STRENGTHENING EFFECTS OF CONCRETE FLEXURAL MEMBERS RETROFITTED WITH HYBRID FRP COMPOSITES

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Abstract

In this paper, a great emphasis is placed on developing an innovative strengthening method with hybrid fiber reinforced plastics (FRP) sheets consisting of different types of fibers. To investigate the mechanical behavior of hybrid fiber sheets, uniaxial tension test is conducted to provide basic knowledge. Then plain concrete and reinforced concrete beams strengthened with hybrid fiber sheets are tested to investigate the strengthening effect and structural behavior. In contrast with the strengthening effects with single type of continuous fiber sheets, it is found that significant enhancements can be achieved in stiffness, load-carrying capacity and ductility of the structures strengthened with hybrid fiber sheets.

Introduction

Today, a lot of in-service civil structures are either structurally deficient or functionally obsolete due to the reasons such as environmental deterioration, increase in design load, misdesign or original construction faults, earthquake or external damage and changes in use. To ensure satisfactory and safe performance, they are in great need of repair and strengthening, which is a major problem confronting the current infrastructure industy. To meet this demand, externally bonding fiber-reinforced plastics (FRP) to the tension surface of the member has been proven to be an effective strengthening method and has seen their wide-spread applications in the past two decades. However, unlike the cold worked steel, FRP composites stay elastic until failure and fail in a noticeably brittle way. Correspondingly, FRP-strengthened concrete structures can fail momentarily without any foreboding due to the FRP rupture or debonding of FRP sheets. Moreover, the strengthening effect of FRP cannot be fully utilized before final failure and the gains in stiffness and yield load are also limited. To improve the performance of the strengthened structures and effectively and efficiently utilize the strengthening effect of FRP, one idea to incorporate the ductility and the stiffness is to use a hybrid composite which consists of different types of fiber sheets such as glass, aramid, vinylon, and carbon fiber composites with different strengths and stiffnesses, which fail at different strains during loading, thereby allowing a gradual failure of the composites [1-3].

The objective of this study is to investigate the strengthening effects of hybrid fiber sheets consisting of those with high strength and high modulus and the corresponding structural performance. First, possible benefits and a rough knowledge about strengthening effect of hybrid fiber sheets are presented. Then tension tests were carried out on fiber sheets consisting of various combinations of high strength and high modulus to provide basic knowledge for further application in flexural strengthening. Finally, bending tests were conducted on plain concrete and RC beams strengthened with various combinations of fiber sheets to investigate the strengthening effect and structural performance. It is found that through the appropriate hybrid of different kinds of fiber sheets significant enhancements can be achieved in stiffness, load-carrying capacity and ductility of the structures strengthened with hybrid fiber sheets.

Outline of Hybrid FRP Strengthening Method

Hybrid fiber composites, consisting of different types of fiber sheets with high strength, high modulus and high strain, can make full use of every material property to demonstrate a superior mechanical property to those of composites made with any one single type of the fiber sheets. The hybrid effects can be observed as an enhancement of stiffness, strength and elongation properties, even for the same reinforcement amount, according to the rule of mixture behavior. In view of this, hybrid fiber sheets are expected to improve the structural performance such as stiffness, load-carrying capacity and durability.

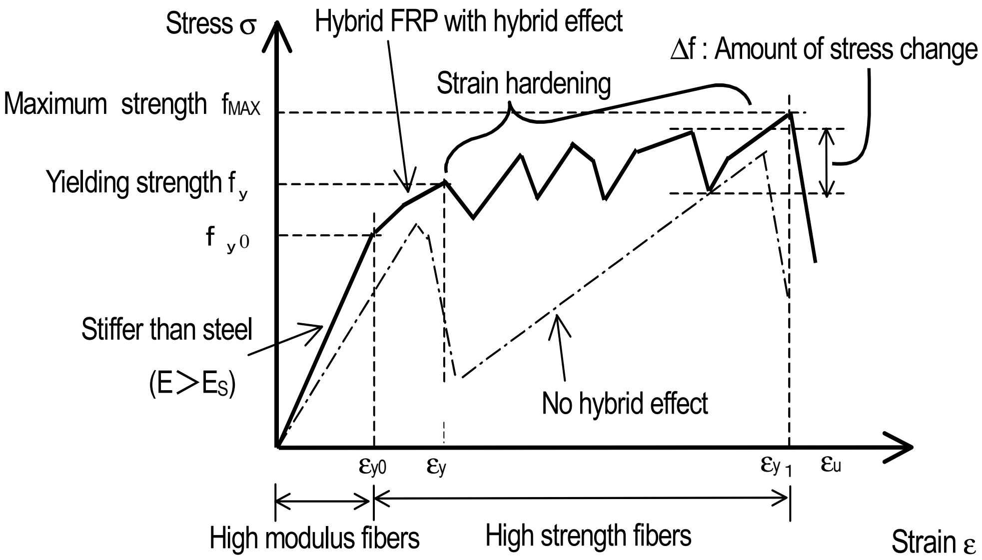

Figure 1. Idealized Stress-Strains Relation of Hybrid FRP Sheets Consisting of Two Types of Fiber Sheets

In this paper, it is focused to investigate the hybrid effects gained from combinations of high modulus and high strength fiber sheets in the strengthened structures. As illustrated in **Figure 1**, the hybrid effect exhibits higher stiffness than steel caused by high modulus fiber. The initial rupture load can be increased by the hybrid fibers and then due to the rupture of high modulus fibers some stress changes can be found by the release of some stresses and the induced impact. With subsequent rupture of different fibers one by one, the strain-hardening behavior can be observed, which is very similar to the yield stage in steel. Based on this, required strength and ductility of structure can be achieved.

