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MECHANICAL BEHAVIORS OF CONCRETE BEAMS REINFORCED WITH GRID-SHAPED FRP AND EFFECTS OF CHEMICAL PRESTRESS

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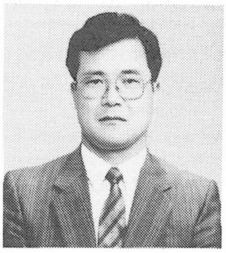
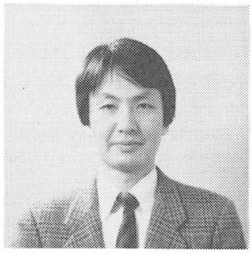
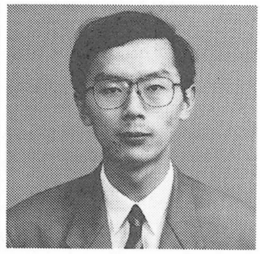


Yukikazu TSUJI   Kenzo SEKIJIMA   Norimichi NAKAJIMA   Hitoshi SAITO

SYNOPSIS

The flexural crack widths of beams reinforced with grid-shaped fiber reinforced plastic (FRP) are large compared with RC beams reinforced with reinforcing steel bars due to small tensile rigidities of the FRP. As expected from the strain increment of tensile reinforcement in FRP beams, the deflections of FRP beams are larger than those of RC beams. In calculating the shear strength of FRP beams, the cross sectional area of FRP should be decreased by the ratio of Young's modulus of elasticity of the FRP to that of reinforcing steel bar in RC beams. During the sustained bending moment for one year, the values of deflection increment of FRP beams are larger than those of RC beams. However, the rates of change in curvature are less than half those of RC beams. In order to improve the mechanical behaviors of FRP beams, chemical prestress was introduced using expansive concrete. Based on the test results, it was assured that the effects of chemical prestress on the flexural crack width and the shear strength of FRP beams were obtained.

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1. INTRODUCTION

In recent years, fiber reinforced plastic (FRP) consisting of continuous fibers shaped with plastic has drawn attention as reinforcing material for concrete to take the place of reinforcing bars or prestressing (PC) steel. In this paper, the flexural and shearing behaviors of concrete beams using three varieties of grid-shaped FRP as axial reinforcement (hereinafter abbreviated as "FRP beams") are first reported, the FRPs being formed by respectively setting carbon fibers, glass fibers, and continuous fibers of combinations of these two in vinyl ester resin[1][2][3]. Next, the basic effects[4] when chemical prestress in the axial direction has been induced using expansive concrete to improve the mechanical behaviors of the beams (hereinafter abbreviated as "CPC beams") are studied.

2. METHOD OF TESTING

2.1 Beam Specimens

The cross sections of beams used in flexural strength tests are shown in Table 1. The particulars of the cross sections of the beams are given in Fig. 1. Reinforcement was arranged in only the axial direction. The distance from the tension fiber to reinforcement was made 25 mm in Aa cross sections, and 15 mm in Bb cross sections.

2.2 Varieties of FRP and Mechanical Properties

The FRPs, as indicated in Table 2, consisted of three varieties, and the prescribed numbers of bundles of carbon fibers (C), glass fibers (G), and a combination of the two (CG) were covered with vinyl ester resin and were formed in grid shape of 10-cm pitch. By forming in grid shape, the drawback of bond of FRP being low was overcome.

The criteria for strengths of the FRPs were all 1.2 times the tensile strength of reinforcing steel (D10, SD345). The mechanical properties of the FRPs are given in Table 2 and Fig. 2.

2.3 Quality of Concrete

The mix proportions of ordinary concrete aimed for water-cement ratio of 0.60, slump of 10 cm, and air content of 4%. The compressive strength of concrete at the age of 28 days was 250 kgf/cm^2. Unit expansive admixture contents were of the two levels of 30 kg/m^3 and 45 kg/m^3. The compressive strength of concrete at the age of 28 days was 356 kgf/cm^2.

