**Zeitschrift:** IABSE reports = Rapports AIPC = IVBH Berichte

**Band:** 60 (1990)

**Artikel:** Application of carbon fiber reinforced cables to concrete structures

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**DOI:** https://doi.org/10.5169/seals-46555

# Application of Carbon Fiber Reinforced Cables to Concrete Structures

## Application des câbles renforcés par fibres de carbone aux structures en béton

## Verwendung von kohlenstoffaserverstärkten Drahtseilen in Betonbauwerken

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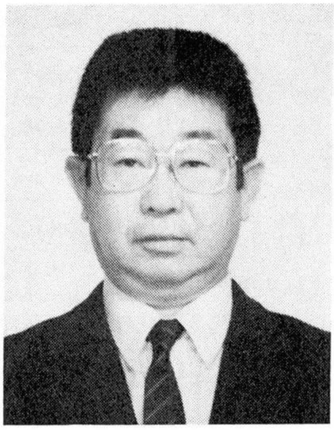

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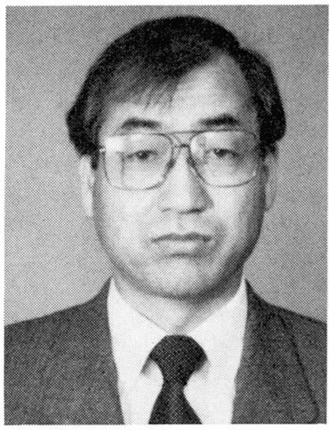

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## SUMMARY
This paper describes the fundamental mechanical properties and the design method for concrete members using carbon fiber reinforced cables as the main reinforcement in place of steel tendons and reinforcing bars.

## RÉSUMÉ
Dans cet article sont décrites les caractéristiques mécaniques fondamentales et les techniques de conception et de calcul des éléments en béton dans lesquels les câbles renforcés par fibres de carbone sont utilisés en tant que matériaux principaux de renforcement à la place des câbles de précontrainte ou des aciers pour béton armé.

## ZUSAMMENFASSUNG
In der vorliegenden Abhandlung werden die grundsätzlichen dynamischen Eigenschaften und Konstruktionsmethoden von Betonbauteilen mit kohlenstoffaserverstärkten Drahtseilen untersucht, die als Spannglieder oder anstelle von Stahlbewehrungen eingesetzt werden.

## 1.INTRODUCTION

Recently, deterioration of durability of concrete structures due to corrosion of steel has become a serious social problem. Furthermore, steel may not be used as reinforcements for the structures used for linear motor trains, which are being planned in Japan and run by strong magnetic power, because steel can be easily magnetized. Only traditional steel and concrete may not satisfy sufficiently the requirements for future structures. New materials which are stronger, lighter and have better characteristics against corrosion than conventional steel are strongly required. Carbon fiber composite cable, called CFCC in this paper, developed recently is one of new structural materials which can satisfy the above requirements. This paper describes the applicability of CFCC to actual concrete structures as main reinforcements in place of steel tendons and reinforcing bars.

## 2.CHARACTERISTICS OF CFCC

Fiber reinforced composite material, such as glass fiber reinforced plastics(GFRP), aramid fiber reinforced plastics(AFRP) and carbon fiber reinforced plastics(CFRP), have been developed recently as structural reinforcements. Table 1 shows their general fundamental characteristics. Comparing each characteristics of them, it is clear that CFRP is the most appropriate material among them as reinforcements for concrete structures. Carbon fiber composite cable(CFCC), shown in Fig.1, made by twisting high strength continuous carbon fibers impregnated with resin has some excellent properties such as 1)high tensile strength and high bond strength in concrete, 2)light weight, 3)non-corrosion, 4)non-magnetization, 5)very small relaxation loss comparing with steel tendons and 6)flexibility like cables. Figure 2 shows a typical stress-strain relation of CFCC and a steel tendon under uniaxial tensile load, and Table 2 indicates the mechanical properties of them. Note that CFCC finally fails in a brittle manner without showing a yield point and a yield plateau like steel as shown in Fig.2.