Tension Test of Hybrid FRP Sheets

Outline of Test Specimens

In this study, the hybrid of high strength type of carbon fiber sheet (C1 sheet) and high modulus type of carbon fiber sheet (C7 sheet) are considered. The material mechanical properties of both continuous fiber sheets and epoxy resin are listed in **Table 1** according to the specification of manufacturer. In accordance with the method described in JSCE Recommendations for upgrading of concrete structures with use of continuous fiber sheets [4], the tensile specimens of FRP through the impregnation of epoxy resin are manufactured. Total 6 types of specimens are considered as shown in **Table 2**. Test specimens are loaded at both ends of glass fiber tab with a length of 60mm. The loading is controlled by displacement at a rate of 1kN/min.

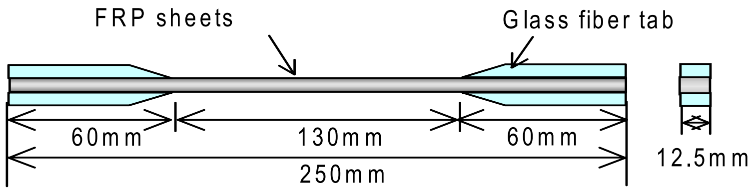

Figure 2. Details of Tensile Specimens

Table 1. Summary of Material Properties

Fibers	High strength Carbon Fiber sheet (C1 sheet)	Modulus of elasticity	2.3×10^6 (N/mm^2)
		Tensile strength	3400 (N/mm^2)
		Thickness	0.111 (mm)
		Unit weight	200 (g/m^2)
	High modulus Carbon Fiber sheet (C7 sheet)	Modulus of elasticity	5.4×10^6 (N/mm^2)
		Tensile strength	1900 (N/mm^2)
		Thickness	0.143 (mm)
		Unit weight	300 (g/m^2)
Epoxy resin		Tensile strength	51.9 (N/mm^2)

Table 2. Test Specimens

Specimens	Fiber sheet type	Total Layers	Number of Specimens
C1	C1(1 layer)	1	10
2C1	C1(2 layer)	2	10
3C1	C1(3 layer)	3	10
C7	C7(1 layer)	1	10
C1C7	C1(1 layer) + C7(1 layer)	2	5
2C1C7	C1(2 layer) + C7(1 layer)	3	5

Test Results and Discussions

The experimental results are shown in **Table 3** for all specimens. It should be noted that the average values are indicated for rupture load, maximum deflection and rupture strain in the case of single types of FRP sheets. In order to discuss the hybrid effects, the average values of initial rupture load, final rupture load, maximum deflection and rupture strain are shown in the cases of hybrid fiber sheets.

Table 3. Experimental Results

	Rupture load (kN)	Maximum deflection (mm)	Rupture stress (N/mm^2)	Rupture strain(%)
C1	5.906	2.960	4256.28	1.534
2C1	11.546	3.115	4160.86	1.641
3C1	17.830	3.374	4283.48	1.476
C7	4.622	0.793	2585.54	0.442

	Initial rupture load (kN)	Final rupture load (kN)	Maximum deflection (mm)	Rupture strain (%)
C1C7	6.706	5.200	2.030	13.3
2C1C7	8.7035	14.013	2.766	14.07

According to the experimental data, the experimental values of tensile strength, elastic modulus and rupture strain can be calibrated for the two fiber sheets of C1 and C7, which are summarized in **Table 4**. It can be found that the calibrated values are larger than the specified ones as shown in **Table 1**. The load-strain curves of each type of carbon fiber sheets are depicted in **Figure 3** through the average of 10 samples, where it can be found that the high modulus type of fiber sheet (C7) presents higher stiffness but lower rupture strain comparing with the high strength type of fiber sheet (C1) and the rupture load increases with increase of the layer number for C1 sheets.

Table 4. Calibrated Material properties of C1 and C7 FRPs

	Tensile strength (N/mm^2)	Modulus of elasticity (N/mm^2)	Rupture strain (%)
C1	4266.0	2.752×10^6	1.550
C7	2585.0	5.848×10^6	0.442

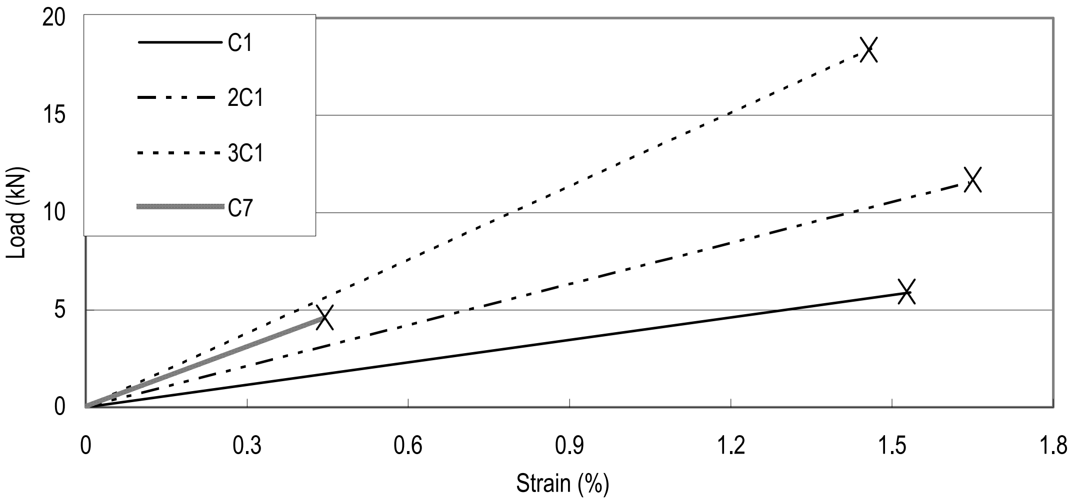

Figure 3. Load-Strain Relationships (Average)