3. FLEXURAL AND SHEARING BEHAVIORS OF FRP BEAMS

3.1 Flexural Cracking Load

The flexural cracking stress intensities of beams are shown in Fig. 3. The flexural cracking stress intensities of FRP beams judged from strains at tension fibers of concrete using wire strain gauges showed almost no difference according to variety of FRP regardless of whether the type of cross section was Aa or Bb. However, when compared with reinforced concrete (RC) beams they were 20 to 30% lower at Aa cross sections, while at Bb cross sections of even thinner cover, they were about one half. The reason for this is thought to have been the FRP being of grid shape. That is, since FRPs were laid out in a manner that they also crossed perpendicularly with the axial direction of the beam, a beam

Table 1 Cross sections of beams

concrete	reinforcement			
	G	CG	C	rebar
ordinary	Aa Bb	Aa Bb	Aa Bb	Aa
expansive	Cc	Cc	Cc	Cc

* Names of cross section as Aa, Bb and Cc are indicated in Fig.1.

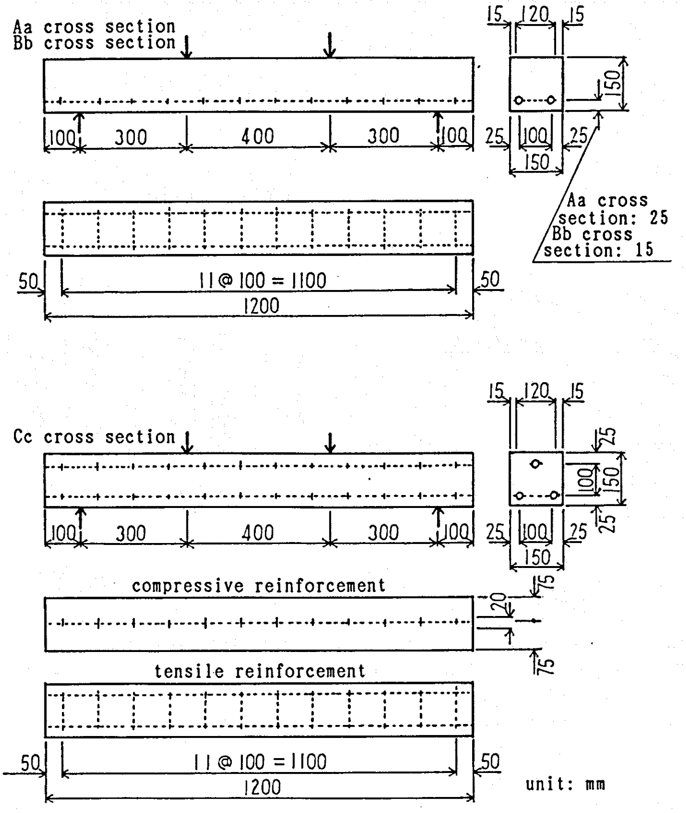

Fig.1 Cross sectional dimensions of beams

having the cross-sectional specifications given in Fig. 1, differing from a slab member, had stresses concentrated in concrete at the grid intersections so that minute flexural cracks occurred, and it is thought these were detected by the wire strain gauges.

Further, on comparing the flexural cracking stress intensities judged by strains at tension fibers of concrete and sudden changes in strains of reinforcements although there were cases with RC beams of stress intensities judged by strains of tension fibers of concrete to be smaller than those judged by strains of reinforcement, the two roughly were in agreement. For FRP beams also, the flexural cracking stress intensities judged from the points of sudden changes in strains at locations apart from the grid intersections of reinforcement were equal to or higher than for RC beams. From this, it was seen that in a grid-shaped FRP beam, even though minute flexural cracks occurred at the grid intersections due to stress concentrations, strains of the reinforcement apart from the grid intersections were not abruptly increased until the stress intensity at the tension fiber of concrete reached the flexural strength of the concrete.

