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Technical Report

Study on Bending Reinforcement Effect of Steel Girder Using CFRP Molded Plate

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Abstract

In composite girders, only steel girders remain when the slab is removed during slab renovation. This can lead to lateral buckling of the steel girders necessitating reinforcement. One method of reinforcing steel structures involves using high-strength, highly elastic, lightweight, and non-corrosive carbon fiber reinforced plastic (CFRP). However, the effectiveness of CFRP reinforcement in preventing lateral buckling has not been fully confirmed. In this study, the effect of reinforcement on lateral buckling was verified through four-point bending tests on steel girder specimens reinforced by the CF bypass method. As a result, it is considered that the load-carrying capacity against lateral buckling can be controlled by improving the bending stiffness of the steel girder through reinforcement, but the effect of improving the stress level at the occurrence of lateral buckling is considered to be small.

1. Introduction

Large-scale renewal works such as slab renovation are currently underway as part of an expressway renewal project.[1] In the case of composite girders, when the existing slab is removed, the composite effect between the steel girders and the slab is lost. The result is an unstable structure consisting of only the steel girders. This condition leads to a concern that the upper flange of the steel girder may be subjected to a large bending compressive stress and laterally deform, resulting in lateral buckling of the steel girder.[2] In the past, it was reported that the lateral buckling of main girders occurred during slab removal, resulting in the collapse of the bridge.[3] Since the occurrence of lateral buckling leads to serious accidents, appropriate measures must be taken during slab removal. If the load-carrying capacity of steel girders is insufficient during slab removal, the steel girders are reinforced by splicing reinforcing members with high-strength friction joining bolts. This reinforcing method is economical and easy to perform and has been employed in many projects.[4] It is more efficient to install the reinforcing members near the upper flange. Since the slab is placed above the upper flange, it is usually difficult to bolt the reinforcing members to the upper flange. In addition, when the girders are composite, the neutral axis of the composite girder is located near the upper flange, and the cross-sectional area of the upper flange is often small. Therefore, bolt-hole drilling exerts a large effect, and the cross-sectional area of the reinforcing members tends to increase. There is concern about the impact of the increase in the dead load on the substructure. Also, a particularly effective measure against lateral buckling is the shortening of the fixed-point distance by adding members such as cross beams and sway bracings. However, this method is difficult to undertake because heavy machinery is required to transport and install members, lengthening the construction period. Specifically, traffic restrictions are required for the slab renovation work, so the construction period must be shortened.

In recent years, the method of impregnating and bonding carbon fiber sheets on site has been applied as a steel bridge repair and reinforcement method.[5, 6] Carbon fiber sheets have properties such as being lightweight, high strength, high elasticity, and having no corrosion. Carbon fibers are lighter than steel, so the increase in dead load after the carbon fiber sheet reinforcement is small. Carbon fiber sheets are bonded to bridge members with a resin. They require no specialized workers and are easy to install. No need for bolt-hole drilling provides another advantage of no reduction in the cross-sectional area of existing members. Furthermore, with regard to the delamination of reinforcing members, which is a problem with bonded

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construction, a method was developed that uses an elongated elastic putty to suppress the delamination of carbon fiber sheets.[7] This method minimized the concern about delamination. Research and development are underway to expand the application scope of the reinforcing method with carbon fibers.[8]

The method of repair and reinforcement with carbon fiber sheets has the capability to reinforce various members and conform to various stress states. A design and construction manual for this method has been published.[9] However, reinforcement methods and design methods against the lateral buckling of steel girders have not yet been established.

We proposed the CF bypass method for reinforcing the upper flange of the steel girder with carbon fiber sheets from below the bottom surface and reinforcing the bends where vertical stiffeners are installed.[10] **Figure 1** shows an overview of the CF bypass method. In this method, carbon fiber sheets with carbon fibers laid only in the axial direction of the member or carbon fiber molded plates (hereinafter referred to as CFRP molded plates) made by curing the carbon fibers with a resin beforehand and molding them into plates are bonded to vertical stiffener-free areas of girders. In the girder areas where vertical stiffeners are located, and CFRP molded plates cannot be continuously installed, bypass members shaped to avoid the vertical stiffeners and connect the CFRP molded plates on both sides of the vertical stiffeners are bonded to ensure continuity of the reinforcing members. This method can reinforce girders against bending in the areas (hereinafter referred to as the bypass areas) where CFRP molded plates cannot be continuously installed. The bypass members are made from CFRP plates. For efficient stress transmission in the member transverse direction (Y-axis direction), the carbon fibers are laminated in the member axial direction (X-axis direction) as well as at an angle of ±45° to the member axial direction. The lamination of carbon fibers in this way increases the shear elastic modulus G_{xy} of the CFRP molded plates and improves the stress transfer efficiency in the member transverse direction (Y-axis direction). In our previous study,[10] we conducted a flexural loading test with steel girder specimens reinforced by this method. We confirmed that the reinforcement by this method reduced the steel bending stress in the bypass area.