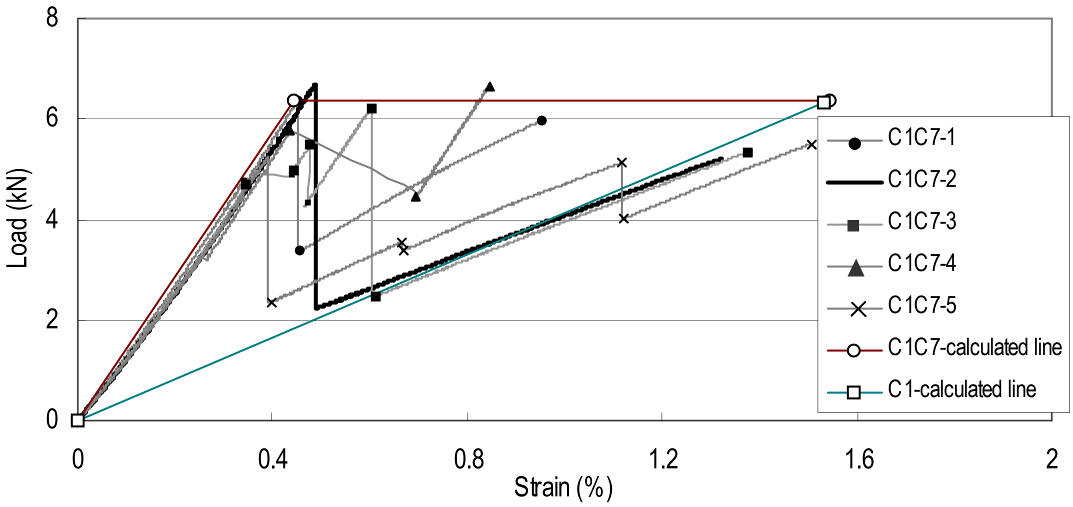

Figure 4. Load-Strain Relationships (C1C7 Hybrid)

For the case of C1C7 hybrid sheets, load-strain curves with 5 samples of specimens are shown in **Figure 4**. It shows that all specimens exhibit same stiffness till the initial rupture of C7 and the initial stiffness can be enhanced by mixing the high modulus type of fiber sheet (C7) into the C1 sheet. Variety of the different drops in load can be found after the initial rupture of C7. From the five curves, C1C7-2 is chosen to make comparison with other specimens.

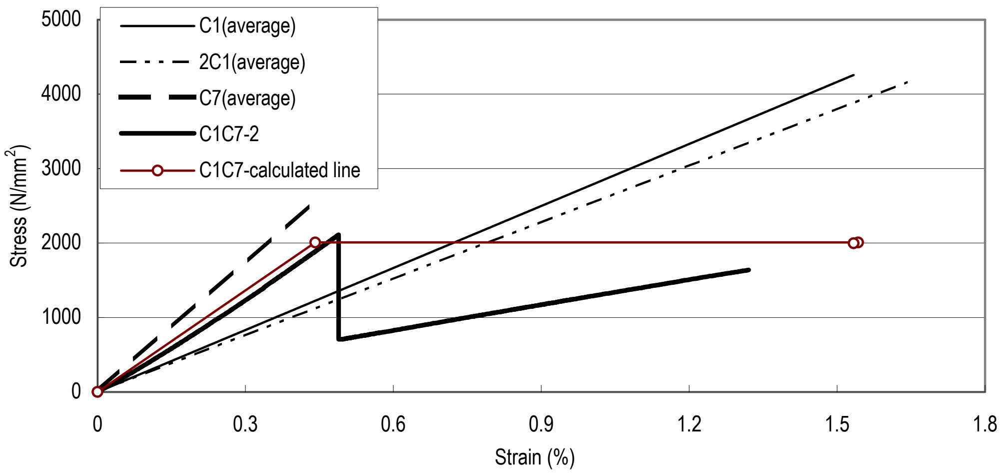

Figure 5. Comparison of Stress-Strain Relationships (Between C1C7-2 and Other Different Types of Specimens)

In **Figure 5**, comparison on stress-strain relationships is made in different types of specimens to represent the hybrid effect in which the initial section area is used for the calculation of stress from load. It is found that C1C7 sheets exhibit stiffness between those of C1 and C7 sheets than those of single type of FRP sheet, C1 and C7, prior to initial rupture of C7 sheet. In comparison with the experimental values, the calculated curve overestimate slightly stiffness of C1C7 hybrid sheet before the initial rupture comparing with the experimental result and then keeps constant till rupture of C1 because the rupture load of C1 sheet is almost equal to the initial rupture load of C1C7 hybrid sheet. The experimental result shows a large load drop due to the rupture of C7. This indicates that nearly no hybrid effect can be found in C1C7 hybrid sheet after the initial rupture of C7 fibers.