Table 2 Mechanical properties of FRPs

rein-force-ment	fiber	numbers of bundle	Vf,%	area, mm^2			strength capacity, kgf/bar	strength, kgf/cm^2	Young's modulus, kgf/cm^2	tensile rigidity, kgf
				fiber	resin	total				
FRP	G	36	37	31.5	53.6	85.1	4880	5730	0.295×10^6	0.250×10^6
	CG	C=9, G=36	C=4, G=30	35.6	69.1	104.7	4960	4740	0.334×10^6	0.348×10^6
	C	32	26	14.6	41.6	56.2	4290	7630	0.673×10^6	0.381×10^6
rebar	SD345 D10			–	–	71.3	3820	3770	1.860×10^6	1.330×10^6

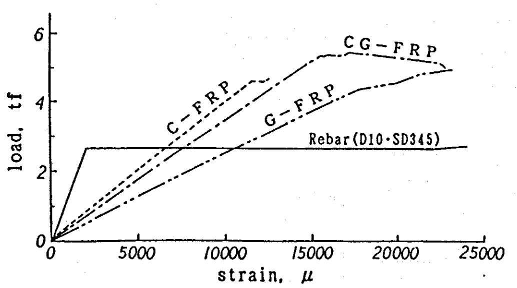

Fig. 2 Mechanical properties of FRPs

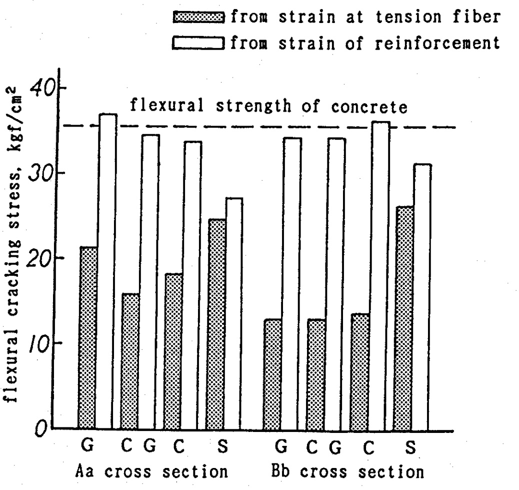

Fig. 3 Flexural cracking stress

3.2 Tensile Strain of Reinforcement and Flexural Crack Width

The relationships between strains of reinforcement up to near failure and loads in beams of Aa cross sections using the various reinforcing materials are shown in Fig. 4. In this figure, ignoring tensile force of concrete the values calculated by the same method as for reinforced concrete by elasticity calculations using a converted cross section are indicated by broken lines. After occurrence of flexural cracks, the increases in strains of reinforcements were larger the smaller the tensile rigidities of the reinforcement. This was the same in cases of Bb cross sections.

The relationships of tensile strains of reinforcement and average flexural crack widths in beams of Aa cross sections are shown in Fig. 5. In FRP beams, flexural crack widths and tensile strains are distributed in more or less straight lines similarly to RC beams until tensile strains of reinforcement reached 7000 μ, close to 3.5 times the value for RC beams. Although the inclinations of the straight lines were roughly the same regardless of variety of FRP, they were seen to be slightly greater compared with RC beams. This is thought to have been because bond between FRP and concrete occurred mainly at the grid intersections, with bond forces small at other parts.

3.3 Deflection

The relationships between load and deflection of beams of Bb cross section using G-FRP and reinforcing steel are shown in Fig. 6. The theoretical values considering the gross cross sections to be effective, the theoretical values ignoring the concrete on the tension side, and the theoretical values using the effective moment of inertia Ie given in the following equation in the Japan

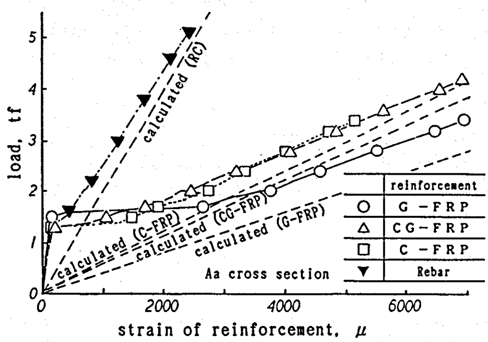

Fig. 4 Relationship between tensile strain of reinforcement and load

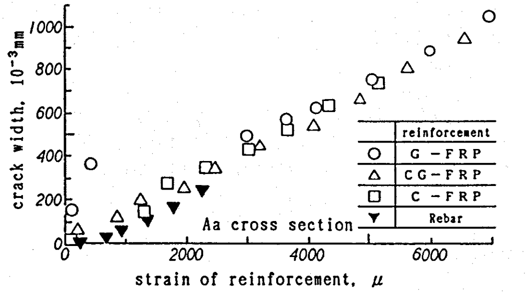

Fig. 5 Relationship between tensile strain of reinforcement and flexural crack width

