Uniaxial Compression test of steel plate bonded various FRP Sheets

In this section, a uniaxial compression test of steel plates bonded by various FRP sheets is carried out. This test is aimed at selecting FRP sheets having a reinforcing effect following large deformation induced by buckling. Furthermore, a layer of polyurea putty, a low elastic material, is inserted between the steel plate and the FRP sheet, and its effects are investigated.

The properties of the FRP sheets are listed in Table 2. In this study, five kinds of FRP sheets are used: high-modulus carbon fiber (CE), high-strength carbon fiber (CU), glass fiber (G), high-strength polyethylene (P), and hybrid fiber (H, C:G = 1:1). Table 2 also lists converted fiber thicknesses to steel used in the design for the proposed repair method. For example, in the case of CE, the thickness of fiber is converted to that of steel by 0.116 (mm) *640 (kN/mm^2) /200 (kN/mm^2) = 0.371 (mm). Here, 200 (kN/mm^2) is Young's modulus of steel. Table 3 lists the material properties of polyurea putty and resin.

Table 2 Properties of FRP sheet

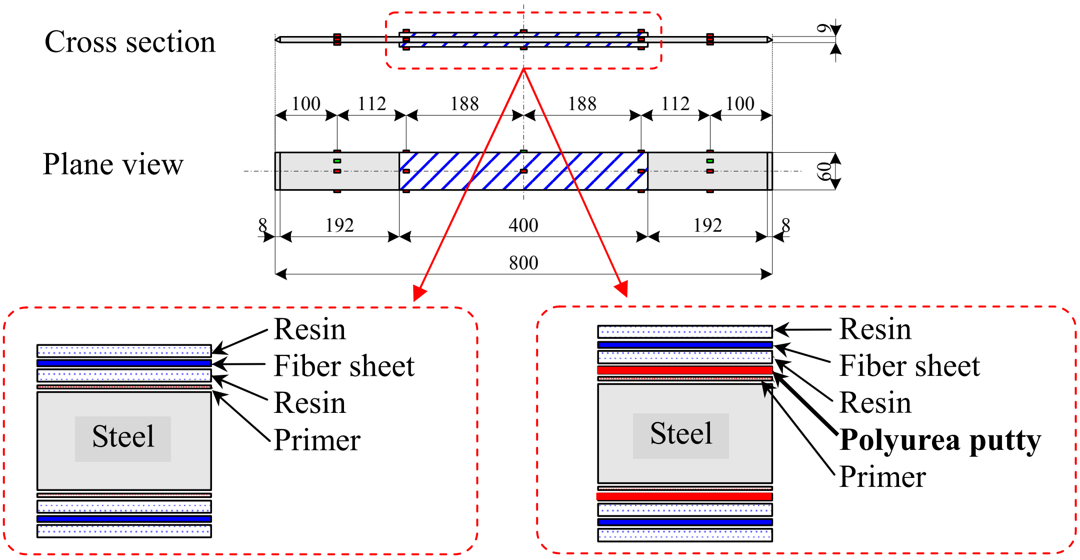
Sign	Type	Thickness (mm)	Young's modulus (kN/mm^2)	Thickness of fiber converted to steel (mm)
CE	High-modulus carbon fiber	0.116	640	0.371
CU	High-strength carbon fiber	0.121	240	0.145
G	glass fiber	0.123	74	0.046
P	High-strength polyethylene	0.108	88	0.048
H	Hybrid fiber	0.121	383	0.232

Table 3 Properties of putty and resin

	Polyurea putty	Resin
Amount of coating (g/m^2)	1000	1000
Resin thickness (mm)	0.80	0.85
Young's modulus* (N/mm^2)	54.7	2533

* measured value

Fig. 6 shows the cross section and the shape of the specimens. FRP sheets are bonded to both sides of the steel plate. Fig.7 shows loading methods and the situation of examination.



