- Technical paper -

EXPERIMENTAL STUDY ON TORSION BEHAVIOR OF PC BEAMS STRENGTHENED WITH CARBON FIBER SHEETS

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ABSTRACT: This paper presents the experimental study results of prestressed concrete (PC) beams strengthened with carbon fiber sheets (CFS). PC beam specimens without reinforcement were fabricated for comparison. The experimental variables are: type of reinforcement method and ratio of CFS reinforcement. From the comparative works, following conclusions were obtained: 1. PC beams strengthened with CFS had higher bearing capacity than PC beam specimens without reinforcement. 2. The different type of reinforcement method and ratio of CFS reinforcement had different reinforcement effect.
KEYWORDS: carbon fiber sheet (CFS), prestressed concrete beam, torsion behavior, static loading test

1. INTRODUCTION

The structural design for many structures is performed so that a large torsional moment may not occur, and the considering of torsion is usually abbreviated. However, there are cases that torsional moment cannot be ignored for large-sized unsymmetrical structures, the direction of eccentric load action and so on. For examples, when the horizontal force due to earthquake acts on a building or a substructure of a bridge which has unsymmetrical configuration, a large torsional moment may occur at columns and slabs. Moreover, it is also important for the problem of torsion such as the large-sized gravity type structures and PC segment type immersed tunnel which are subjected to non-uniformed subsidence of soft ground, the floating type structures which are applied by wave force from slant direction and the pile type structures which receive eccentric load by an earthquake or loading of a vessel in recent years [1] [2]. On the other hand, as the one type of the reinforcement method, the application of the Fiber Reinforcing Plastics (FRP) to improve the capacity of civil structures especially in concrete elements, creates a great issue in the field of civil engineering.

Many researches as to mechanical properties have been conducted on reinforced concrete members. The mechanical properties and characteristics have been considerably grasped by experimental studies etc. However, the mechanical properties of PC members subjected to torsion are not well known in contrast to reinforced concrete members subjected to bending, shear and axial force, and it is hard to say that those are enough checked about applicability.

Thus, static loading tests of pure torsion were carried out in order to investigate basic properties of torsion and mechanical behaviours, and reinforcement effect of different type of reinforcement method by carbon fiber sheets. The loading tests are performed on PC beams and PC beams strengthened with CFS with square cross section on condition that one end is fixed and the other end is applied by torsion. Property of mechanical joint that will be applied to the tunnel are also studied.

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2. EXPERIMENTS

2.1 SPECIMENS

The list of test specimens is presented in **Table 1**. The loading tests were divided into two test groups. Test series 1 is the specimens without reinforcement, included one specimen with shear key joint and one specimen without the joint. Test series 2 is the specimens strengthened with CFS, included three specimens with joints and three specimens without joint. In test series 2, the CFS was cut at joint section. CFS at joint is arranged to reinforcement of the joint because the specimen without CFS shows brittle property by loading test in advance. The dimensions and outline of the specimens are shown in **Fig. 1** and **Fig.2**. The length of the specimen was 1m and cross section was square with 150mm×150mm by any specimens. Reinforcement of end boxes for each specimen was performed by outside steel plate arranged in the range of 200mm from both ends. The prestress introduced for all of the specimens is 22.5kN (1N/mm^2 for concrete).

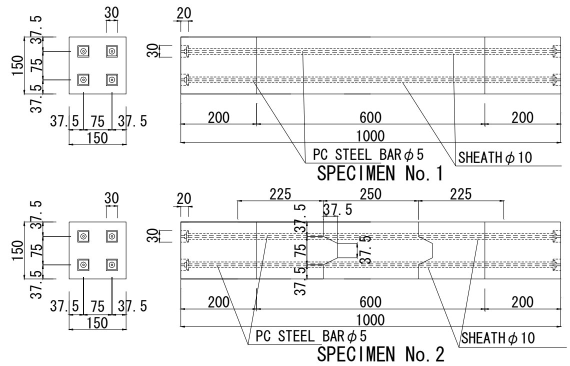

Fig. 1 Dimensions and basic structure
Specimens of the Test series 1

Table 1 List of test specimens

Tests	Specimen	Joints	Reinforcement
Series 1	No.1	No	No
	No.2	Yes	No
Series 2	No.3	No	Complete reinforcement
	No.4	No	Zebra type reinforcement
	No.5	No	Zebra type(two sheets) reinforcement
	No.6	Yes	Complete reinforcement
	No.7	Yes	Complete reinforcement (two sheets)
	No.8	Yes	Zebra type reinforcement