| Characteristic | Steel | CFRP | AFRP | GFRP |
|---|---|---|---|---|
| Tensile Strength | ○ | ○ | ○ | △ |
| Elongation | ○ | △ | △ | △ |
| Elastic Modulus | ○ | △ | × | × |
| Relaxation and Creep | ○ | ○ | × | △ |
| Fatigue Strength | ○ | ○ | ○ | ○ |
| Alkali Proof | ○ | ○ | △ | × |
| Corrosion Resistance | × | ○ | ○ | ○ |
| Specific Gravity | × | ○ | ○ | ○ |
| Magnetization | × | ○ | ○ | ○ |

○ ; Excellent, △ ; Poor, × ; Bad

Table 1 General characteristics of FRP

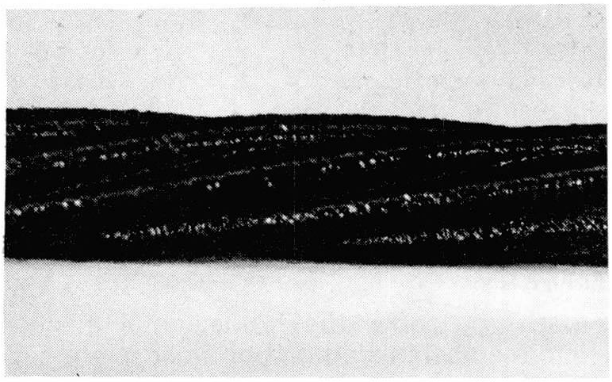


Fig.1 Carbon fiber composite cable

## 3.APPLICATION OF CFCC TO PC MEMBERS

In order to use the high strength of CFCC effectively, the applicability of CFCC to PC members was investigated. Figure 3 shows the details of the test beams. All beams were cured in wet condition for one month after placing of concrete, and then prestress was

| Mechanical Properties | Steel Tendon | CFCC |
|---|---|---|
| Tensile Strength (MPa) | 1460 | 1803 |
| Elongation (%) | >3.0 | 1.5 |
| Young's Modulus (GPa) | 201 | 123 |
| Bond Strength (MPa) | —— | 4.2 |

Table 2 Mechanical properties

introduced. An anchorage device consists of nuts and steel tubes. The loosened strands, the length of which is 20 cm from each end of CFCC, are fixed with resin in the steel tube. This anchorage device was used also for uniaxial tensile tests and bond tests. No damage was observed even at the failure of CFCC in the tensile tests. The magnitude of the design prestress was 40 to 60% of the tensile strength. The prestress was introduced by controlling an oil jack with a load cell installed on an anchorage plate. To compare the behaviour of PC members using CFCC with that using steel tendons, the test beams using ordinary steel tendons were made in the same manner as those using CFCC. Table 3 indicates the experimental variables. All beams were tested up to the failure under monotonic loading. The average loss of the introduced prestress just before the tests was about 5% in all beams.

