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論 文

[2160] Flexural Behavior of Composite Beam Using a U-Shaped Short-Fiber-Reinforced Concrete Form Prestressed with FRP Tendons

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1. INTRODUCTION

Fiber Reinforced Plastic (FRP) tendons have recently been developed for application to structures . FRP tendons are characterized by their high durability, high strength and light weight. However, when these materials are used in partially prestressed concrete beams, their low stiffness produces problems at higher than concrete cracking loads. Moreover, Reinforced Concrete (RC) structure construction utilizing precast concrete forms has been popularized in Japan. To reduce transport cost of elements, these forms must be light and strong. Therefore, they must have small cross sections and they must utilize light-weight high-strength concrete.

Flexural loading tests were carried out to investigate the structural performance of a U-shaped concrete beam form using discontinuous-short-Carbon-Fiber-Reinforced Concrete (CFRC) pretensioned-prestressed with Aramid-FRP (AFRP) tendons and including steel reinforcing bars. The flexural behavior of composite beams comprising this form filled with insitu concrete was also scrutinized. These tests were performed to verify: 1) the applicability of unsupported prestressed CFRC forms to the construction process, and 2) the structural superiority of composite beams using these forms.

If steel tendons were used for these forms, cover thickness would have to be increased due to their high corrosibility. This would reduce the prestressing effect and increase form weight. Furthermore, if plain concrete were used, much higher prestressing force would be necessary to realize the required performance. Use of the AFRP tendons and CFRC enable these problems to be resolved. This study assisted in development of a new type of beam element which can be applied to actual structures.

2. EXPERIMENT

2.1 SPECIMEN AND MATERIAL

Table-1 shows all the specimens tested, and the experimental parameters. The parameters are: beam type, reinforcing and prestressing type (reinforcement type), and prestressing level. Three types of reinforcement were tested. Specimens prestressed with AFRP tendons and reinforced with deformed steel bars are called 'Hybrid reinforcement type'. These specimens are designed to overcome the disadvantages of AFRP-only reinforcement type, whose low stiffness leads to beam stiffness decline after concrete cracking occurs.

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Fig.-1 shows the elevation and section of the specimens, and Table-2 indicates the specimen section design. The specimens were approximate 1/2.5 down-scale models of a 7m-span beam, designed for a building with three stories and a 7x5.5m-span grid.

Table-3 shows the materials for the concrete used in this study. Table-4 shows the mix proportions of the concretes and their mechanical properties. The mechanical properties of the prestressing and reinforcing materials are indicated in Table-5.

Table-1 Experimental Parameters

Specimen type	*1) Reinforce-ment type	Prestressing Level: Full Prestressing	Partial Prestressing	No Prestressing
Precast Form	*2)Hybrid	-	HB-PPS-F	-
Composite	AFRP-only	-	FRP-PPS-C	-
Beam	*2)Hybrid	HB-FPS-C	HB-PPS-C	HB-NPS-C
	Steel-only	-	S-PPS-C	-
RC Beam	*2)Hybrid	-	-	HB-NPS-RC

*1) Type of combination for prestressing and reinforcing

*2)Combination of AFRP tendons and steel reinforcing bars

Table-3 Concrete Materials

	Cement	Aggregate: Fine	Aggregate: Coarse	Fiber Type
CFRC	Low Shrinkage Cement	Silica Powder		Pitch Carbon Fiber *Lf=3mm ϕf=7 μ
Plane Concrete	Ordinary Portland Cement	Pit Sand	Crashed Stone	

*Lf: Length of Fiber, ϕf: Diameter of Fiber

Table-2 Specimen Section Design

Specimen	Specimen type	Prestress-ing Force (KN)	Concrete Type: Form	Concrete Type: Insitu Concrete	Reinforcing: Reinforcing Material	Reinforcing: Amount of Material (cm²)	Prestressing: Prestressing Material	Prestressing: Amount of Material (cm²)
HB-PPS-F	Precast Form	25	*1) CFRC	-	Deformed Steel Bar 2-D10	1.42	*2)AFRP 1-400KF	0.94
HB-NPS-RC	Reinforced Concrete	0	-	Plain Concrete		*3) [Pt=0.42%]		*4) [Pp=0.28%]
HB-PPS-C	Composite	25	*1) CFRC					
HB-FPS-C		50						
HB-NPS-C		0						
FRP-PPS-C		25			*2)AFRP 2-200KF	0.98 *3) [Pt=0.30%]	*2)AFRP 1-200KF	0.49 *4) [Pp=0.15%]
S-PPS-C					Deformed Steel Bar 2-D10	1.42 *3) [Pt=0.42%]	Prestressing Steel Bar 1-D11	0.90 *4) [Pp=0.27%]