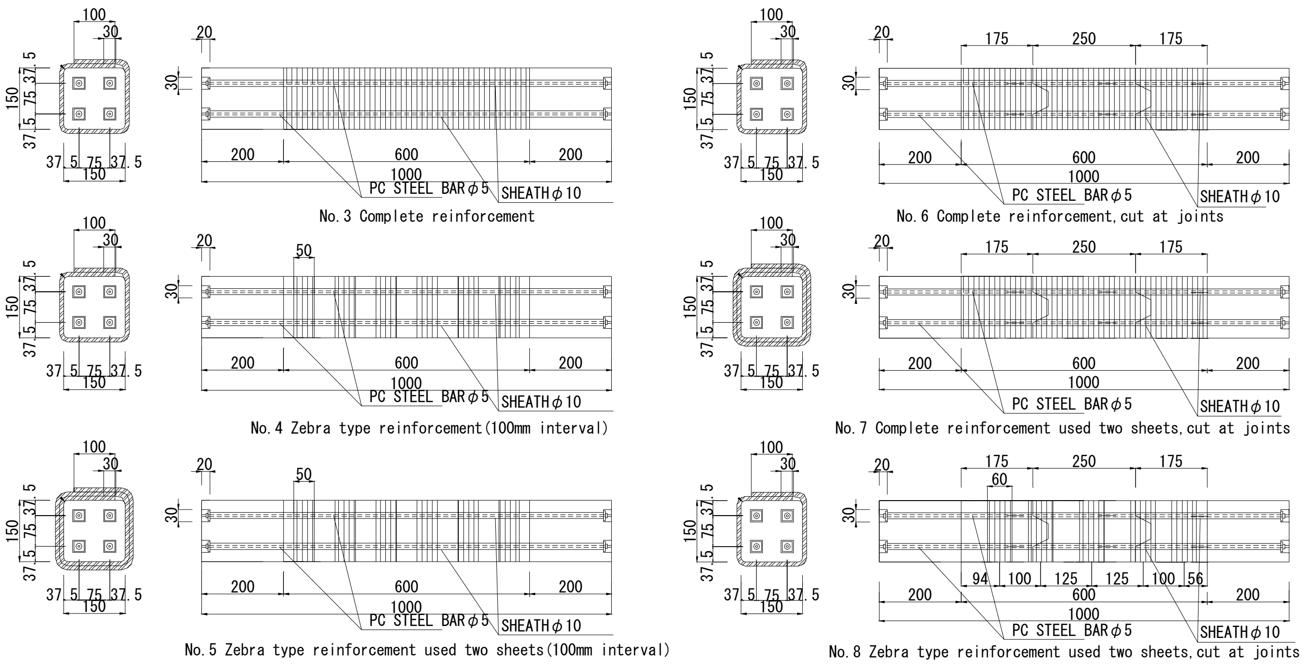

Fig. 2 Dimensions and reinforcement arrangement
Specimens of the Test series 2

2.2 MATERIALS

Table 2 shows the specified mix proportion of concrete used for the specimens. The basic strength for the design of concrete was 24MPa. The slump and the air content of concrete were 12cm and 4.0%, respectively. Concrete using ordinary Portland cement and strength loading tests were carried out at the day of the loading test. **Table 3** shows the material properties of the concretes. These values were obtained from the tests with the control cylindrical specimens which size was ϕ 10×20cm. **Table 4** indicates the material properties of CFS. The CFS has strengthened at one direction. The adhesion side applied epoxy resin plastic primer after disk sander processing, and the sheet was pasted up using epoxy resin adhesives.

Table 2 Specified mix proportion of the concrete

Max. size of coarse aggregate (mm)	Water-cement ratio (%)	Sand-Aggregate Ratio (%)	Unit contents(kg/m^3)				
			Water	Cement	Fine aggregate	Coarse aggregate	Admixtures
20	56.5	46.7	168	298	847	982	2.98

Table 3 Material properties of the concrete

Specimens	Test series 1	Test series 2
Compressive (MPa)	28.5	30.3
Tensile (MPa)	2.42	3.00
Young's Modulus Ec (GPa)	2.27	2.58
Poisson's Ratio υ	0.173	0.187

Table 4 Material properties of the CFS

Ratio (g/m^2)	Thickness (mm)	Young's Modulus (GPa)	Tensile (GPa)
200	0.111	230	3.4

2.3 TEST PROCEDURES

Fig. 3 shows the loading set-up. A pure torsional moment was applied through the overhang beam from upper bearing pressure plate to the top end of a specimen. To produce the required torsion, two hydraulic jacks were installed to apply reversal tensile forces. Supporting point of bottom end was fixed and the other end was free for torsion. The monotonous load was applied statically, taking care of that the amount of drawing in of two hydraulic jacks becomes almost equal at loading steps.