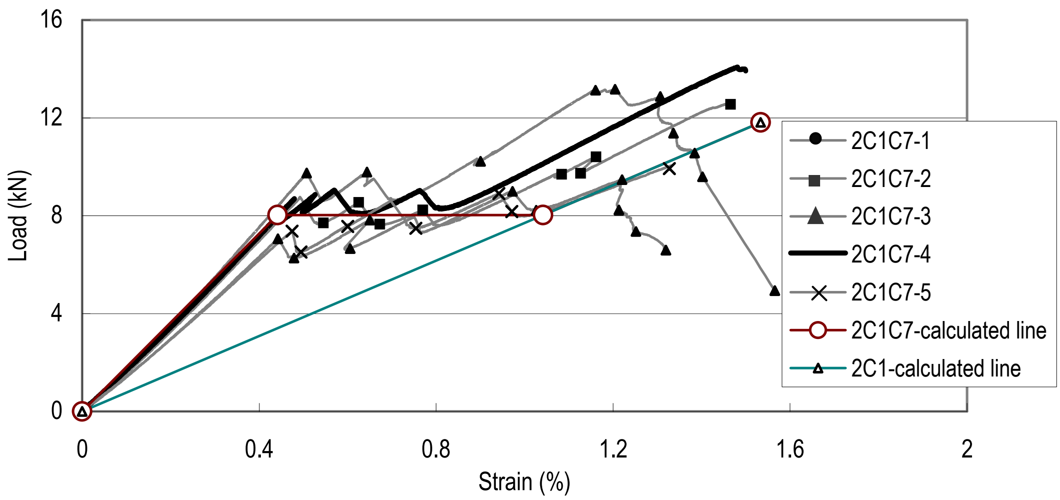

Figure 6. Load-Strain Relationships (2C1C7 Hybrid)

Figure 6 demonstrates load-strain relations for 2C1C7 specimens. In contrast with that of C1C7, 2C1C7shows increase in load after the initial rupture of C7 fibers. Although there are some differences among the specimens, they all give a same trend. Here 2C1C7-4 is used as a typical one to compare with other type of specimens. It is found that a stable behavior similar to yielding plateau can be achieved in 2C1C7 after the initial rupture of C7 fibers. It can be concluded that with increase of proportional ratio of high strength fiber sheets in the hybrid sheets with high strength type and modulus type of carbon fiber sheets, load drop can be reduced to a certain degree that nearly constant load can be attained despite gradual rupture of high modulus fiber sheet, and thus the expected hybrid effect can be achieved.

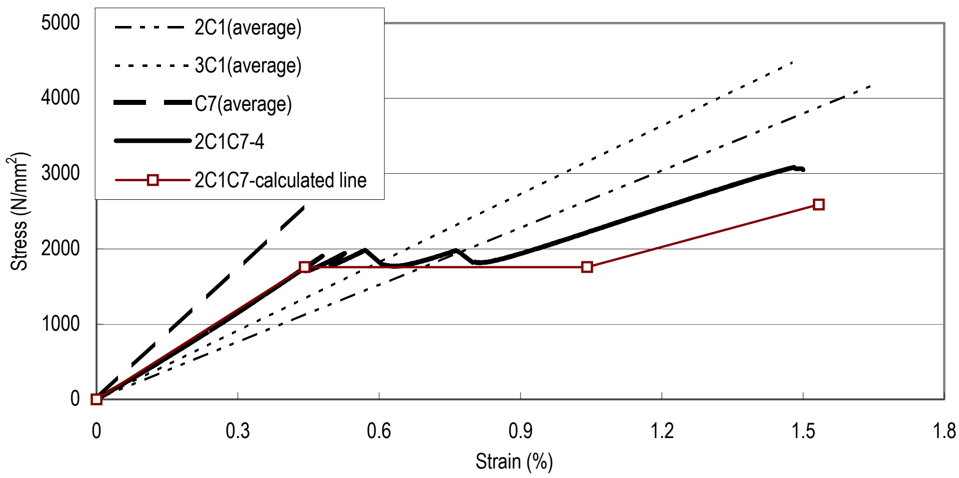

Figure 7. Comparison of Stress-Strain Relationships
(Between 2C1C7-4 and Other Different Types of Specimens)

Similar to the discussion on **Figure 5**, **Figure 7** shows the comparison of Stress-Strain relationship between the specimen 2C1C7-4 and some of other specimens.

Test of FRP - Strengthened Plain Concrete Beams

Outline of Test Specimens

The dimensions and cross-sectional details of the concrete beam specimens are shown in **Figure 8**. **Table 5** gives the material properties of concrete specimens. Four specimens shown in **Table 6** is prepared in order to discuss the reinforcing effect of plain concrete beams strengthened with different hybrid fiber sheets in which two types of hybrid fiber sheets with different contents of C7 sheet are provided to make comparison on the strengthening effects. The detailed reinforcing sheets are listed in **Table 6**.