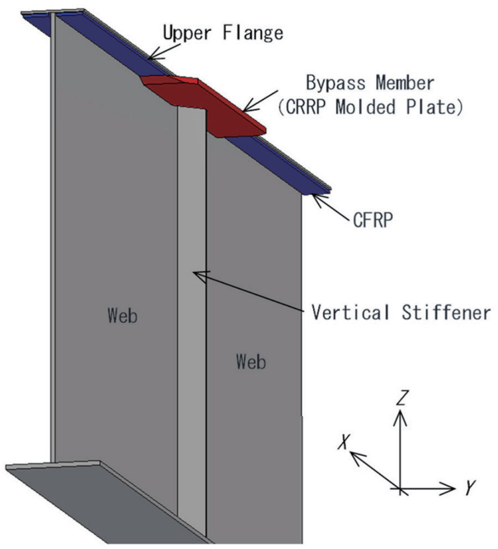

Fig. 1 CF bypass method outline

In this study, we conducted a four-point bending test on steel girder specimens of the lateral buckling precedence type with the bottom surface of the upper flange reinforced by the CF bypass method. We verified the effectiveness of the CF bypass method against lateral buckling.

2. Materials

The properties of the materials used in the four-point bending test are shown in **Table 1**. The SS400 steel was used to prepare the specimens. Medium-modulus carbon fiber sheets were used to make CFRP molded plates. High-modulus carbon fiber sheets are generally used for the repair and reinforcement of steel members.[9] In our previous study[11] in which a beam bending test was performed using CFRP molded plates, CFRP molded plates made from high-modulus carbon fiber sheets failed by compression before the matrix yielded. According to these test results, the test reported here used medium-modulus carbon fiber sheets with lower elastic modulus but higher strength than high-modulus carbon fiber sheets to increase the compressive strength of the CFRP molded plates. The CFRP molded plates were made using medium-modulus carbon fiber sheets and an epoxy-based matrix resin. An epoxy resin was used to bond the CFRP molded plates. An elongated elastic putty was used to suppress the delamination of the CFRP molded plates. This material meets the quality standards of the existing design and construction

Table 1 Used material property

(a) Steel

Material	Item	Unit	Design value	Test value
Steel (SS400)	Elastic modulus	N/mm^2	200 000	–
	Yield strength	N/mm^2	240	326 (Flg) 308 (Web)
	Tensile strength	N/mm^2	–	430 (Flg) 454 (Web)

(b) CFRP sheet

Material	Item	Unit	Design value	Test value
Medium modulus CFRP sheet	Fiber weight	g/m^2	300	310
	Design thickness	mm	0.165	–
	Elastic modulus	N/mm^2	390 000	405 000
	Poisson's ratio	–	0.3	–
	Tensile strength	N/mm^2	2 900	4 033
	Fracture strain	$\times10^{-6}$	7 436	9 958
High modulus CFRP strand sheet	Fiber weight	g/m^2	900	933
	Design thickness	mm	0.429	–
	Elastic modulus	N/mm^2	640 000	692 000
	Tensile strength	N/mm^2	1 900	2 830

(c) Resin

Material	Item	Unit	Design value	Test value
Matrix resin (Epoxy resin)	Elastic modulus	N/mm^2	2 860	–
	Poisson's ratio	–	0.4	–
Adhesive (Epoxy resin)	Elastic modulus	N/mm^2	2 500	3 317
	Poisson's ratio	–	0.35	–
Elongated elastic putty (Polyurea resin)	Elastic modulus	N/mm^2	65	74
	Poisson's ratio	–	0.499	–

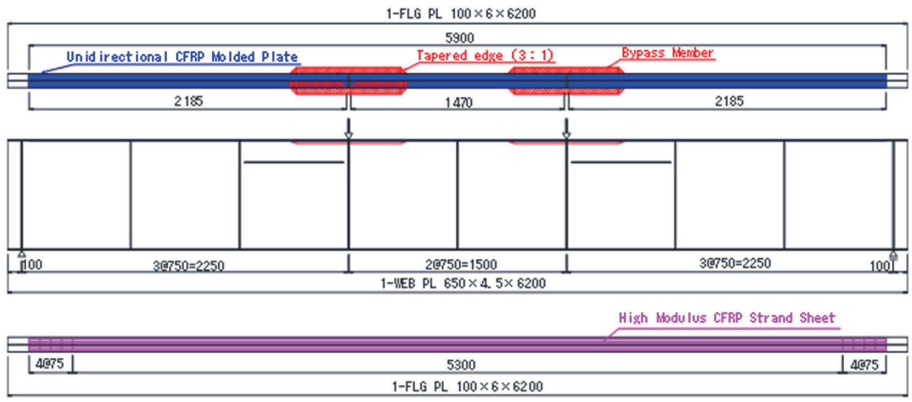

Fig. 2 Specimen outline

manual.[9] High-modulus strand sheets were used to reinforce the lower flange.