*1) Carbon Fiber Reinforced Concrete *2) Reference to Table-5

*3) Pt: Reinforcing ratio, Pt=At/bd, At:Area of reinforcing bars, b:Width of beam section, d:Depth of beam section

*4) Pp:Prestressing Ratio, Pp=Ap/bd, Ap:Area of tendons, b:Width of beam section, d:Depth of beam section

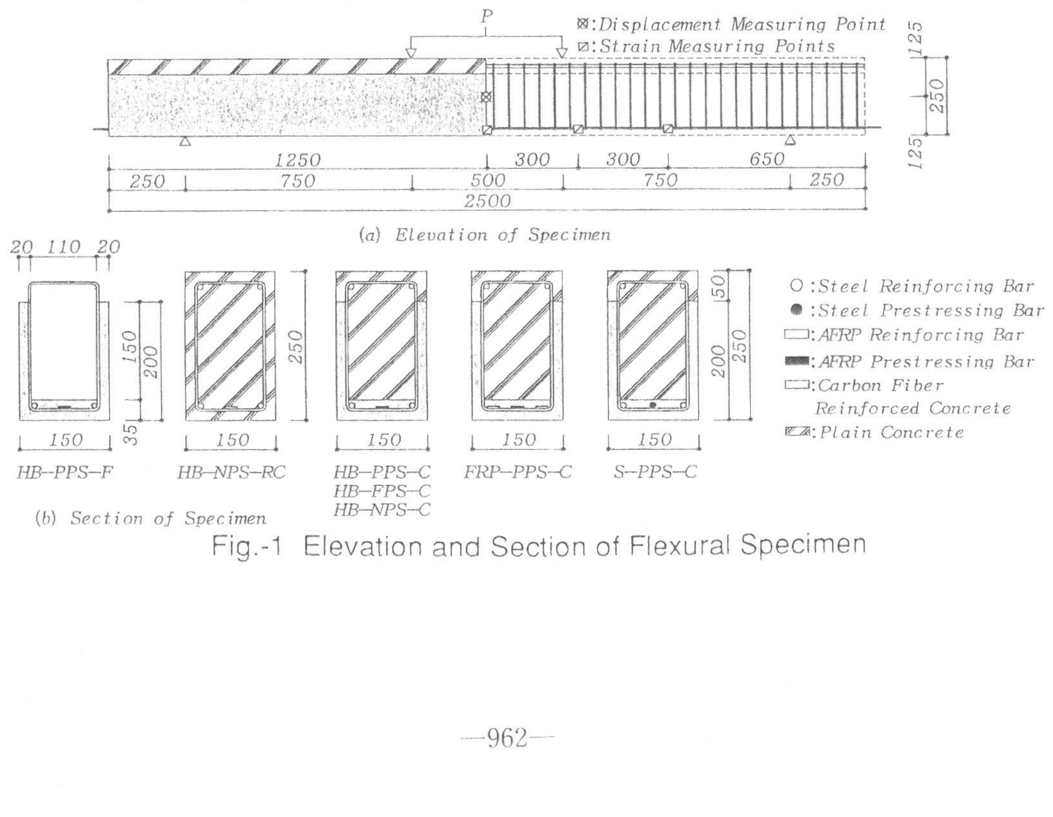


Fig.-1 Elevation and Section of Flexural Specimen

Table-4 Concrete Mix Designs and Mechanical Properties

		CFRC	Plane Concrete
Mix Proportion	Cement (kg)	1000	302
	Water (kg)	450	187
	Sand (kg)	397	926
	Coarse aggregate (kg)	-	860
	Fiber (kg)	32.6	-
	W/C Ratio (%)	47.0	62.0
	Fiber Volume(%)	2.0	-
Properties at Prestressing	Compressive Strength (MPa)	21.7	-
	Young's Modulus (GPa)	9.9	-
Properties at Flexural Exp.	Compressive Strength (MPa)	35.5	32.2
	Young's Modulus (GPa)	12.2	22.1
	*Bending Strength (MPa)	15.0	-