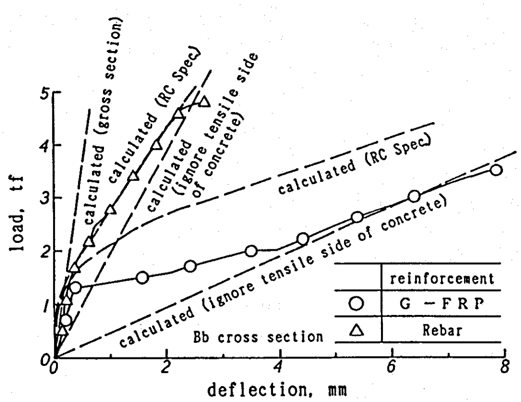

Fig. 6 Deflection

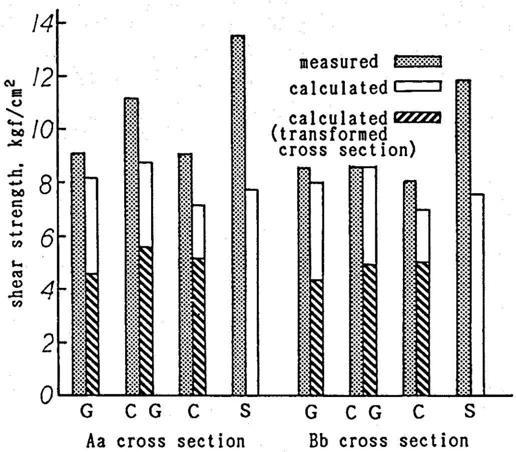

Fig. 7 Shear strength

Society of Civil Engineers Standard Specifications for Concrete [6] (hereinafter abbreviated as "RC Specifications") are respectively indicated with broken lines in the figure.

$$I_e = \left[\left(\frac{M_{crd}}{M_{dmax}}\right)^3 I_g + \left(1 - \left(\frac{M_{crd}}{M_{dmax}}\right)^3\right)\cdot I_{cr}\right] \leqq I_g \qquad \cdots\cdots\cdots\cdots (1)$$

where, I_e: effective moment of inertia
M_{crd}: moment causing flexural cracking at cross section
M_{dmax}: maximum design flexural moment when displacements and deformations computed
I_g: moment of inertia computed based on gross cross sections
I_{cr}: moment of inertia computed based on cracked cross sections

The deflections of RC and FRP beams until flexural cracks occurred roughly coincided with the theoretical values assuming gross cross sections to be effective, and the two were more or less equal. After occurrence of flexural cracking, the deflections of G-FRP beams having smaller tensile rigidities of reinforcement became larger than those of RC beams.

The measurements on RC beams after occurrence of flexural cracking showed values close to the theoretical values of the RC Specifications. However, the measurements on FRP beams were larger than the theoretical values according to the RC Specifications, and were values roughly equal to the theoretical values when ignoring concrete at the tension side. This trend was the same with other FRP beams also.

Based on the above, it was seen that when using reinforcement of low tensile rigidities like the FRPs employed in this study there is a possibility that deflection would be underestimated using effective moment of inertia according to the RC Specifications.