a) Cross section without polyurea putty b) Cross section with polyurea putty

Fig.6 Specimen of steel plate bonded FRP

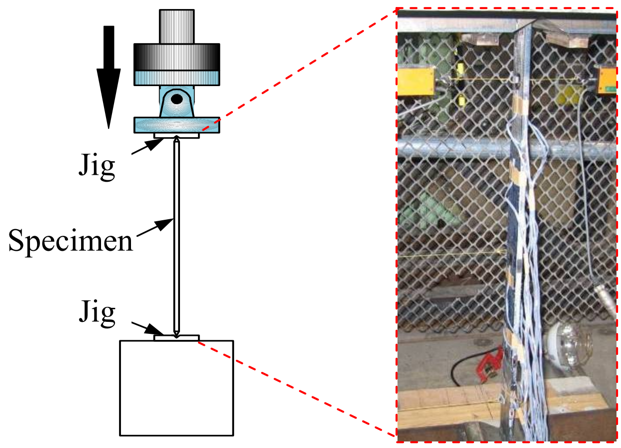


Fig.7 Loading method and test situation

Generally, the critical buckling load (elastic stability limit) is given by Euler's formula. Therefore, the test result can be arranged as relations of the reinforcing effect and the radius of gyration. The reinforcing effect and the radius of gyration are respectively expressed by the following equations.

$$\text{Reinforcing effect (\%)}: \frac{P_{max} - P_E}{P_E} \times 100(\%), \quad \text{Radius of gyration: } r = \sqrt{(I/A)_{composite}}$$

where P_{max} is the maximum load in the experiment, P_E is the Euler buckling load of a steel plate without CFRP sheets, I is the moment of inertia, and A is the area of the composite cross section.

Fig.8 shows the relations between the radius of gyration and the reinforcing effect. Fig.8 reveals that all FRP sheets have reinforcing effects, and that the reinforcing effect is proportional to the radius of gyration. We can also confirm that high modulus carbon fiber (CE) shows the best reinforcing efficiency because its Young's modulus is the highest.

In addition, Fig.9 shows a representative example of relations between load and center displacement in specimen using CE. The maximum load using polyurea putty is not significantly different from without polyurea putty. However, in the results without polyurea putty, the load dropped suddenly when the central displacement exceeded 45 mm as a result of fracture of the FRP sheets. Therefore, it can be said that the polyurea putty used in this study can help prevent debonding or breaking of the FRP and improves flexibility.

Therefore, we select CE sheet and polyurea putty as repair materials for corroded steel girder ends, and they are used in the following experiments.