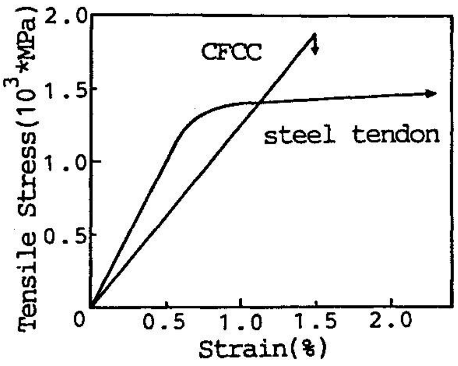



Fig.2 Stress-strain curve

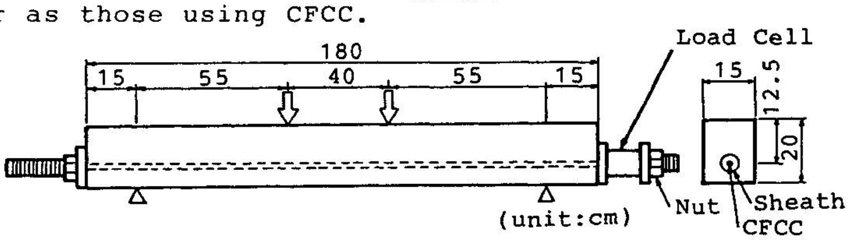



Fig.3 Details of test beams

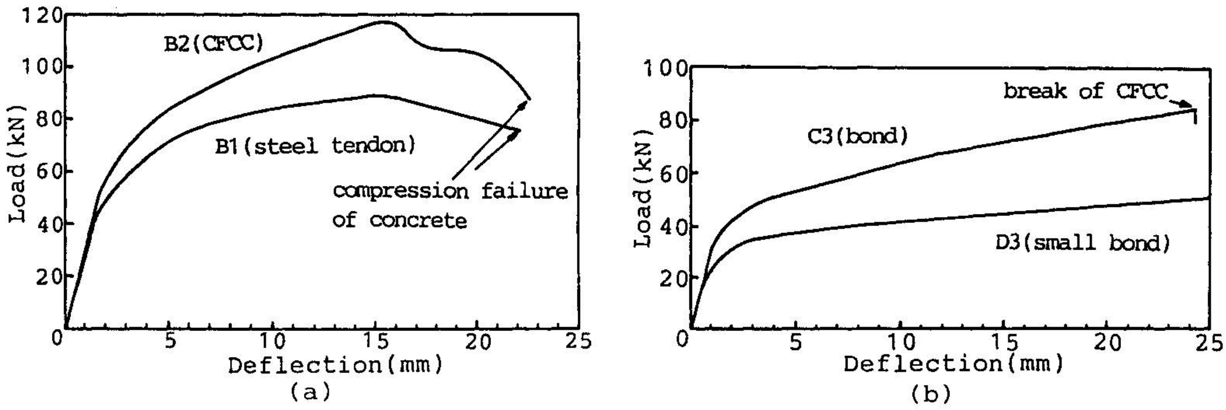
Figure 4 shows the load-deflection curves of Beams A1, A2, B1, B2, C3 and D3. Comparing Beam B1(steel tendon) with Beam B2(CFCC), both beams showed almost the same stiffness and behaviour before the initial cracking. The difference of the maximum strength between both beams may depend on the magnitude of the introduced prestress and the amount of the CFCC and the steel tendons. After the maximum strengths in both beams, the loads decreased gradually. Beam B1 reached the ultimate state with the failure of concrete after yielding of the steel tendon while Beam B2 failed finally due to crushing of the concrete in the compression zone. In Beams C3 and D3, they showed ductile behaviour until the failures.

| Beam No. | Material (Number X Diameter) | Bond Type | Introduced Pre-stressing Stress (MPa)(*) | Concrete Strength (MPa) |
|---|---|---|---|---|
| A 1 | CFCC ($\phi$10.5) | A | 694 (0.42) | 53.7 |
| A 2 | CFCC ($\phi$10.5) | C | 695 (0.43) | 53.7 |
| B 1 | steel tendon ($\phi$13) | A | 1012 (0.74) | 51.3 |
| B 2 | CFCC (2X$\phi$12.5) | A | 2X878 (0.44) | 51.3 |
| C 1 | steel tendon ($\phi$13) | A | 536 (0.39) | 53.7 |
| C 2 | steel tendon ($\phi$13) | A | 573 (0.41) | 51.3 |
| C 3 | CFCC ($\phi$12.5) | A | 879 (0.44) | 53.7 |
| D 1 | CFCC ($\phi$12.5) | B | 1329 (0.67) | 45.4 |
| D 2 | CFCC ($\phi$12.5) | A | 1224 (0.61) | 45.4 |
| D 3 | CFCC ($\phi$12.5) | B | 954 (0.48) | 45.4 |