3.4 Failure Mode and Failure Strength

Whereas RC beams showed flexural tensile failure, the failure modes of FRP beams were all shear failures due to occurrence of diagonal cracks. The measured and theoretical values of shear stress intensities at failure of these beams are shown in Fig. 7. The theoretical values were obtained by determining shear stress intensity fvcd using the equation below given in the RC Specifications and the cross-sectional area of reinforcement accumulating the total cross sections of fibers and matrix with cross-sectional area as As.

$$f_{vcd} = 0.9\beta_d \cdot \beta_p \cdot \beta_n \cdot \sqrt[3]{f'_{cd}} \quad (kgf/cm^2) \qquad \cdots\cdots\cdots\cdot (2)$$

$$\beta_d = \sqrt[4]{100/d} \quad (d: cm), \text{ when } \beta_d > 1.5, \ \beta_d \text{ is taken as } 1.5$$

$$\beta_p = \sqrt[3]{100\ p_w} \quad \text{when } \beta_p > 1.5, \ \beta_p \text{ is taken as } 1.5$$

$$\beta_n = 1 + M_o/M_d \quad (N'_d \geq 0), \text{ when } \beta_n > 2, \ \beta_n \text{ is taken as } 2$$

$$= 1 + 2\ M_o/M_d \quad (N'_d < 0), \text{ when } \beta_n < 0, \ \beta_n \text{ is taken as } 0$$

where, N'_d: design axial compressive force
M_d: design flexural moment
M_o: decompression moment
A_s: area of longitudinal reinforcing steel
b_w: web width of member
d: effective depth
p_w: $A_s/(b_w \cdot d)$
f'_{cd}: design compressive strength of concrete

The measured values of RC beams compared with theoretical values were amply on the conservative side for both Aa and Bb cross sections. In contrast, the differences between measured and theoretical values of FRP beams were small, and there were cases of the two being equal as with the CG-FRP beams of Bb cross sections using carbon fibers and glass fibers in combination. This is thought to have been due to decreases, respectively, of shear force carried by concrete, interlocking effect of aggregates, and dowel action of axial reinforcement as a result of increase in crack width on rising of the neutral axis position because of the low modulus of elasticity of FRP.

Consequently, when using FRP of the modulus of elasticity lower than that of reinforcing steel as reinforcement, it is necessary to take the modulus of elasticity of the reinforcement into consideration in calculating shear strength. Therefore, calculations were made with the cross-sectional area As in the equation of the RC Specifications as As(Ef/Es) of the transformed cross section multiplying by the ratio of the moduli of elasticity of FRP and reinforcing steel. These results are shown in Fig. 7. With this calculation method, the theoretical values of FRP beams became amply small compared with measured values, similarly to RC beams.

4. BEHAVIORS OF BEAMS SUBJECTED TO SUSTAINED LOAD

4.1 Deformation Behaviors under Sustained Load

Strains of reinforcements and average curvatures under sustained loads were smaller the greater the tensile rigidity of the reinforcement. And, a difference was prominently seen between rates of change in curvatures in the deformation behaviors of RC and FRP beams subjected to sustained loads. In Fig. 8, the amount of increase in curvature from immediately after loading divided by the value immediately after loading is indicated as the rate of change in curvature. The absolute values of curvature, as mentioned previously, were higher for beams using FRP of low tensile rigidity than for RC beams. However, on scrutinizing the rates of change of curvatures, the values for FRP beams were less than half those of RC beams. This is thought to have been because the flexural cracking of FRP beams developed rapidly to reach close to the compression fiber so that the increase in curvature accompanying development of cracks while subjected to subsequent sustained load was small. Further, since the sustained load converted to reinforcing steel stress intensity of RC beam was low at 1000 kgf/cm^2, with the G-FRP and C-FRP beams in which flexural cracking did not develop suddenly immediately after loading, the curvatures increased during sustained loading due to growth of flexural cracks. Therefore, the rates of change in curvature were more than double those in CG-FRP beams in which sudden development of flexural cracking immediately after loading had already occurred as shown in Fig. 9.

4.2 Mechanical Behaviors of Beams Subjected to Different Sustained Loads

Flexural strength tests were performed on beams after loads had been sustained for one year, and strains of reinforcements, flexural crack widths, deflections, and failure loads were determined.

The relationships between average flexural crack widths and loads of G-FRP beams subjected to different sustained loads are shown in Fig. 10. The crack width at load of 0 tf corresponds to the residual crack width immediately before flexural strength testing. The arrows in the figure indicate values of initial loads during sustained load tests.