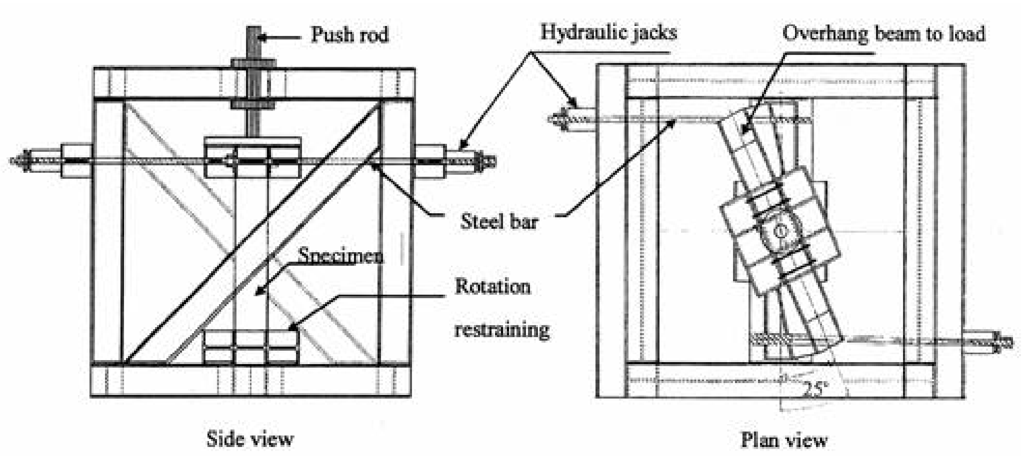

Fig. 3 Test set-up

2.4 MEASUREMENT PROCEDURE

Photo. 1 shows the general view of test set-up. The applied load was measured using load cells installed on the jacks. Movement of the jack axis was measured by displacement transducers. **Fig. 4** shows the positions of rotation angle measurements. Aluminum bars were arranged in the 300mm location from the both ends of specimen. Each rotation angle was measured from the difference between the displacement of V1 and V2, and the difference between the displacement of V3 and V4. The angle of twist was determined by the change of the rotation angle per unit length from the differences of these rotation angles [3].

Photo. 1 General view of test set-up

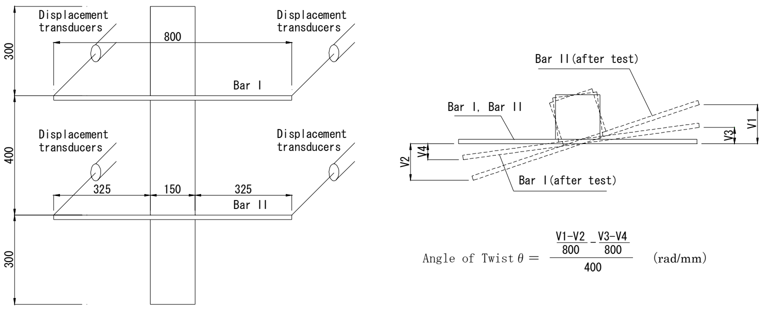

Fig. 4 Arrangement of displacement transducers

3. EXPERIMENTAL RESULTS

The outline of test results for specimens is presented in **Table 5**.

Table 5 The list of test results

Specimen	No.1	No.2	No.3	No.4	No.5	No.6	No.7	No.8
Maximum load (kN･m)	3.08	1.60	6.03	5.29	4.87	3.11	4.30	3.37
Maximum angle of twist at maximum load (rad/m)	0.0073	0.0313	0.1856	0.0079	0.0071	0.0740	0.0202	0.0081
Initial torsion rigidity (kN･m^2)	578.29	307.86	786.13	824.47	836.21	274.86	395.43	551.38

3.1 Test series 1

3.1.1 Torsion rigidity

Torque-rotation curves of test series 1 obtained from the loading tests are plotted in **Fig. 5**. The general behaviors about No. 1 specimen were such that, initially linear elastic behavior at a low loading stage was observed. The load gradually increased up to M_{tcd} (concrete crack torsion moment) [4] where the torque-rotation curve is little bent (first part), and it appears that rapid collapse after reaching peak load (second part). In contrast to No. 1 specimen the general behaviors about No. 2 specimen with joints were difficult to describe. After torque reached 0.8 kN･m, the rigidity decreased to the maximum load and the maximum load was smaller than that of No.1 specimen. The influence of the crevice between junction parts and the fall of torsion rigidity by the crack at the junction part are mainly