A;Perfect bond. B;Vinyl tape was wrapped around CFCC to reduce bond strength. C;Unbond method.
* ;(Introduced Prestress/Tensile Strength)

Table 3 Experimental variables

The CFCC of Beam C3 finally broke due to its high bond strength and brittleness, and the load decreased suddenly after breaking of CFCC. The beam seemed to be failing showing some warning until the collapse even if CFCC finally broke. However, such a failure mode should be avoided as far as possible in actual structures. On the other hand, Beam D3, the bond strength of which was reduced by wrapping a vinyl-tape around CFCC, showed ductile behaviour up to the failure without breaking of CFCC. As a matter of fact, Beam A2, which is an unbonded system, showed a ductile load-deflection behaviour though its maximum strength was smaller than that of Beam A1, which is a bonded system and failed due to breaking of CFCC. It is clarified that CFCC can be used as suitable tendons for




PC members in place of ordinary steel tendons if the magnitude of introduced prestress and the bond strength are appropriately designed.

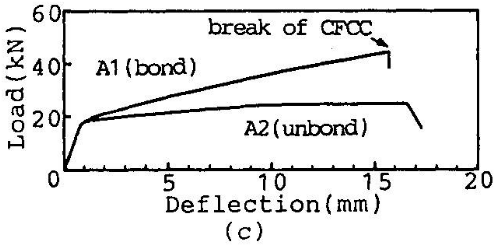



Fig.4 Load-deflection curves

4.APPLICATION OF CFCC TO R/C MEMBERS

This chapter describes the applicability of CFCC to concrete members as non-prestressed main reinforcements in place of reinforcing steel bars. Flexural behaviour of concrete members using CFCC was mainly studied. The dimensions of the test specimens used for the tests were the same as those of the previous ones. The specimens were designed changing the amount of CFCC and compressive strength of concrete in order that three final failure modes may occur, namely, 1)breaking of CFCC, 2)crushing of concrete in the compression zone and 3)the balanced failure. The properties of the test specimens are shown in Table 4. Load was applied monotonically to each specimen up to the failure.

| Beam No. | CFCC | Concrete Strength (MPa) | Cracking Load (KN) | | Ultimate Load (KN) | | Failure Mode |
|---|---|---|---|---|---|---|---|
| | | | Cal. | Exp. | Cal. | Exp. | |
| F 1 | 2Xϕ7.5 | 29.3 | 10.9 | 8.8 | 60.5 | 60.5 | ● |
| F 2 | 2Xϕ12.5 | 33.8 | 12.3 | 10.0 | 94.0 | 91.8 | ○ |
| F 3 | 4Xϕ12.5 | 32.2 | 12.0 | 11.8 | 114.8 | 122.2 | ○ |
| F 4 | 2Xϕ7.5 | 65.7 | 19.4 | 13.2 | 63.3 | 61.4 | ● |
| F 5 | 4Xϕ12.5 | 64.3 | 19.6 | 19.3 | 181.9 | 166.3 | ○ |
| S 6 | 2XD16 | 60.4 | 19.4 | 14.4 | 70.3 | 74.2 | * |

S 6 ; Usual deformed bars were used.
○ ; Concrete in compression zone failed finally.
● ; CFCC was finally broken.
* ; Flexural tensile failure.