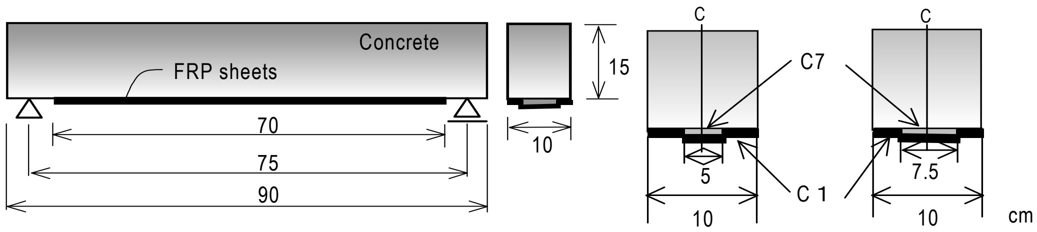

Figure 8. Details of Beam Specimen

Table 5. Material Properties of Concrete

Concrete	Modulus of elasticity (GPa)	21.5
	Compressive strength (MPa)	24.5
	Poisson's ratio	0.16

Table 6. Test Specimens

Specimens	FRP reinforcement
CB-C1	C1(width:10cm)x1laryer
CB-2C1	C1(width:10cm)x2laryers
CB-C1C7-5	C1(width:10cm)x1laryer+C7(width:5cm)x1laryer
CB-C1C7-7.5	C1(width:10cm)x1laryer+C7(width:7.5cm)x1laryer

All the specimens are subjected to three-point bending test, as shown in **Figure 9**. The loading rate is controlled as 1kN/min, but prior to occurrence of crack, step loading of 1KN is used to examine crack initiation. The instrumentation of each beam specimen is composed of : 1)two LVDTs at mid-span for the deflection measurement as shown in **Figure 9**, 2)electrical strain gauges bonded on the surface of fiber sheets for the measurement of strain distribution of FRP sheet as shown in **Figure 10**.

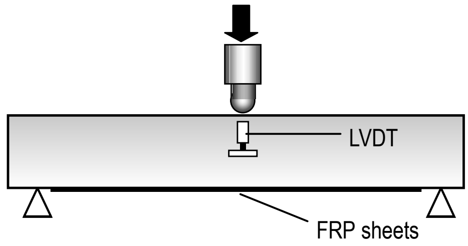

Figure 9. Loading Scheme

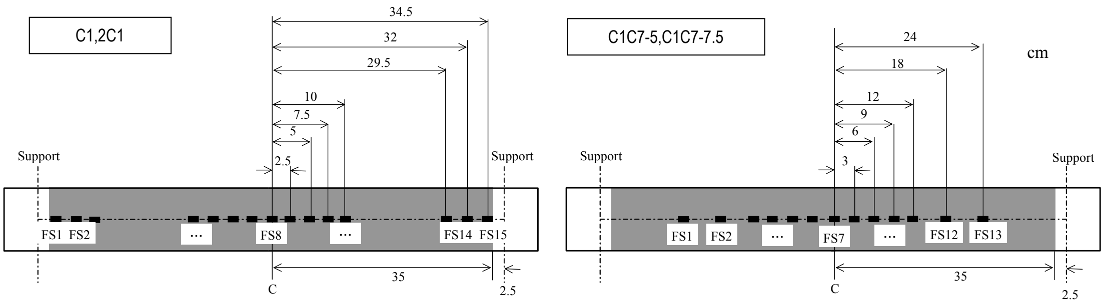

Figure 10. Arrangement of FRP Stain Gauges

Test Results and Discussions

The cracking load, maximum load and final failure load and failure modes of all specimens are summarized in **Table 7**, where mode A indicates debonding failure initiated from the ends of flexural cracks, and mode B indicates peeling-off caused by shear cracks. Cracking patterns of specimens are shown in **Figure 11**. The strengthening effect of different fiber sheets on the retrofitted system can be clearly illustrated in **Figure 12**. The detailed discussions will be made in what follows.

Table 7. Experimental Results

Specimens	Initial cracking load (kN)	Maximum load (kN)	Failure load (kN)	Failure mode
CB-C1	3.1	26.2	26.2	A
CB-2C1	5.0	33.9	33.9	B
CB-C1C7-5	17.5	32.4	31.9	A
CB-C1C7-7.5	15.6	33.3	30.0	B

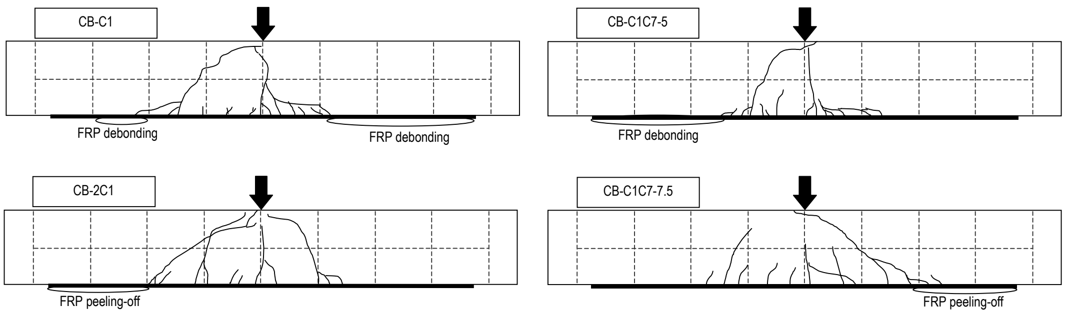

Figure 11. Cracking and Debonding Patterns of Specimens

With increase of FRP reinforcement amount, failure mode can be shifted from debonding by flexural cracks to peeling-off by shear cracks. In comparison with CB-C1 and CB-2C1, CB-C1C7-5 and CB-C1C7-7.5 exhibit significantly higher cracking load and stiffness after cracking to the maximum load.