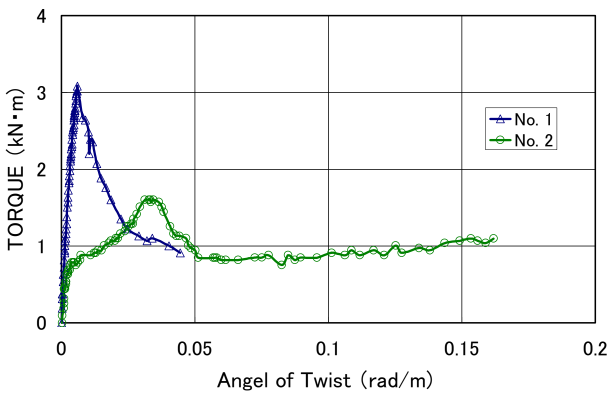

Fig. 5 Torque-rotation diagram of test series 1

related to the decrease of both the rigidity and maximum load.

3.1.2 Description of the crack pattern

Fig. 6 shows the crack pattern of the test series 1. In No. 1 specimen, the first crack was observed at the middle of the specimen and the load was near the maximum load, the angle of the crack is about 45°. With the increase of the load, the crack extended to the other sides of the specimen, eventually the crack was connected to four sides of specimen and the specimen was destroyed. In No. 2 specimen, the cracks occurred at the joints firstly and extended with the increase of the load. Eventually specimen was destroyed by the destruction of joints.

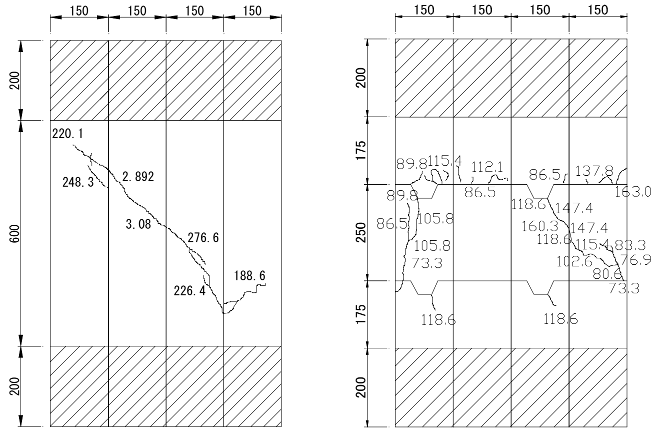

Fig. 6 Developed Elevation of Cracks (test series 1)

3.2 Test series 2

3.2.1 Torsion rigidity

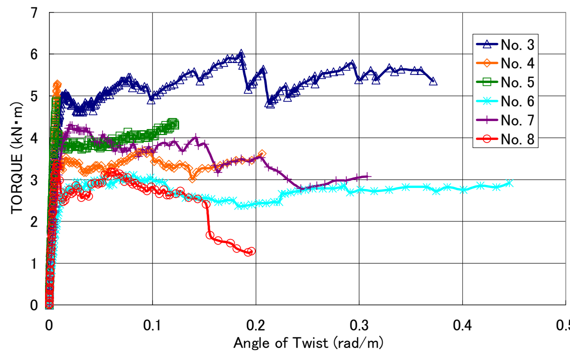

Fig. 7 Torque-rotation diagram of test series 2

Torque-rotation curves of test series 2 obtained from the loading tests are plotted in **Fig. 7**. The general behaviors about specimens without joints (No.3, No.4 and No.5) were similar to No.1 specimen at the first part of the curve. In second part of torque-rotation curve, specimens show the different behaviors due to the different type of reinforcement method. Torsion bearing capacity on the loading test of the No.3 specimen did not fall where the angle of twist even reaches 10 times or more than the point where the torque-rotation curve is flat. Torsion bearing capacity on the loading test of the No.3 and No.4 specimens fell a little after reaching the maximum load, then held the value of load, only angle of twist was increased. The general behaviors about specimens with joints (No.6, No.7 and No.8) were also similar to specimens without joints at the first part of the curve. In second part of torque-rotation curve, No.6 and No.7 specimen held the value of load, only angle of twist was increased While No.8 specimen rapid collapsed after the angle of twist reached to 0.15.