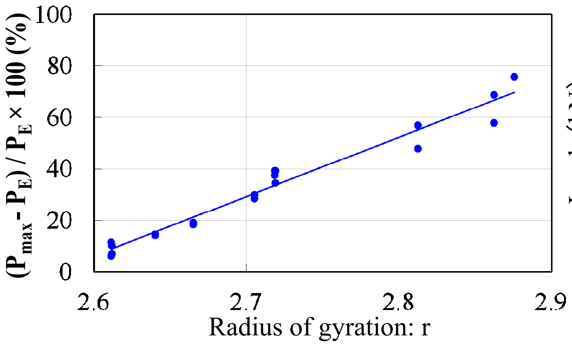


Fig.8 Relations between the radius of gyration and the reinforcing effect

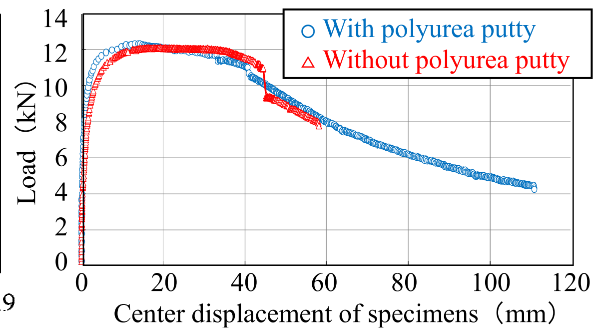


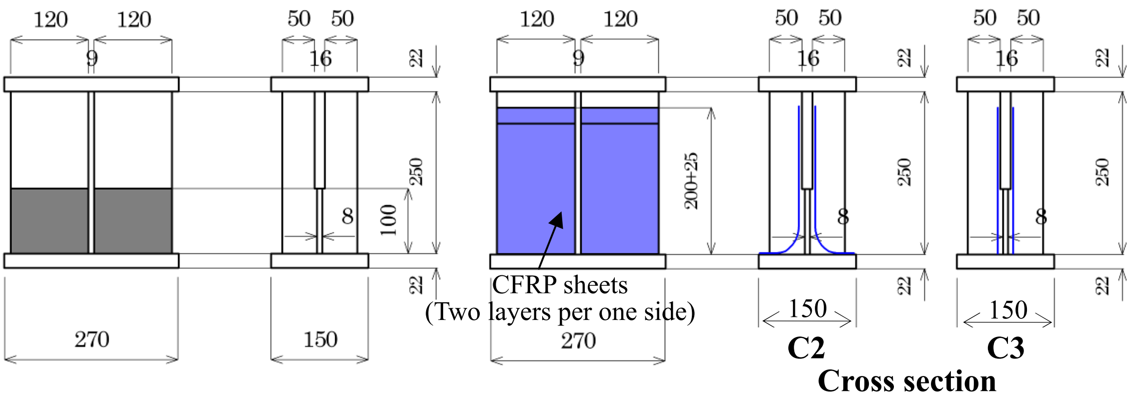
Fig.9 Load-displacement Curve

Uniaxial compression test of column for corroded vertical stiffeners

There are many examples of corrosion at the bottom of vertical stiffeners in steel girder ends. Therefore, we carry out uniaxial compression tests of columns whose thicknesses of the bottom are reduced to simulate corrosion similar to real world conditions.. Based on the previous experimental results, CE sheets are bonded on the corroded parts for repair, and its improvement effect on load-carrying capacity is confirmed.

The height of column is designed short enough to not totally buckle but locally buckle. The number of experimental cases is 3 as shown in Fig.10. They are named as C1, C2 and C3. C1 is the case without repairing. C2 and C3 are the case with repairing using CFRP sheets. In the case of C2, the bottom ends of CFRP on vertical stiffeners are anchored on the lower flanges providing R-shape as shown in Fig.10 (b). The space between the steel and CFRP sheets in the anchorage is filled with epoxy putty. On the other hand, in the case of C3, the bottom ends of CFRP on vertical stiffeners are not anchored on the lower flanges for comparison.

Table 4 lists the property of test columns. In this table, ultimate load without repairing, which is C1, is determined at the reduced sections. In the case of repairing using CFRP, which is C2 and C3, the thickness of CFRP sheet is converted to the one of steel using the ratio of Young's modulus of CFRP to steel's one when the ultimate load is calculated. Herein, the converted thickness of CFRP sheet becomes 0.143*640 / 200 = 0.4576 mm. The number of CFRP layer is decided to be larger than the reduced thickness by corrosion using this converted thickness of CFRP sheet. This design concept is also adopted in the shear buckling test of girder in the next section.



a) Column without repairing

b) Columns with repairing (C2, C3)

Fig.10 Detail Columns for uniaxial compression test

C1 C2 C3

Fig.11 Columns for uniaxial compression test

Table 4 Properties of columns for uniaxial compression test

		C1	C2, C3
Webs	Thickness (mm)	9	
Vertical stiffeners	Thickness (mm)	8	
Carbon fiber sheets	Mass per unit area (g/m^2)	300	
	Thickness (mm)*	0.143	
	Young's modulus (kN/mm^2)	640	
	Number of layers	0	4
radius of gyration (mm)		19.96	18.70
theoretical value of the ultimate load (kN)		866	987

* Thickness of CFRP sheets in this test is different from it in the previous test (sign CE) because each mass per unit area is different.

Fig.12 shows the measurement point of strain in this test. Fig.13 shows the relation between applied load and averaged axial strain in the cross section, and Fig.14 shows the specimen after the test. In Fig.13, there are two dotted lines. One is theoretical value calculated from P=EAε, where P is load, E is Young's modulus of steel, A is area of cross section converted to steel and ε is strain. The other is theoretical value of yield load. It is found from Fig.13 that all measured strain in the range from 0 to 4500μ is approximately equal to the theoretical values. And also, in the case of C3, the case without anchorage on the lower flange, the expected improvement effect are sufficiently obtained.