Table 4 Experimental variables and test results

Figure 5 shows the load-deflection curves of Specimens F4(CFCC), F5(CFCC) and S6(ordinary reinforcing bar). The initial cracks were produced at relatively small loading stages in all specimens, and after initial cracking, the loads of F4 and F5 increased linearly. Since the stiffness of F4 and F5 after initial cracking, which depend on the

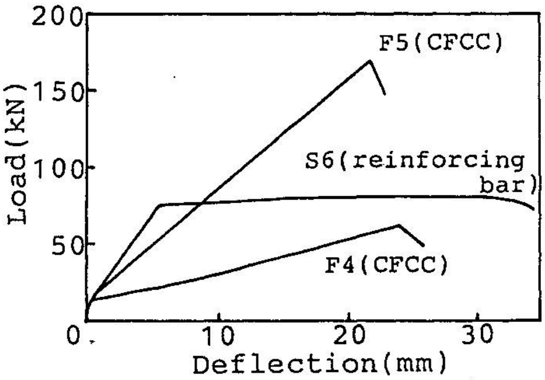



Fig.5 Load-deflection curves

amount of CFCC, became smaller than that of S6 due to the low Young's modulus of CFCC, the deflections of F4 and F5 at the maximum strength were clearly larger than that of S6. The ultimate failure mode was due to either breaking of CFCC or crushing of concrete as expected in the design of the specimens, so that the loads of F4 and F5 at the ultimate state decreased suddenly without showing any warning of approaching the beam failure. Figure 6 shows the moment-curvature relations obtained from the tests and analysis. The curvature was obtained from two displacement transducers installed at the compression and tension sides of the beam. The theoretical moment-curvature relation was obtained from the ordinary flexural theory assuming the stress-strain curve of CFCC and concrete. The calculated values agreed well with the experimental ones. The loads at the initial cracking and the ultimate state obtained from the tests and analysis are shown in Table 5. These results indicate that the usual flexural theory used for reinforced concrete also can be applied for concrete members reinforced with CFCC.

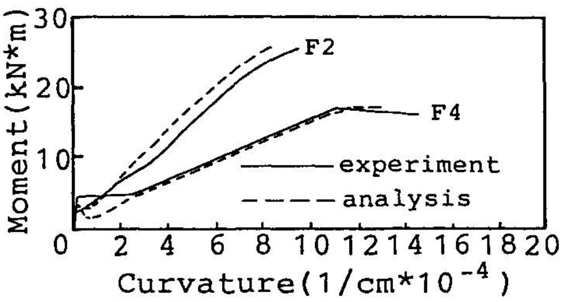


Fig.6 Moment-curvature relation

5. PROPOSAL OF DESIGN CONCEPT FOR CONCRETE MEMBERS USING CFCC

Though CFCC has some excellent properties, it has also some mechanical defects such as a low Young's modulus and a small elongation at failure comparing with steel. However, as described above, it was clarified that CFCC can be used for concrete members if design factors are properly selected. Applying CFCC to actual concrete structures as main reinforcements in place of reinforcing bars or steel tendons, the main problem is how the structure should be designed reasonably as well as safely. When concrete structures are designed, it is well known that the limit state design method, based on an ultimate state, a serviceability state and a fatigue state of a structure, is the most reasonable one. This chapter describes one example of flexural design concepts for concrete members using CFCC based on the ultimate limit state. The ultimate flexural failure mode of the concrete members using CFCC is classified into 1)breaking of CFCC and 2)crushing of concrete. It was proved that if CFCC breaks finally, the whole member will fail suddenly. On the other hand, in the case of a compression failure of concrete, the load also may decrease suddenly. However, the concrete in a compression zone can be strengthened by arranging CFCC as compression reinforcements and confining the concrete with ties to prevent the member from failing suddenly. Furthermore, controlling the bond condition of CFCC by wrapping with a tape is also a appropriate method to avoid the sudden failure. Consequently, the following assumptions were made for the flexural design concept:

1)the concrete in the compression zone fails before breaking of CFCC at the ultimate state,
2)the high strength of CFCC is used effectively at a serviceability state as well as an ultimate state without breaking.