The increases in flexural crack width of beams of large sustained loads, since flexural cracking during sustained loading had developed considerably, showed

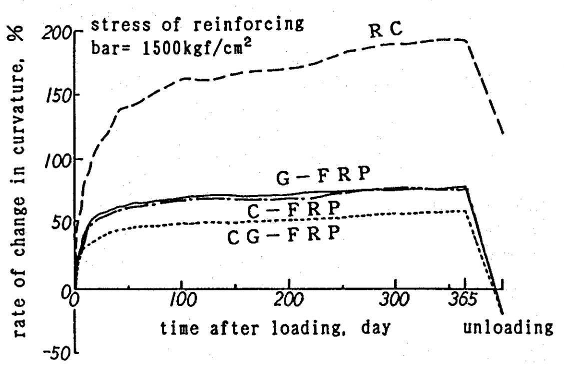

Fig. 8 Rate of change in curvature

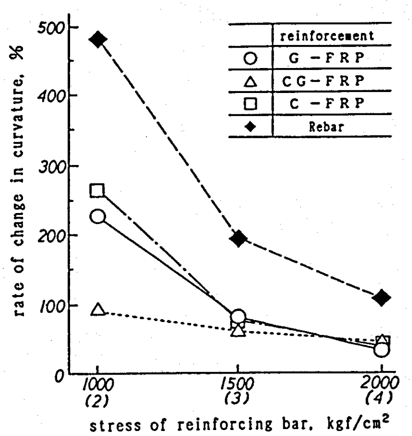

Fig. 9 Rate of change in curvature after one year

roughly the same trends, and the effects of initial loads being different could hardly be seen. Beams subjected to sustained load of 1000 kgf/cm^2 converted to stress intensity of reinforcing steel in RC beams had large flexural crack widths at low load compared with beams tested at 28-days age without subjecting to sustained loads and beams with load of 0 tf applied, but with increase in load, the differences between the three beams became small. And, they became closer to beams with heavy sustained loads.

As a result of the above, it was recognized that with FRP beams, the flexural behaviors in flexural strength tests after sustained loading were influenced by whether or not flexural cracks had developed considerably, and there were cases when they were hardly affected by the magnitude of the sustained load.

5. EFFECT OF CHEMICAL PRESTRESS

5.1 Effect of Alleviating Strain of Reinforcement, Flexural Crack Width, and Deflection

The relationships between strains of tensile reinforcement in FRP beams using G-FRP as reinforcement and loads are shown in Fig. 11. With CPC beams having chemical prestress induced using expansive concrete, the incremental strains of tensile reinforcement at same load were decreased compared with beams using ordinary concrete.

The reductions in strains of tensile reinforcement of CPC beams at 2.1 tf corresponding to stress intensities of tensile reinforcement of RC beams being approximately 2000 kgf/cm^2 and initial tensile strains of tensile reinforcement immediately before flexural strength tests are given in Table 3. With an RC beam, the difference between reduction in strain and initial tensile strain in tensile reinforcement was about 1.7 times. However, with an FRP beam, the reduction in strain of tensile reinforcement was much larger than the initial tensile strain due to expansion, and was as much as 6 times at maximum.

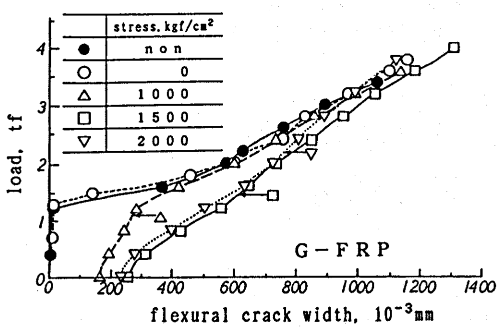

Fig. 10 Relationship between flexural crack width and load

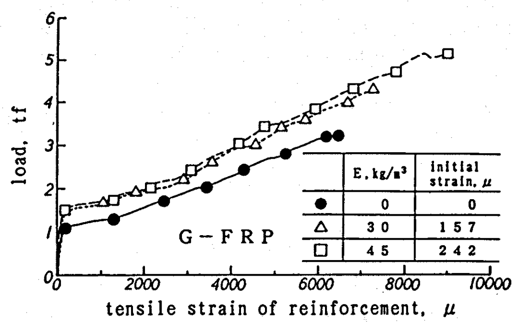

Fig. 11 Relationship between tensile strain of reinforcement and load of CPC beam