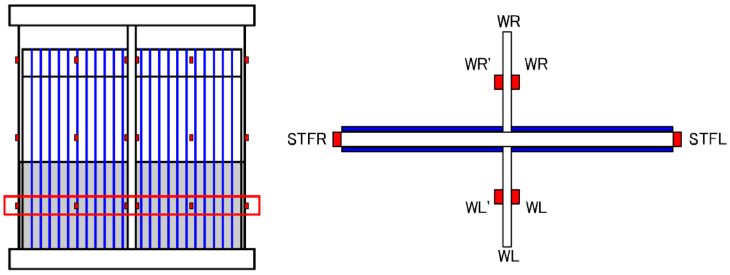


Fig.12 Measurement point of strain

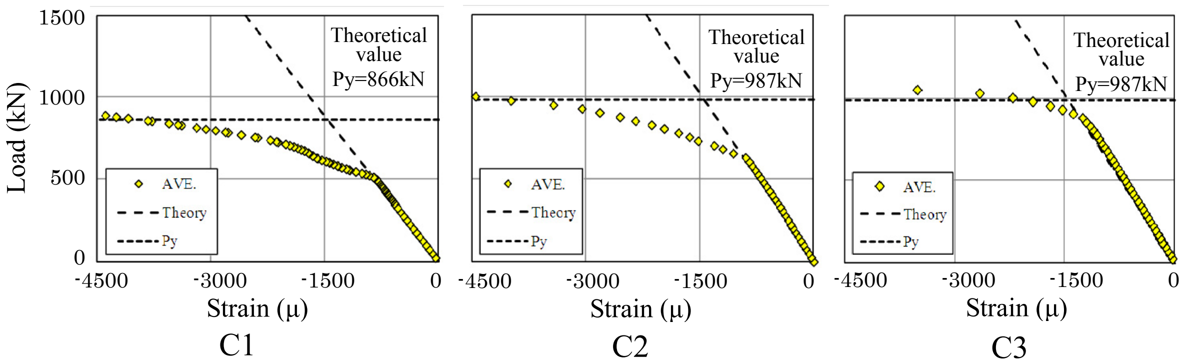


Fig.13 Load-Strain Curve

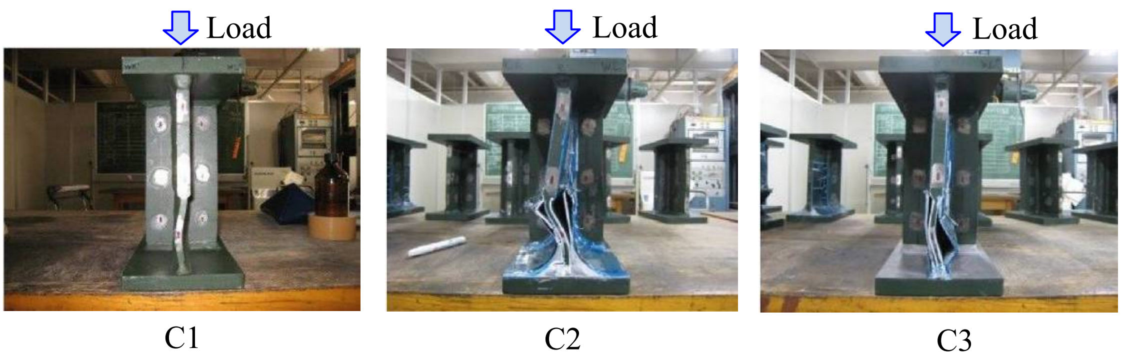


Fig.14 Columns After Testing

Based on the experimental results, when this proposed repair method is applied to corroded vertical stiffeners in existing bridges, the number of CFRP layers should be decided to exceed the reduction in thickness caused by corrosion using the thickness of CFRP sheet converted to the property of steel. Moreover, the bottom ends of CFRP are not necessarily anchored on the lower flange.

Shear buckling test of girder for corroded webs

Corrosion in a steel girder often occurs at not only flanges and vertical stiffeners near supports but also at end web panels. In this case, because the shear -load-carrying capacity of the girder falls due to corrosion, it is necessary to repair corroded webs in order to re-attain their initial performance. For this purpose, we consider the application of CFRP sheets to repair corroded webs. To check the validity, shear buckling tests are carried out for steel girders having simulated corrosion at the bottom of web panel.

Fig.15 shows the configuration of test girders, Table 5 lists the test cases, and Fig.16 shows an experimental condition. The area simulating corrosion is indicated by diagonal lines in Fig.15. The number of experimental cases are two; one is the case named the G1 series that the reduced rate of thickness of the web at simulated corrosion part is 50%. The second is the case named the G2 series where reduced rate of thickness of the web is 100%, i.e. through-hole. In each case, there are the cases with and without repairing using CFRP sheets. The design method determining the number of CFRP sheets is the same way in previous section; the thickness of CFRP sheet is converted to the one of steel using the ratio of both Young's modulus.