**Test result for 4x4x16cm specimen*

Table-5 Mechanical Properties of Reinforcement materials

Properties	Tendon			Reinforcing Bar
	Deformed Steel Tendon	AFRP 400KF	AFRP 200KF	Deformed Steel Bar
Section Shape	D11	Rectangular 5x20mm	Rectangular 2.5x20mm	D10
Section Area (mm^2)	90.0	94.0	49.0	71.0
Yield Strength (MPa)	1373	-	-	393
Rapture Strength (MPa)	1480	1049	1176	572
Young's Modulus (GPa)	198	58.8	58.8	194

2.2 FLEXURAL LOADING TEST

Fig.-1 shows the loading method for the specimens in the flexural loading test. The flexural specimens are loaded by means of a four-point loading method as shown in this figure. The test was performed with one way amplitude cyclic loading. Peaks at the cycles were at: 1/2 of the concrete cracking load, concrete cracking load, yield load of the tension reinforcing bars, and specimen deflection angles of 1/100 and 1/50. Values measured were flexural load, specimen displacement, and specimen material strain. The flexural load was measured with a load transducer built into the loading apparatus, and the displacement was measured with a displacement transducer at the specimen center point as indicated in Fig.-1. The strain in the reinforcing bars and tendons was measured with strain gauges attached to theeir surfaces at the points shown in the figure. The profiles and widths of cracks appearing on the specimen surface were also measured.

3. TEST RESULT

Table-6 shows the tension force in the tendons during and after the prestressing process. Tension in the tendon was estimated from the product of measured tendon strain and Young's modulus for the tendon. An example of tension force change in AFRP and steel tendons, is indicated at three time points. The prestressing force reduction after 1 month was about 15%.

Load- displacement profiles obtained from the tests are presented in Fig.-2. The design load in the construction process is indicated in the HB-PPS-F diagram in this figure. The cracking load for this specimen was higher than the design load. In the AFRP-only composite specimen (FRP-PPS-C), displacement remaining after unloading was significantly reduced. However, in the Hybrid composite specimen (HB-PPS-C), remaining displacement was not reduced after reinforcing bar yield. This corresponds to the results for specimens that were prestressed over their full cross sectional areas, as described in TANIGAKI et al[1]. The specimen failure mode is indicated in Fig.-2. Three types of failure mode occurred in the specimens. These are compressive failure of concrete, bonding failure of an AFRP tendon, and combined failure of these two. Bonding failure of AFRP tendons was dominant as the failure mode of specimens using these tendons. In this bonding failure, an AFRP tendon slipped because it lost its bond with the concrete. The load resistance of the specimens reduced immediately by the amount of the tendon's resistance, but the specimens kept some load capacity after failure due to the contribution of reinforcing bars as shown in the FRP-PPS-C specimen result in Fig.-2. The HB-FPS-C specimen showed a much smaller maximum displacement than the others. This specimen received an impact load during the prestressing process due to a mechanical accident in a hydraulic jack device, and was

Table-6 Prestressing Effective Ratio

	Specimen	HB-PPS-F	S-PPS-C
	Tendon Type	AFRP	Deformed Steel bar
Tension in Tendon	Design Tension (KN)	25	25
	(a)Before Prestressing (KN)	29.6	28.7
	(b)Just after Prestressing (KN)	28.4	25.3
	(c)1-month after Prestressing (KN)	25.4	-
Effective Ratio	Reduction Ratio Just after Prestressing (b)/(a)	0.96	0.88
	Effective Prestressing Ratio (c)/(a)	0.86	-

Table-7 Outline of Flexural Test Results

Beam Specimen	Experimental Results					Calculated Results	*3) Failure Mode
	Stiffness (MN · m²)						
	*1) Elastic	*1) Post Cracking	Cracking Moment (KN · m)	Reinforcing Bar Yielding Moment (KN · m)	Ultimate Moment (KN · m)	*2) Ultimate Moment (KN · m)	
HB-PPS-F	0.65	0.37	5.6	-	12.2	-	C
HB-NPS-RC	4.39	0.9	4.7	14.9	28.2	30.4	C and B
HB-PPS-C	4.34	1.17	12.1	24.3	37.8	30.4	
HB-FPS-C	4.13	1.15	15.9	-	(29.9)	30.4	B
HB-NPS-C	4.26	1.12	8.4	17.8	35.4	30.4	C
FRP-PPS-C	4.05	0.34	12.1	-	26.7	34.0	B
S-PPS-C	4.76	1.42	12.1	31.8	43.8	35.3	C