3.2.2 Description of the destruction

The crack patterns were shown in **Photo 2** and **Photo 3**. **Photo 2** shows the crack pattern of specimens without joint. Just like No.1 specimen, the first crack was observed at the middle of the specimen, but simultaneously with occurrence of the first crack, many cracks were occurred through the other sides of specimen, the angle of the cracks are about 45°. The effect of reinforcement is large, all of the specimens without joint did not collapse at the loading tests. **Photo 3** shows the crack pattern of specimens with joints. The cracks occurred at the joints firstly and extended with the increase of the load. Also the effect of reinforcement is large, No.6 and No.7 specimen did not collapse at the loading tests while No.8 specimen rapid collapsed after the angle of twist reached to 0.15.

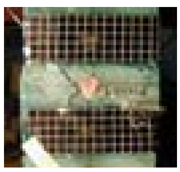

Photo 2 Cracks on specimen (Test series 2, without joint)

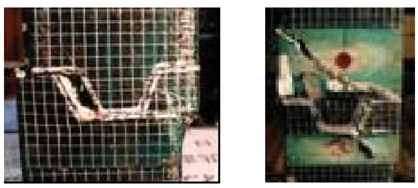

Photo 3 Cracks on specimen (Test series 2, with joint)

4. COMPARISON

The effects of reinforcement are compared between the specimens without reinforcement and the specimens strengthened with CFS by the different type of reinforcement method and ratio of CFS reinforcement.

4.1 Comparison of the specimens without joint

The relationships between torsional moment and angle of twist about each result obtained from the loading tests are shown in **Fig. 8**. At the point where the torque-rotation curve is bent, the value of the torsional moment is 3.08kN・m (No.1), 5.06 kN・m (No.3), 5.29 kN・m (No.4) and 4.87 kN・m (No.5), respectively. The specimens strengthened with CFS have 1.5 times or more then the specimen without reinforcement. After the point where the torque-rotation curve is bent, Contrast to rapid collapse of the specimen without reinforcement, the specimens strengthened with CFS did not collapse at the loading tests.

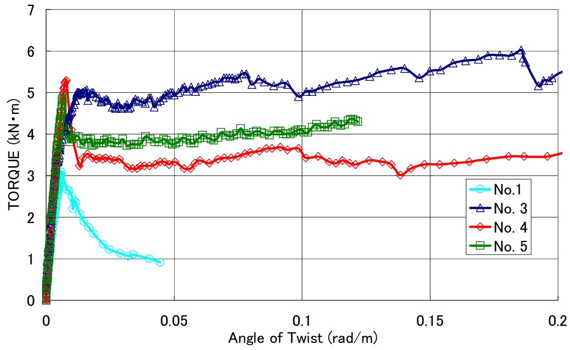

Fig. 8 Torque-rotation diagram of the specimens without joint

4.2 Comparison of the specimens with joint

The relationships between torsional moment and angle of twist about each result obtained from the loading tests are shown in **Fig. 8**. The specimens strengthened with CFS have 2 times or more than the specimen without reinforcement. With the comparison of the No.6 and No.8 specimens, it shows that the reinforcement of the joint is most important in specimens with the joint.

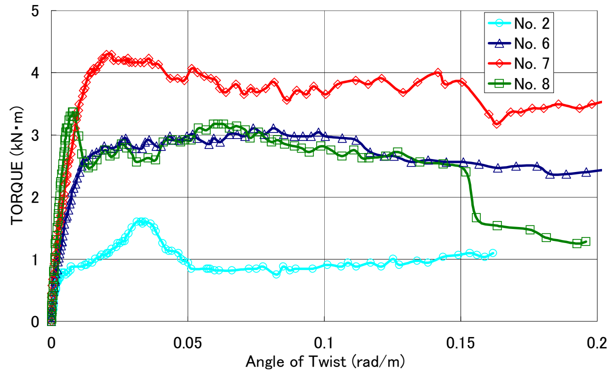

Fig. 9 Torque-rotation diagram of the specimens with joint

5. CONCLUSIONS

Through the loading tests, following conclusions are obtained. (1) With the reinforcement by CFS, bearing capacity of the specimen becomes much higher, especially in specimen with joint. (2) In specimen without joint, the more ratio of CFS used, the bearing capacity becomes more high. With the same ratio of CFS, complete reinforcement is better than zebra type reinforcement. (3) In specimen with joint, the reinforcement of the joint the most effective than any other parts.

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