Fig.17 shows the bonding shape of CFRP sheets in G2 series. Here, considering the direction of principle stress under shear, the directions of carbon fiber sheets are set to be ±45 degrees. The same number of CFRP sheets is bonded on the web in the directions of compression and tension.

Table 5 Properties of girders for shear buckling test

Sign	Reduced thickness	Case	Angle of fiber	Number of layer*
G1-1	1.5mm per one side (Loss rate: 50%)	Without CFRP	–	–
G1-2		With CFRP	±45° (Opposite angle direction)	8 layer (4 layer at each direction) per one side, both sides
G2-1	Through-hole (Loss rate: 100%)	Without CFRP	–	–
G2-2		With CFRP	±45° (Opposite angle direction)	14 layer (7 layer at each direction) per one side, both sides

* Thickness and Young's modulus of CFRP sheet is equal to the case of axial compression test of columns.

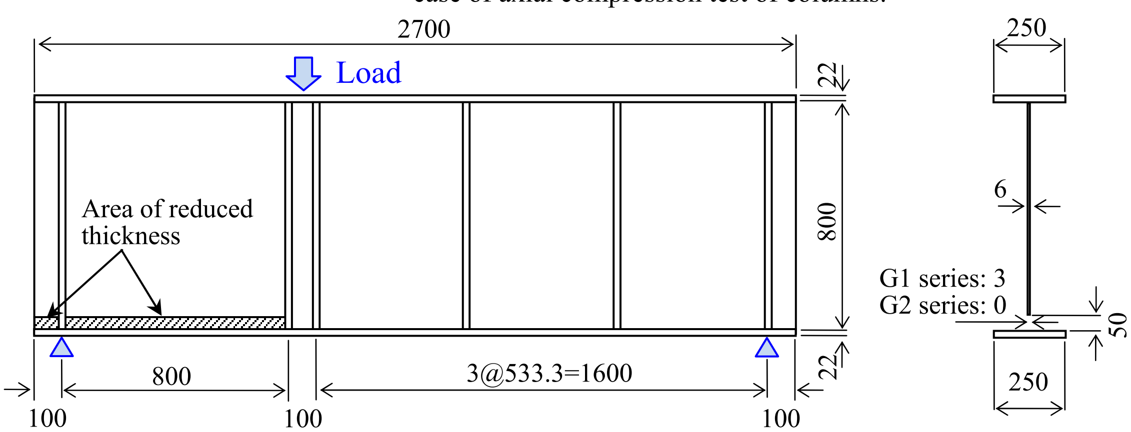


Fig.15 The Girders for the Shear Buckling Test

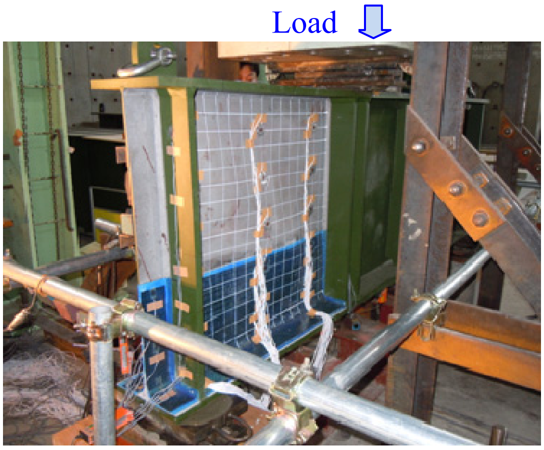


Fig.16 Shear buckling test situation

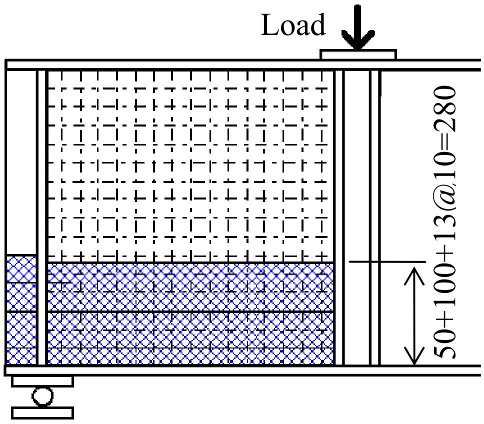


Fig.17 Bonding shape of CFRP sheet (G2-2)