Table 3 Reduction in strain of tensile reinforcement and initial tensile strain

rein-force-ment	strain at load of 2.1tf. ,μ		reduction in strain, μ	initial strain, μ
	E=0kg/m³	E=45kg/m³		
G	3638	2257	1381	242
CG	2262	1011	1251	203
C	2778	1576	1202	410
rebar	449	175	274	162

Based on the above, it was learned that with reinforcement securing bond to concrete by the intersecting points of grids as with the FRPs used in this study, there is a possibility that it would not be suitable to employ the conventional concepts concerning RC beams[7][9]. Or, it is also conceivable that there is a possibility the measurements of tensile strains of reinforcements at the stage of expansion came out smaller than the correct values for some reasons.

Through inducement of chemical prestress, an alleviation effect was seen in flexural crack widths of FRP beams also. The relationships between strains of tensile reinforcement and average flexural crack widths in CG-FRP beams are shown in Fig. 12. Roughly similar proportionate relationships hold between the two regardless of the variety of concrete. Therefore, as the alleviation effect regarding flexural crack width a quantity corresponding to the reduction in tensile reinforcement strain is obtained.

The relationships between deformations of C-FRP beams and loads are shown in Fig. 13. Through inducement of chemical prestress, the flexural rigidities of FRP beams increased and the deflections decreased.

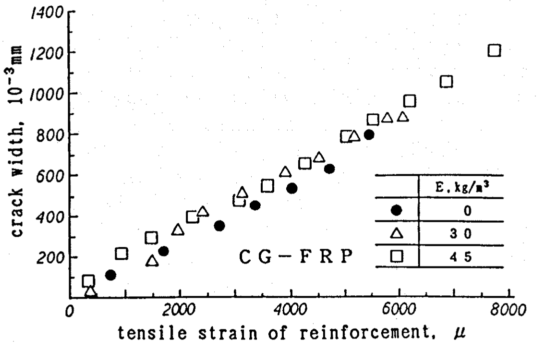

Fig. 12 Relationship between tensile strain of reinforcement and flexural crack width of CPC beam

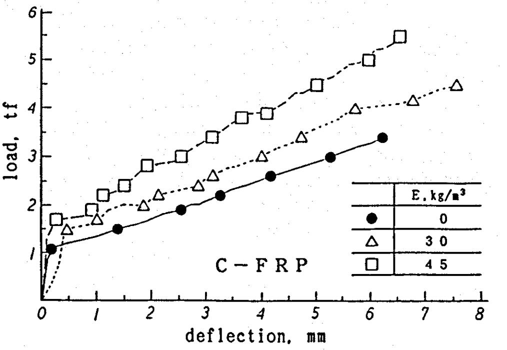

Fig. 13 Deflection of CPC beam

Table 4 Shear strength of CPC beam

reinforcement	E, kg/m³	Pcr, tf	Pu, tf	shear strength, kgf/cm²					calcu. Pu, tf
				measured value	calculated value, figure in ( ) is considered Ef *	(1)	(2)	(3)	
C	0	3.2	3.2	8.5	8.5 (4.6)	−	−	−	7.8
	30	3.9	4.3	11.5	9.6 (5.2)	9.7 (5.2)	9.8 (5.3)	9.9 (5.4)	7.8
	45	4.6	5.2	13.9	8.9 (4.8)	9.0 (4.9)	9.1 (4.9)	9.3 (5.0)	7.8
CG	0	4.0	4.0	10.7	9.1 (5.1)	−	−	−	7.8
	30	5.3	5.3	14.1	10.3 (5.8)	10.4 (5.9)	10.5 (5.9)	10.6 (6.0)	7.9
	45	5.2	6.4	17.1	9.5 (5.4)	9.6 (5.4)	9.7 (5.5)	9.9 (5.6)	7.9
G	0	3.4	3.8	10.1	7.4 (5.3)	−	−	−	6.8
	30	4.0	4.5	12.0	8.1 (5.8)	8.2 (5.8)	8.2 (5.8)	8.2 (5.8)	6.8
	45	5.5	5.5	14.7	8.0 (5.7)	8.2 (5.9)	8.5 (6.0)	8.7 (6.2)	6.8
rebar	0	−	5.1	13.6	8.1 (8.1)	−	−	−	4.1
	30	−	6.0	16.0	8.8 (8.8)	8.9 (8.9)	8.9 (8.9)	8.9 (8.9)	4.1
	45	−	6.6	17.6	8.7 (8.7)	9.4 (9.4)	9.6 (9.6)	9.6 (9.6)	4.1