*1) Calculated from experimental data, neglecting shear displacement

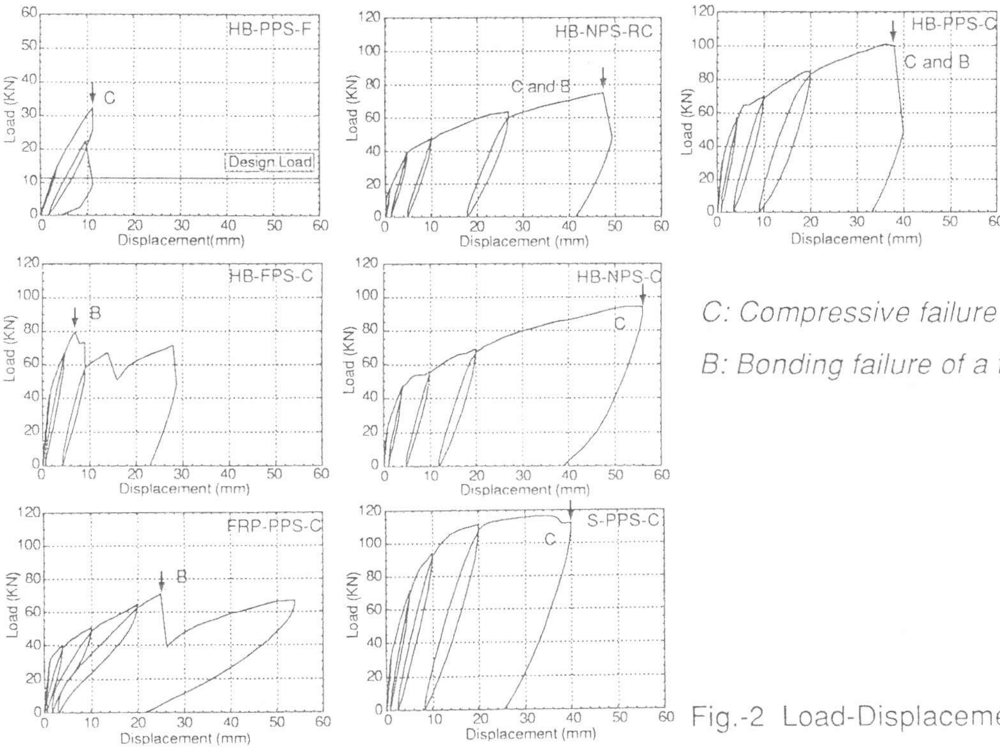
*2) Calculated Ultimate Moment: $Mcu=7/8 \cdot at \cdot \sigma y \cdot d + ap \cdot \sigma p(dp-1/8 \cdot d)$

at: Total section area of tension reinforcing bars, σy: Yield strength of tension reinforcing bars

d: Effective height of tension reinforcing bars, ap: Total section area of tendons

σp: Yield strength of tendons, dp: Effective height of Tendons

*3) C: Compressive failure of concrete, B: Bonding failure of an AFRP tendon



C: Compressive failure of concrete

B: Bonding failure of a tendon

Fig.-2 Load-Displacement Profiles

damaged in its anchorage area. This seems to have caused its lower ductility and low load capacity.

Fig.-3 shows an example of the specimen cracking state after loading. The crack pattern on the CFRC in the HB-NPS-C specimen was different from that on the plain concrete in the HB-NPS-RC specimen. Cracks on the plain concrete in the RC specimentended to go through the side and extend far beyond the pure bending zone to the ends. However, the cracking zone on the CFRC was smaller than on the plain concrete, and fewer cracks reached the top of the side than that on the plain concrete. Moreover, these cracks propagated linearly, whereas the average crack interval in the pure bending zone was almost the same in these two specimens.

The results of this experiment are summarized in Table-7. Here, Calculated Ultimate Moment is estimated by assuming that specimen failure occurs due to reinforcement rupture[2], as shown in the note of this table. For the Hybrid specimens, AFRP rupture strength was used instead of yield strength in this equation.