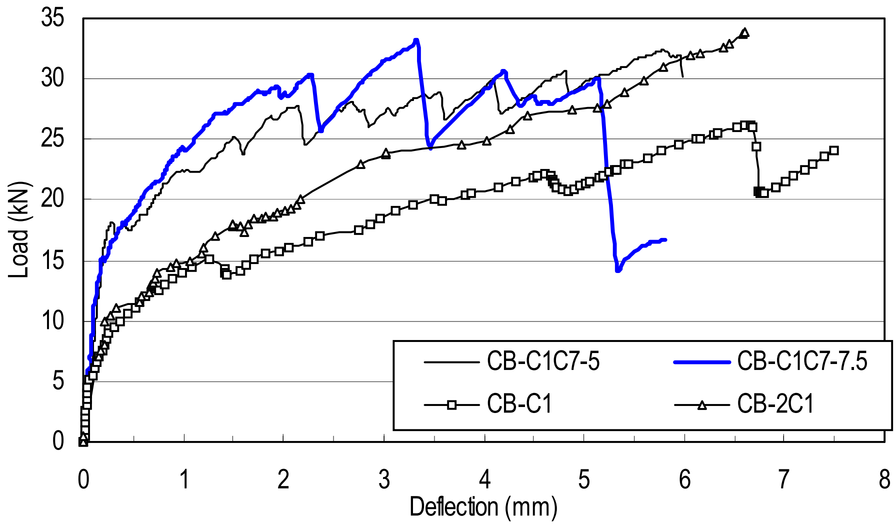

Figure 12. Load-Central Deflection Relations

In **Figure 12**, it can be found that CB-2C1 exhibits higher strengthening effect on maximum load than C1 due to higher reinforcement amount but no significant enhancements on crack loading and stiffness after cracking. For the hybrid ones, CB-C1C7-5 with small content of high modulus type of C7 fibers presents smaller and more stable load drop than C1C7-7.5. By considering the previous experimental studies on FRP materials, it can be realized that the load drop depends on the volume ratio of C7 to C1 and therefore the amount of load drop may be controlled by an appropriate hybrid design.

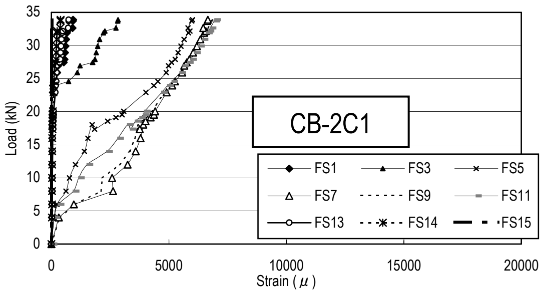

Figure 13. Load-FRP Strain Relations of CB-2C1

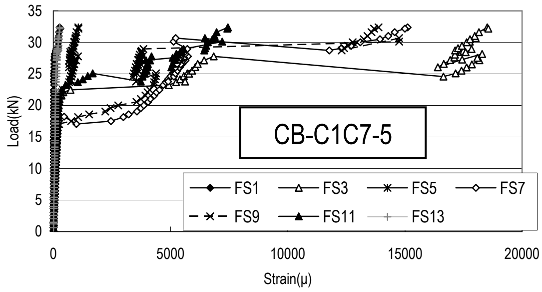

Figure 14. Load-FRP Strain Relations of CB-C1C7-5

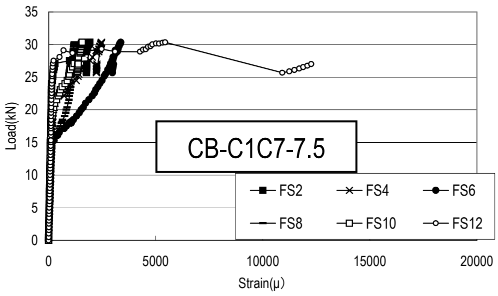

Figure 15. Load-FRP Strain Relations of CB-C1C7-7.5

The load-FRP strain relations are shown in **Figure 13 ~ 15** for CB-2C1, CB-C1C7-5 and CB-C1C7-7.5. **Figure 13** shows that FRP strains increase in a linear way after crack initiation for the case of 2C1 and the overall strains are relatively small. For the cases of CB-C1C7-5 and CB-C1C7-7.5, two-stage behavior can be found after cracking. Nearly all the measured FRP strains increase to 15,000με in CB-C1C7-5 but due to occurrence of shear cracks only the adjacent strain exhibit a large value in CB-C1C7-7.

Flexural Test of FRP - Strengthened RC Beams

Outline of Test Specimens

Two types of beam specimens are designed in this study. The dimensions and cross-sectional details of the test beams are shown in **Figure 16**, where type A is FRP-strengthened notched RC beam with 2 pieces of main D19 reinforcing steel bars as tensile reinforcement, Type B was unnotched one with 2 pieces of D13 main reinforcing steel bars as tensile reinforcement.