Figure 7 shows the relation between Mu/(b*d$^2$*fc') and As*fsd/(b*d*fc') changing the ratio of introduced prestress to the specified tensile strength of CFCC from 0 to 0.8, where Mu=ultimate resisting moment, b, d=width and effective depth of a cross section respectively, fc'=compressive strength of concrete, As=area of CFCC and fsd=specified tensile strength of CFCC. In addition to the above relation, Fig. 7 also shows the relation between As*fsd/(b*d*fc') described above and the ratio of the stress of CFCC at Mu to the specified tensile strength of CFCC under the same variables as the previous ones. The specified

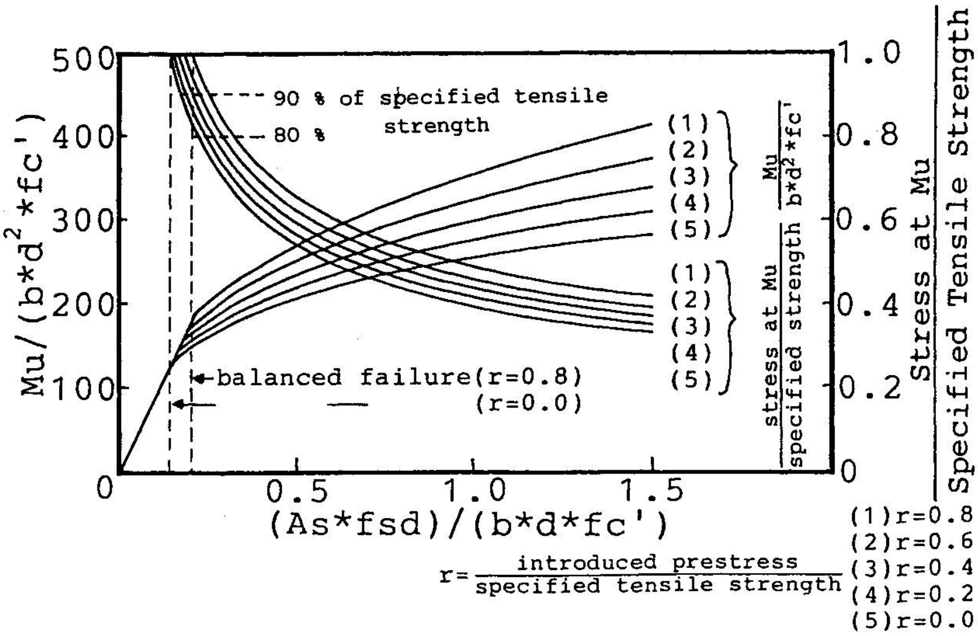



Fig.7 Flexural ultimate state of rectangular beam reinforced with CFCC

tensile strength of CFCC was defined as follows; $fsd=\overline{fs}-3*\sigma$, where $\overline{fs}$=average tensile strength of CFCC and $\sigma$=standard deviation obtained from a number of tensile test results.

Based on the first assumption, the value of As*fsd/(b*d*fc') must be in the right part of the balanced failure line drawn with broken lines in Fig.7 because a compression failure of concrete must occur before breaking of CFCC at the ultimate state. Furthermore, supposing that the available stress limit of CFCC at Mu is between 80 and 90 % of the specified tensile strength of CFCC according to the second assumption, the range of (As*fsd/b*d*fc') can be determined depending on the magnitude of the introduced prestress. The concrete member reinforced with CFCC can be designed efficiently as well as safely in accordance with this method. The proposed design concept is only one example based on the ultimate limit state. Moreover, the other design concepts on serviceability and fatigue should be also investigated in the future.

## 6. CONCLUSIONS

Carbon fiber composite cable(CFCC), which has some excellent properties such as high tensile strength, light weight, non-corrosion, non-magnetization, and flexibility like cables, can be used for concrete structures as main reinforcements in place of ordinary steel tendons and bars. In order to use CFCC efficiently for concrete members, the flexural design concept was proposed newly based on the ultimate limit state.

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