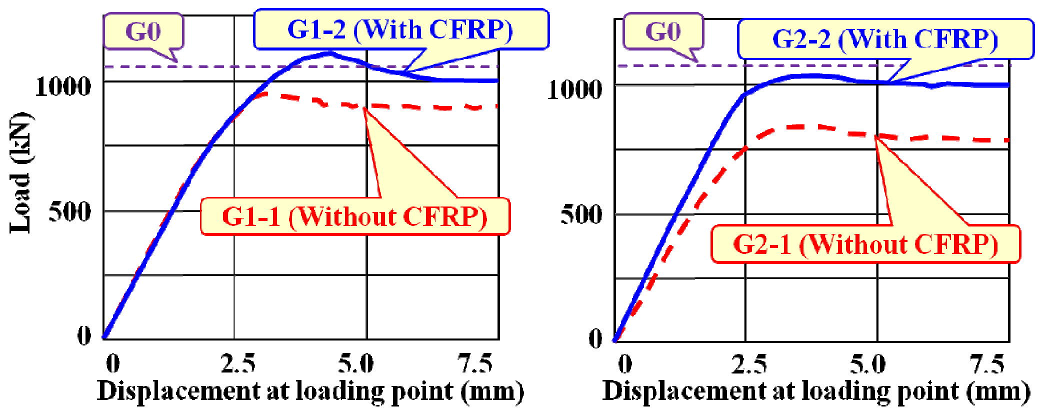
Table 6 lists the results of the shear buckling test. Here, G0 is the case without corrosion, and its maximum load is theoretically calculated using Baslar's equation. Fig.18 shows the load-displacement curves in each case. It is found that the maximum loads without repairing decrease about 10% and 20% in the case of G1-1 and G2-1 respectively comparing to G0. On the other hand, although there are some errors, the girders bonded CFRP, which are G1-2 and G2-2, recovered their initial performance.

Table 6 The result of shear buckling test

Sign	Reduced thickness	Case	Maximum Load	Load increase/ decrease ratio *2
G0 *1	Nothing	—	1063	—
G1-1	1.5mm per one side (Loss rate: 50%)	Without CFRP	952	-10.4%
G1-2		With CFRP	1111	+4.5%
G2-1	Through-hole (Loss rate: 100%)	Without CFRP	840	-21.0%
G2-2		With CFRP	1029	-3.2%

*1 Maximum Load of Sign G0 shows the value calculated by Baslar's equation because the test does not be carried out

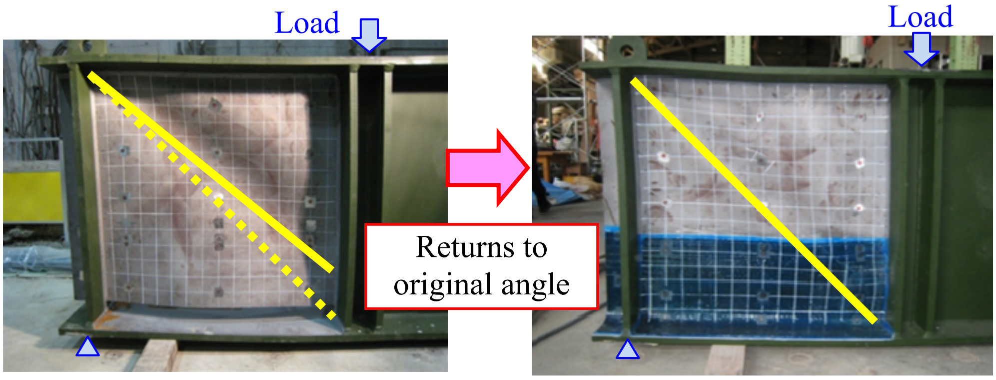
*2 The ratio of maximum load in comparison with G0



a) G1 series (50% losses) b) G2 series (through-hole)

Fig.18 Load-displacement curve

Fig.19 shows the girders after loading test. In the case of G2-1, the angle that shear deformation is prominent does not correspond to diagonal direction of the web due to the existence of through-hole. On the other hand, in the case of G2-2, the angle is equal to the diagonal direction because the web is repaired completely by CFRP sheets.



a) G2-1 a) G2-2

Fig.19 Residual deformation of the girders after shear buckling test (G2 series)

Based on the experimental results, it can be said that load-carrying capacity in shear is recovered by CFRP sheets appropriately bonded on the corroded webs even when sever corrosion such as through-hole occurs. The necessary number of CFRP sheets is determined from the thickness of CFRP sheet converted to steel, which is calculated from both Young's modulus. The converted thickness of CFRP sheet should be larger than the reduced thickness of corroded part, and then CFRP sheets should be bonded on the corroded parts in the direction of ±45 degrees.