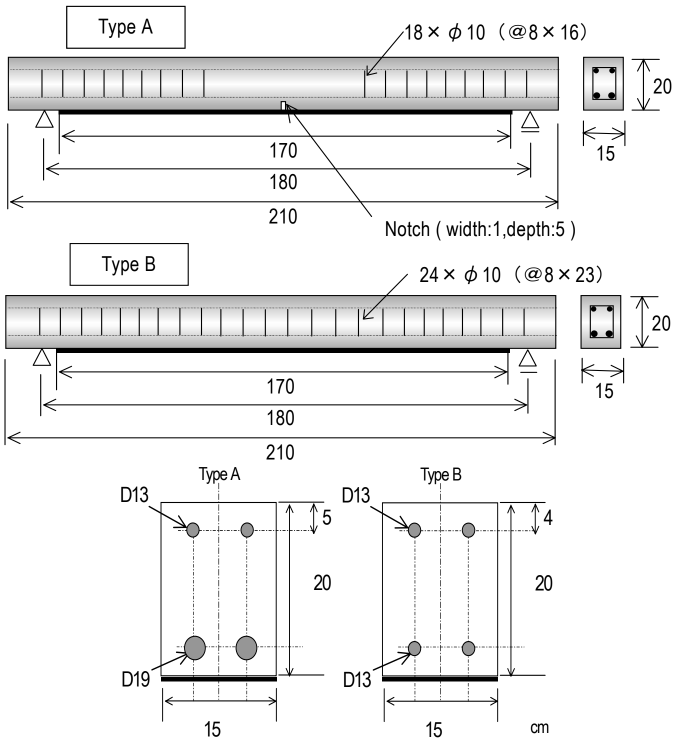

Figure 16. Details of Beam Specimens

Table 8 summarizes the material properties of specimens. 6 specimens are provided to investigate the strengthening effect of hybrid fiber sheets and the detailed reinforcing sheets are listed in **Table 9**. Based on the previous investigation on plain concrete specimens, only the reinforcement ratio 2C1:C7 is employed to investigate the strengthening effects of hybrid FRP sheets.

Table 8. Material Properties of Concrete

Concrete	**Modulus of elasticity (GPa)**	49.3
	Compressive strength (MPa)	35.1

Table 9. Test Specimens

Specimens	**Fiber sheet type**	**Loding scheme**
RCB-NR-D19	—	four-point bending
RCB-2C1-D19	C1(2 layres)	
RCB-2C1C7-D19	C1(2 layres)+C7(1 layre)	
RCB-C1-D13	C1(1 layre)	three-point bendikg
RCB-2C1-D13	C1(2 layres)	
RCB-2C1C7-D13	C1(2 layres)+C7(1 layre)	

Type A and B beams were subjected to four-point and three-point bending loading, respectively, as shown in **Figure 17**. The loading rate is controlled as 1kN/min, but prior to occurrence of crack, step loading of 1KN is used to examine crack initiation similar to the previous plain concrete specimens. The instrumentation of each beam specimen is composed of two LVDTs at mid-span for the deflection measurement in **Figure 17**.

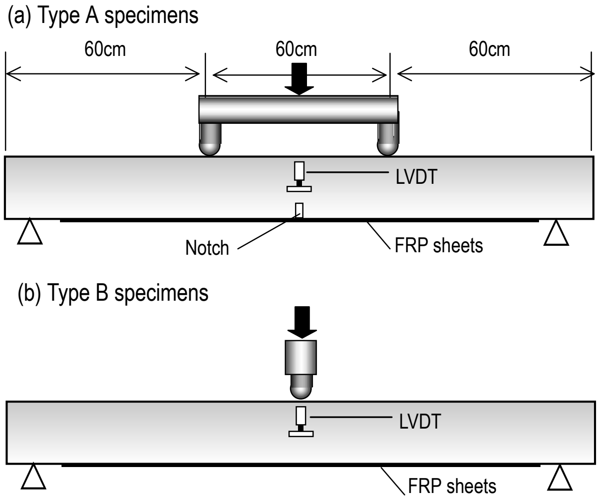

Figure 17. Load Scheme

Test Results and Discussions

Table 10. Experimental Results

Specimens	Initial cracking load (kN)	Steel yielding load (kN)	Failure load (kN)	Falure mode	Concrete crushing	FRP Peeling by shearing	Partial rupture of sheet
RCB-NR-D19	15.5	70.0	96.9	Flexural failure	O	-	-
RCB-2C1-D19	12.1	83.0	122.0	Deb. failure	-	O	-
RCB-2C1C7-D19	16.5	104.5	118.5	Shear failure	-	-	-
RCB-C1-D13	9.1	42.0	63.4	Flexural failure	O	-	O
RCB-2C1-D13	12.5	46.5	71.2	Deb. failure	O	O	-
RCB-2C1C7-D13	13.0	61.5	86.5	Deb. failure	O	O	O

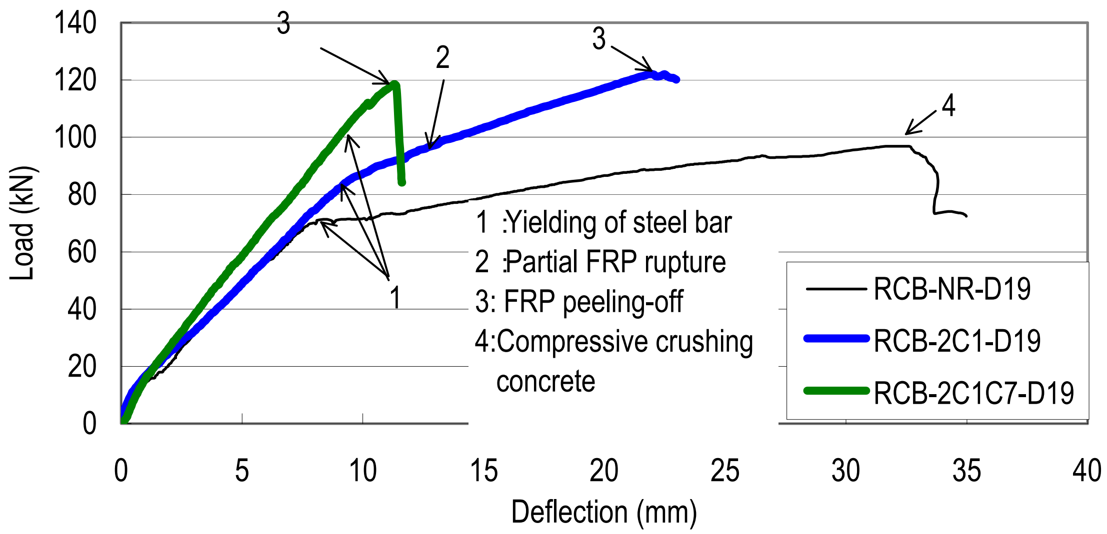

Figure 18. Load-Deflection Relations (Type A Specimens)