3. Steel Girder Bending Test

3.1 Specimens

Figure 2 shows a specimen outline after reinforcement. The specimen was about 1/3 to 1/2 the size of an actual bridge. The length is 6200 mm, the upper and lower flange width and thickness are 100 and 6 mm, respectively, and the web plate height and thickness are 650 and 4.5 mm, respectively. An I-section girder was used so that it would first undergo lateral buckling.

3.2 Reinforcement

The cross-section of the reinforced specimen is shown in **Fig. 3**. The material properties of the CFRP molded plates used as reinforcements in the test are shown in **Table 2**. The CFRP molded plates were made by the hand lay-up molding method. The unidirectional CFRP molded plates were made by laying up the carbon fibers only in the axial direction (0° direction). The bypass members were made by laying up the carbon fibers in the axial direction (0° direction) and in the ±45° directions to transmit the stress from the bonded surface to the width direction of the CFRP molded plate. Based on the results of our previous studies,[10, 11] the layer number ratio was set to 1/2/1 layers in the −45/0/45° directions. The thickness of the CFRP molded plate in Table 2 is the measured value. The fiber volume fraction V_f and the axial elastic modulus were calculated from the plate thickness and the values shown in Tables 1 (b) and 1 (c) based on the composite rule and lamination theory.[12] The shape of the bypass member is shown in **Fig. 4**. The width of the bonded area of the bypass member was set to 42 mm in the same way as the width of the unidirectional CFRP molded plate. The width of the unbonded area protruding from the CFRP molded plate in the width direction was also set to 42 mm. The number of layers was determined so that the tensile stiffness of the bypass member at its center with the smallest cross-sectional area became the same as that of the unidirectional CFRP molded plate. The edges of the unidirectional CFRP molded plate and the bypass member were tapered after molding to prevent their delamination.[6] The edge taper ratio was set to 3:1, as investigated by Sakurai et al.[13]

The unidirectional CFRP molded plates were bonded to the steel girder by cleaning the bonding areas of the steel girder, applying a urethane primer to the bonding areas of the steel girder, followed by a polyurea putty, as described in the design and construction manual.[9] After the polyurea putty dried, the bonding surface of the unidirectional CFRP molded plate was polished with sandpaper. The unidirectional CFRP molded plate was then bonded onto the steel girder using the epoxy resin. After the initial hardening of the epoxy resin, the bonding areas of the unidirectional CFRP molded plate and

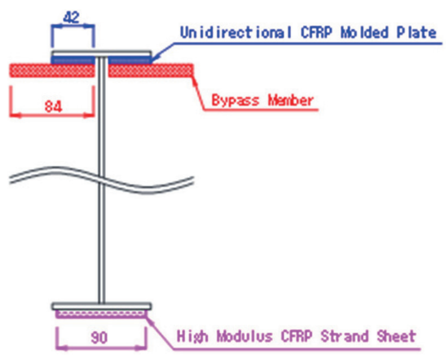

Fig. 3 Reinforced cross-section

Table 2 Material property of CFRP molded plate

Material	Item	Unit	Value
Unidirectional CFRP molded plate	Number of layers	–	$[0°]_{23}$
	Thickness	mm	7.88
	Fiber volume V_f	–	0.48
	Axial elastic modulus	N/mm²	196530
	Tensile strength*	N/mm²	1957
Bypass member	Number of layers	–	$[0°/\pm45°/0°]_{11}$ (Symmetrical layering)
	Thickness	mm	14.40
	Fiber volume V_f	–	0.50
	Axial elastic modulus	N/mm²	107615
	Tensile strength*	N/mm²	1072

* Stress when the strain generated in carbon fiber reaches the fracture strain

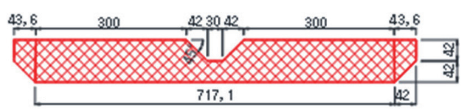

Fig. 4 Bypass member shape

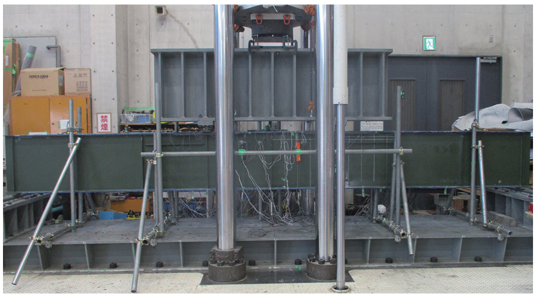

Photo 1 Test situation

Table 3 Test result

Item	Unit	Before reinforcement	After reinforcement
Yield load (Calculated value)	kN	146	232
Maximum load	kN	111 (1.00)	160 (1.44)
Stress at maximum load	N/mm²	178 (1.00)	162 (0.91)
Failure mode	–	Lateral buckling No delamination of CFRP in reinforced specimen	