<u>Bonding pattern of CFRP sheets for combined corrosions at steel girder end</u>

When the proposed repair method is applied to existing bridges, it is necessary to consider the combination of repairing vertical stiffeners and webs depending on the types of corrosions as shown in Fig.20. Fig.20 shows an example of bonding pattern of CFRP for corroded vertical stiffeners, flanges and webs near a girder end. Each member is repaired by each CFRP sheet for recovering load-carrying capacities in compression, bending and shear.

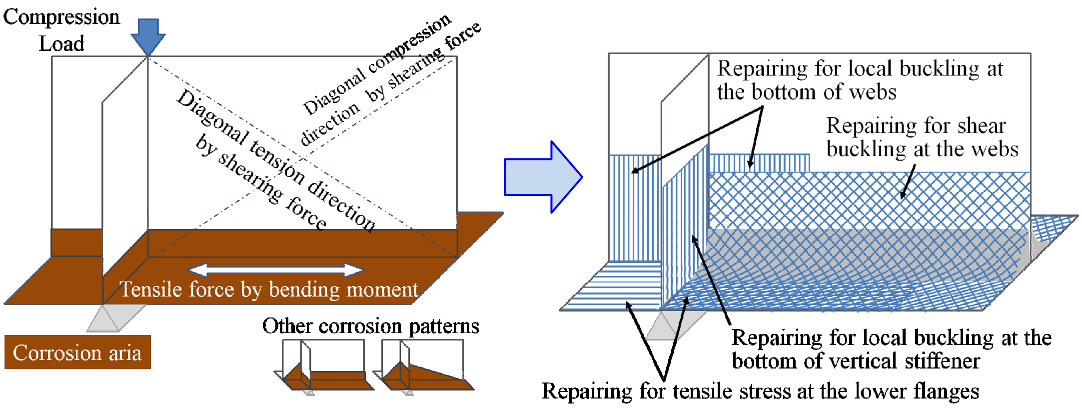


Fig.20 Example of bonding pattern of CFRP sheets for combined corrosions at steel girder end

Conclusion

In this study, in order to investigate the applicability of CFRP sheets for corroded steel girder ends as an appropriate repair method, various laboratory experiments were carried out. The conclusions can be summarized as follows.

1) In order to choose FRP sheet and resin materials following large deformation under buckling, uniaxial compression test of steel plate bonded various FRP sheets was conducted as the fundamental study. As a result, it was confirmed that high modulus carbon fiber sheet had the best repair efficiency, and polyurea putty inserted between the steel plate and CFRP sheet could help prevent delamination under large deformation.
2) In order to confirm the applicability of CFRP sheets for repairing corroded vertical stiffeners at the girder ends, we carried out uniaxial compression test of columns whose thicknesses of the bottom were reduced to simulate corrosion. As a result, it was found that initial performance could be recovered by CFRP sheets. Herein, the number of CFRP layer was decided to be larger than the reduced thickness by corrosion using the thickness of CFRP sheet converted to the property of steel. Moreover, the bottom ends of CFRP were not necessarily anchored on the lower flange.
3) In order to confirm the applicability of CFRP sheets for repairing corroded web near support, we conducted shear buckling test of girder having simulated corrosion at the bottom of web panel. Experimental results revealed that load-carrying capacity in shear could be recovered by CFRP sheets bonded on the corroded webs even when sever corrosion such as through-hole occurred. The necessary number of CFRP sheets should be determined from the thickness of CFRP sheet converted to steel similar to the uniaxial compression test of columns. Then, CFRP sheets should be bonded on the corroded part in the direction of ±45 degrees in consideration of principle stress under shear.
4) Considering the situation of combined corrosions at a steel girder end, an effective bonding pattern of CFRP sheets was proposed. For practical application of this repair method, appropriate bonding pattern should be decided depending on the type of corrosion and cost.

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