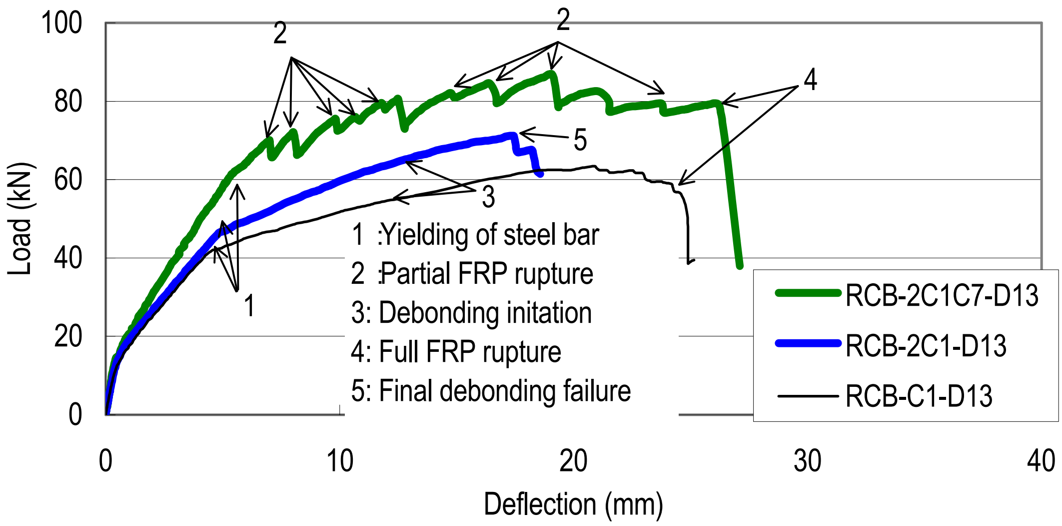

Figure 19. Load-Deflection Relations (Type B Specimens)

The cracking load, yielding load and final failure load and failure modes of all specimens are summarized in **Table 10**. The strengthening effect of different fiber sheets on the retrofitted system can be clearly illustrated in **Figure 18** and **19**.

Four-Point Bending Test on Type A

As shown in **Figure 18**, the yielding and failure loads can be enhanced through bonding two layers of C1 fiber sheets to the bottom of RC beams as compared to those of the RC control beam. However, due to the brittle failure of FRP peeling-off at the ends of shear cracks, amount of the structural ductility is decreased. Adopting hybrid fiber sheets with higher modulus type of carbon fiber sheet yields great enhancements in yielding load and stiffness of the strengthened beams after concrete cracking and before steel yielding, comparing with both control beam and strengthened beam with single type of C1 fiber sheet (2 layers). Unfortunately, due to over-reinforcement of RCB-2C1C7-D19 failed in brittle shear failure and did not show superior to the ones strengthened with 2 layers of fiber sheets in ductility. Therefore the structural strengthening design should avoid brittle shear failure due to over-reinforcement to effectively and efficiently utilize the strengthening effect of FRP composites, which means rational and appropriate strengthening design with hybrid reinforcement should also consider the existing structural behavior.

Three-Point Bending Test on Type B

In order to avoid such shear failure as happened in Type A beam strengthened with hybrid sheets and fully utilize the hybrid effect, tension steel bars were changed from D19 to D13 and three-point loading was applied.

Figure 19 shows that the stiffness, yielding and failure loads, and ductility of strengthened beams with hybrid fiber sheets of 2 layers of C1 sheets and high modulus of 1 layer of C7 sheets can be enhanced largely as compared to those of the 2 layers of C1 sheets. In addition, a pseudo-yielding plateau can be observed in **Figure 19** after yielding of steel bars, which can be attributed to the fact that gradual rupture of high modulus fiber sheet leads to the stress redistribution in hybrid sheets in order to avoid the premature debonding. It indicates again that high modulus type of fiber sheet plays an important role in strengthening effects on the enhancement of the stiffness, yielding load. Moreover, through an appropriate hybrid design of FRP sheets with the consideration of existing structural behavior, a strengthening effect for the enhancement of overall structural performances can be realized.

Conclusions

Through the experimental investigations on the material behavior and the strengthening effects of hybrid fiber sheets on plain/reinforced concrete beams, the following conclusions can be drawn:

(1) The hybrid effects and controlling the stress drop of hybrid fiber sheets can be achieved through an appropriate volume ratio of high strength type of fiber sheets to high modulus type of fiber sheets.

(2) Through the hybrid of high modulus type of fiber sheets, the strengthening effects on stiffness within the loading stage after concrete cracking and before steel yielding, cracking load, and yielding load of strengthened beams are significantly enhanced.

(3) The gradual rupture of high modulus fibers may result in the stress redistribution of FRP to reduce the interfacial bond stress and then to avoid the FRP premature debonding.

(4) Through an appropriate hybrid design of FRP sheets with the consideration of existing structural behavior, a strengthening effect for enhancing overall structural performances on stiffness, strength and ductility, and controlling loading drops due to the gradual rupture of high modulus fibers can be realized.

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