* ignore axial load

(1) Md is calculated according to flexural tensile failure strength.

(2) Md is calculated according to bending moment corresponding to value of shear strength not considering axial force.

(3) Md is calculated according to bending moment corresponding to value of shear strength considering both axial force and Ef.

5.2 Effect of Improvement in Shear Strength

The measured values of diagonal cracking load and shear stress intensity at failure of beam, and the theoretical values according to the RC Specifications are given in Table 4. In the calculations, as the criterion for evaluating axial force produced in a beam through inducement of chemical prestress, Md of Mo/Md in calculation of βn in Eq.(2) was calculated according to three kinds as indicated below. Namely, (1) flexural tensile failure strength, (2) bending moment corresponding to the theoretical value of shear strength not considering axial force, and (3) bending moment corresponding to the theoretical value of shear strength reducing the cross-sectional area considering the modulus of elasticity of FRP.

With FRP beams into which chemical prestress had been induced, along with diagonal cracking load being increased, the shear strength at failure was improved through improvement in the interlocking effect of aggregates due to reduction in crack width and increase in area of concrete at the compression side sharing shear strength.

Since the flexural tensile failure strength of an FRP beam becomes large compared with an RC beam, as Md the theoretical value based on (1) does not adequately express the effect of improving shear strength. That the shear strength of an FRP beam is reduced compared with an RC beam due to increase in deflection and flexural crack width is as previously stated. Consequently, as criteria for calculating shear strength of an FRP beam into which chemical prestress has been induced, it is thought (2) and (3) are suitable. Furthermore, although it cannot be said to be sufficiently, it may be seen that the conformity of theoretical values based on (3) to measured values has improved slightly.

6. CONCLUSIONS

Concrete beams (FRP beams) were made using three varieties of FRP formed by respectively setting carbon fibers, glass fibers, and a combination of the two in vinyl ester resin in grid shape as axial direction reinforcement, and flexural strength tests and sustained loading tests were performed. Further, the effect of chemical prestress induced using expansive concrete on the mechanical behaviors of FRP beams was also experimentally examined. The following may be said within the scope of this study.

1) When grid-shaped FRP is used as reinforcement for beams of small width, flexural cracks are liable to occur from grid intersections.

2) When calculating deflections of beams, there are cases of deflections being underestimated if the effective moment of inertia indicated in the Japan Society of Civil Engineers Standard Specifications for Concrete (RC Specifications) is used.

3) In case of calculating the shear strength of an FRP beam not using shear reinforcement, if the cross-sectional area of FRP is converted as effective cross section considering modulus of elasticity in the calculation equation of the RC Specifications, a safety factor roughly the same as for an RC beam can be obtained.

4) The absolute value of curvature of an FRP beam subjected to a sustained load test is large compared with an RC beam, but the rate of change of curvature dividing the amount of increase in curvature by the curvature immediately after

loading is smaller for the FRP beam.

5) With an FRP beam, whether or not flexural cracking has developed considerably during sustained loading tests greatly affects the flexural behaviors of the beam in subsequent flexural strength tests.

6) By inducing chemical prestress, the flexural behaviors of an FRP beam such as flexural crack width and deflection, and shearing behaviors such as diagonal cracking load and shear strength can be improved. Further, the degree of reduction in strain of tensile reinforcement due to inducement of chemical prestress is greater than for an RC beam. And for shear strength, a result slightly greater than the effect of axial force given in the RC Specifications is obtained.

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