4. DISCUSSION

Fig.-4 reveals the effect of the Hybrid reinforcement on structural performance. Three specimens with different reinforcement types are shown in this figure. Stiffness after cracking varied remarkably among these specimens, although their elastic stiffnesses were similar. The stiffness of AFRP-only specimen reduced by over 9/10 after cracking. However, that of the Hybrid specimen did not significantly decline until the steel reinforcing bar yield. In the flexural test, an AFRP tendon in the AFRP-only specimen showed bonding failure before the AFRP reinforcing bars reached their full load capacities. Thus, its load resistance was lower than the calculated value, as shown in Table-7. However, because the AFRP tendon in the Hybrid specimen showed bonding failure after steel reinforcing bar yield, this specimen resisted a much higher load than the AFRP-only specimen. Consequently, it can be said that Hybrid reinforcement is quite effective in improving load resistance.

Fig.-5 well explains the difference between the failure modes of the Hybrid specimen and the Steel-only one. The ratio of tendon strain to reinforcing-bar strain was defined as the strain matching ratio on Y-axis in this figure. Variation in strain matching ratio in a specimen is plotted against flexural load in this figure. The strain matching ratio outside a loading point in the Hybrid specimen noticeably increased near the maximum load of 100KN. However, this ratio in the Steel-only specimen remained at almost 1. This implies that the bond-loss of a AFRP tendon in the Hybrid specimen extended from the pure bending zone to the end zone as the load approached the capacity of this specimen. This phenomenon seemed to be caused by a lower bonding performance of AFRP tendons compared to that of deformed steel bars.

Fig.-6 represents the effect of prestressing on a specimen's structural performance. The stronger the prestressing force in the specimens, the higher both concrete cracking load and reinforcing bar yielding load. These effects are similar to those of ordinary prestressing in a full beam section.

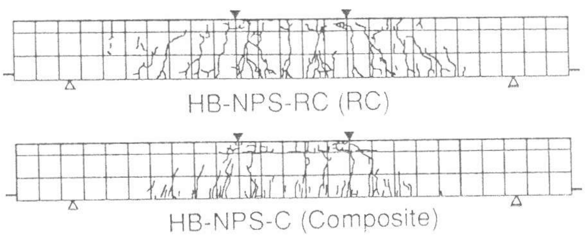


Fig.-3 Specimen Cracking after Loading

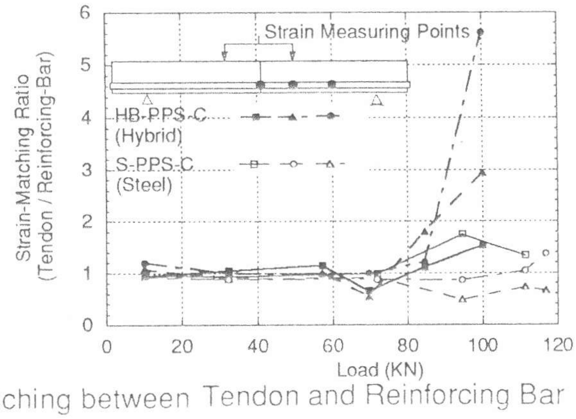


Fig.-5 Strain Matching between Tendon and Reinforcing Bar

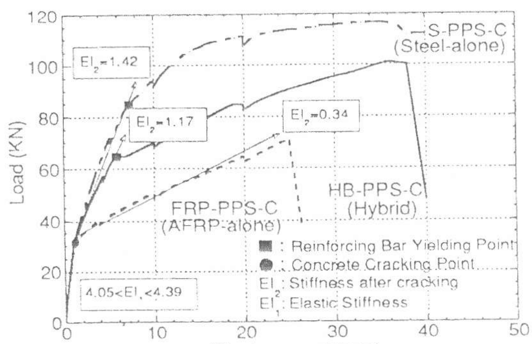


Fig.-4 Load-Displacement Envelope
(Effect of Hybrid Reinforcement)