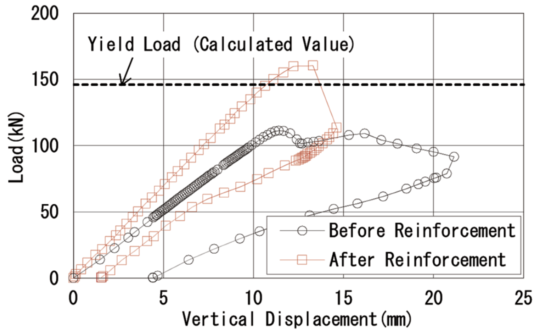

Fig. 5 Relationship between load and vertical displacement of center of support

the bypass member were cleaned. The bypass member was bonded onto the unidirectional CFRP molded plate using the epoxy resin. The resin was then left to be cured for more than one week until it was completely hardened.

The number of layers in the high-modulus CFRP strand sheets for the lower flange of the steel girder was determined so that the neutral axis after the reinforcement moved to the center of the girder height. 5 layers of high-modulus strand sheets were adopted. They were applied with their layers offset by 75 mm on each end as described in the design and construction manual.[9)]

3.3 Test procedure and specimen preparation procedure

In this test, the steel girder specimen before reinforcement, as shown in Fig. 2, was bending loaded to lateral buckling, and its load-bearing capacity was verified. After that, the girder specimen was unloaded and bonded with the CFRP molded plates and carbon fiber strand sheets and was again bending loaded. The test was a four-point bending test with a span length of 6000 mm and a loading span of 1500 mm. The test situation is shown in **Photo 1**.

4. Test Results and Discussion

4.1 Test results and failure mode

The test results are given in **Table 3**. The calculated initial yield load is the applied load when the stress intensity at the upper edge of the specimen is a characteristic flange yield strength of 235 N/mm^2. The values in parentheses in the table indicate the ratio to the value before reinforcement. The failure mode was lateral buckling both before and after reinforcement. After reinforcement and lateral buckling, delamination did not occur in the CFRP molded plates and in the carbon fiber strand sheets reinforcing the lower flange. As shown in Table 3, the maximum load was 111 kN before reinforcement and 160 kN after reinforcement. The reinforcement increased the maximum load by 1.44 times. The stress intensity at the maximum load is the stress intensity at the upper edge of the specimen calculated from the maximum load. This stress intensity was 178 N/mm^2 before reinforcement and 164 N/mm^2 after reinforcement. The reinforcement increased the stress intensity by 0.91 times.

4.2 Relationship between load and vertical displacement at center of span

Figure 5 shows the relationship between the load and the vertical displacement at the center of the span before and after reinforcement. Before reinforcement, the load increased almost linearly until the ultimate state, then decreased due to lateral buckling at a vertical displacement of 11.7 mm and reached the ultimate state. The residual displacement after unloading was 4.4 mm. After reinforcement, the bending stiffness improved compared to before reinforcement. The load exceeded the yield load before reinforcement and calculated from the characteristic yield strength, increased almost linearly until the ultimate state, then decreased due to lateral buckling at a vertical displacement of 13.3 mm, and reached the ultimate state.

Reinforcement by the CF bypass method improved the maximum load, but the upper flange stress intensity at the maximum load was lower than before the reinforcement. The vertical displacement at the maximum load was about the same as before the reinforcement. This condition may be partly ascribed to the residual deformation caused by the load applied before the reinforcement. In addition, the load bearing capacity during lateral buckling is affected by the moment of inertia around the vertical axis and the warping torsion constant.[14)] The method reported here is considered to be less effective in improving these properties. Therefore, we think that the load-bearing capacity against lateral buckling can be controlled by improving the bending stiffness of the steel girder. Our method is considered to be less effective in improving the stress intensity during lateral buckling.

5. Conclusions

In this study, steel girders were tested for four-point bends to ascertain the reinforcement effect of the CF bypass method using CFRP-molded plates against lateral buckling. As a result, the CF bypass method is considered capable of controlling the load bearing capacity against lateral buckling by improving the bending stiffness of steel girders by reinforcement. However, the effect of the CF bypass method in improving the stress intensity during lateral buckling is considered to be small.

In the future, we will have to establish load-bearing capacity evaluation methods and design methods through experiments and FEM analyses.

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