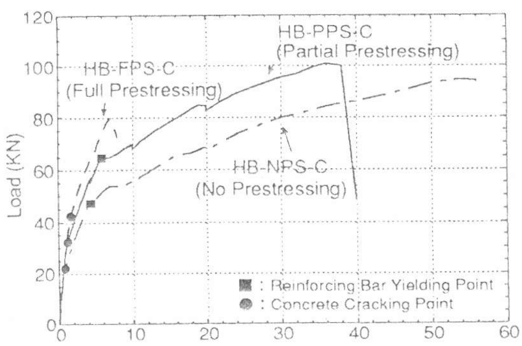


Fig.-6 Load-Displacement Envelope
(Effect of Prestressing)

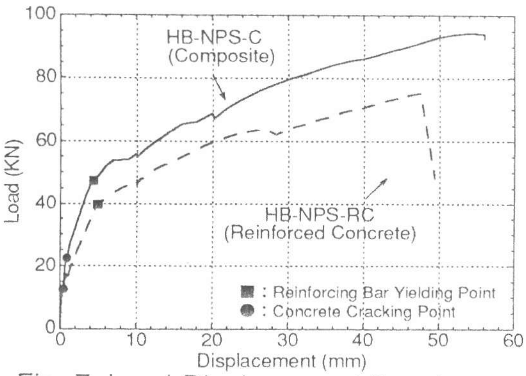


Fig.-7 Load-Displacement Envelope (Effect of CFRC Form)

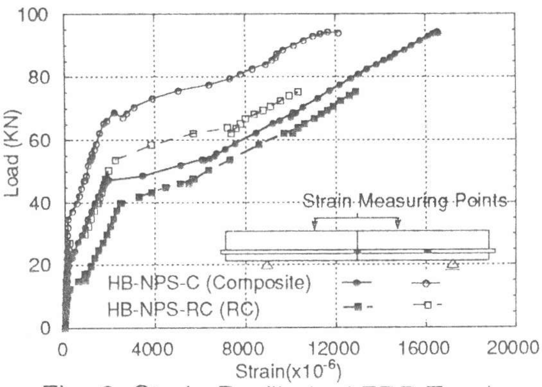


Fig.-8 Strain Profile in AFRP Tendon

Fig.-7 also shows the performance of the composite beam with the CFRC form. The concrete cracking resistance load of the composite specimen was 80% higher than that of the RC beam. Thus, it can be said that the use of CFRC forms can considerably improve the cracking resistance performance of beams, as shown in KAGE et al[3]. Moreover, this diagram shows that the use of CFRC forms can increase beam stiffness after concrete cracking, and after reinforcing bar yield. These effects are respectively represented by about a 20% increase in value, according to Table-7. Fig.-7 also shows that the CFRC form can considerably increase ultimate resistance load of a specimen (by 25% in Table-7).

Fig.-8 clarifies these CFRC effects on structural performance. This figure shows the relationship between flexural load and tendon strain. Tendon strain in the composite specimen was clearly lower than that in the RC one. This seemed to be caused by the contribution of the CFRC to tension load resistance. This contribution produced a higher structural performance in the composite specimen than in the RC one.

5. CONCLUSION

This study investigated the flexural behavior of pretensioned-prestressed U-shaped CFRC forms and composite beams using these forms. The following conclusions can be made: 1) these forms can be applied unsupported to actual construction processes, 2) Hybrid reinforcement combining AFRP tendons and steel reinforcing bars produces a beam that is stronger than an AFRP-only reinforcement beam, 3) the effect on a composite-beam's structural behavior of prestressing in a U-shaped form is similar to that of ordinary prestressing in a full beam section, and 4) with the use of CFRC, these forms can produce composite beams with excellent.

REFERENCE

1. TANIGAKI, M. and et al. "Experimental Study on Flexural Behaviors of Partially Prestressed Concrete Beams Reinforced with Braided Aramid Fibre Rods", J. of Structural Construction Engineering, AIJ, No. 420, Feb., 1991, pp 31-41 (in Japanese).
2. Architectural Institute of Japan, "Recommendation for the Design and Construction of Partially Prestressed Concrete (Class III of Prestressed Concrete) Structures", 1986, pp 63-68 (in Japanese).
3. KAGE, T. and et al. "Effect of Clad Reinforcements of Carbon Fiber Reinforced Concrete (CFRC) in Reinforced Concrete Beams (Part I)", J. of Structural Construction Engineering, AIJ, No. 419, Jan., 1991, pp 47-56 (in Japanese).