Research on Weight Reduction of PC Composite Members Using Ultra High Strength Fiber Reinforced Cementitious Composites (UFC)

H. Murata[1), J. Niwa[2), and C. Sivaleepunth[3)

1) Master course 2nd year student, Department of Civil Engineering, Tokyo Institute of Technology, Japan
2) Professor, Department of Civil Engineering, Tokyo Institute of Technology, Japan
3) Master course 1st year student, Department of Civil Engineering, Tokyo Institute of Technology, Japan
hmurata@cv.titech.ac.jp, jniwa@cv.tiech.ac.jp, chunyakom@cv.titech.ac.jp

Abstract: In the improvement of seismic performance of a bridge structure, the weight reduction of a girder is one of the significant factors. Recently, prestressed concrete (PC) composite bridge girders, which web member is made by various materials, have been developed. In this study, new PC composite structural members using Ultra High Strength Fiber Reinforced Cementitious Composites (UFC) in a web truss member are examined. UFC has high compressive strength around 200MPa, high ductility, and high durability. Due to its predominant mechanical properties, UFC is applied to the web member of PC composite bridge girders and the self-weight of girders can be significantly reduced. The aim of this research is to investigate the mechanical properties of PC composite members using UFC truss and evaluate the effect of weight reduction. Then, PC composite beams are designed and experiments and analyses are carried out. In addition, the level of weight reduction of a web member is examined.

1 Introduction

As for the improvement of seismic performance of bridge structures, the weight reduction of girders is one of the promising factors. A PC composite girder, of which web member is made of different material from a flange member, has been developed. Because of high strength of a web member, the cross sectional area of a web member can be reduced. As a result of volume reduction, the total weight of a bridge is also reduced.

Ultra High Strength Fiber Reinforced Cementitious Composites (UFC) (Sagawa et al. 2001) has been developed since 1994. This material provides high compressive strength around 200MPa with high ductility because of the existence of steel fiber reinforcement and high durability.

In this study, a PC composite girder utilizing UFC truss as web members is focused as shown in Figure 1. In case that UFC is used as a precast truss, the complexity in the construction can be solved and the total cost of construction can be reduced. Then, in order to clarify mechanical properties of this PC composite structural member, PC composite beams utilizing UFC precast truss as web members were constructed, and the loading test was carried out. Parameters to be considered in this study were the joint method and the variation of cross sectional area of UFC truss.

In addition, in order to clarify mechanical properties by analytical approach, nonlinear finite element method (FEM) analysis was performed and obtained analytical results were compared with experimental results.

Finally, the PC composite beams were compared with RC beams, which provide the same load carrying capacity, in order to discuss the reduction in weight.

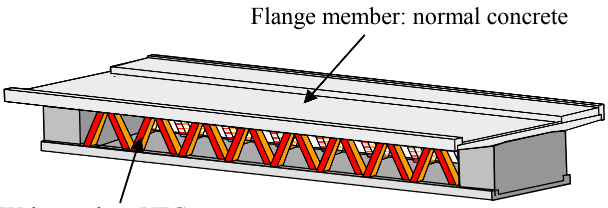
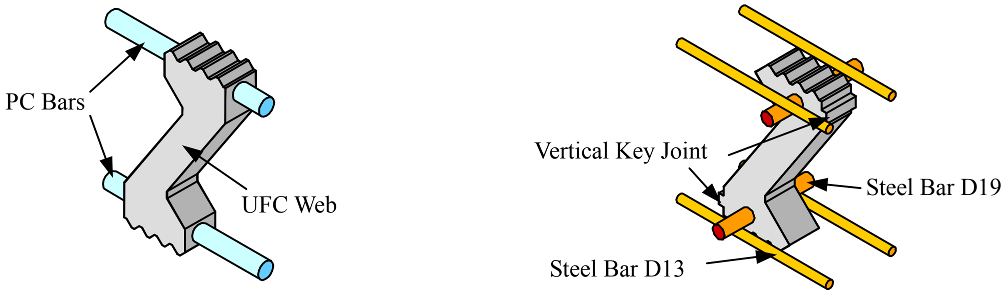


Figure 1 PC composite bridge using UFC

Table 1 Test parameters

Specimen name	Joint method (See Figure 2)		Thickness of truss b_w [mm]	
	A	B	40	60
60A	○	-	-	○
60B	-	○	-	○
40B	-	○	○	-



(a) Joint A: Penetration of PC bar with key joint (b) Joint B: Reinforcing bar with vertical key joint
Figure 2 Joint methods

2 Experiments

2.1 Experimental procedures

In this study, there were 3 specimens of PC composite beams using UFC truss as a web member: named as 60A, 60B and 40B as listed in Table 1. There were 2 parameters, which were considered in this study: joint methods between flange and web and the thickness of UFC in web. The number in the specimen name stands for the thickness of truss in mm and the alphabet A or B represents the joint method. Figure 2 illustrates two types of joint method, which are the penetration of PC bar with key joint (Joint A) and the reinforcing bar with vertical key joint (Joint B) as shown in the work by Kawaguchi et al. (2003).

The test of simply supported PC composite beams under two points load was performed to compare the applicability of the joint A (specimen 60A) and the joint B (specimen 60B). The vertical force, P, was applied monotonically to the specimen with two loading points as shown in Figure 3. In order to reduce the friction at the supports, friction-reducing pads, i.e., two Teflon sheets sandwiching the grease, were inserted between the specimen and the support plates. After determined the suitable joint method, the cross sectional area of UFC truss as a web member was discussed.

In the web of PC composite beams, UFC was introduced because of its superior strength (compressive strength = 200MPa). It results in significant weight reduction and provides nearly limitless structural member shape. The mix proportion of UFC truss member is shown in Table 2. The mixing time of UFC is about 12-14 minutes. There was no segregation and sinking of steel fiber from the matrix due to its high viscosity. After casting, the formwork was covered by plastic sheet and put into the chamber, in which the temperature was controlled at 20˚C for 48 hours. After the formwork was removed, the specimens were cured again in air with 100% humidity at 90˚C for 48 hours.

The outlines of experiments and properties of specimens were summarized in Figure 4 and Table 3, respectively. The shear span for all specimens was set to be 1500mm. In specimen 60A (Joint A), two ϕ17 PC bars (SBPR1080/1230; yield strength, f_y = 1229MPa, Young's modulus, E_s = 200GPa) were applied to both top and bottom flanges (one bar per each flange). The longitudinal reinforcement ratio was set to be 1.89%. In specimens 60B and 40B (Joint B), four ϕ13 PC bars

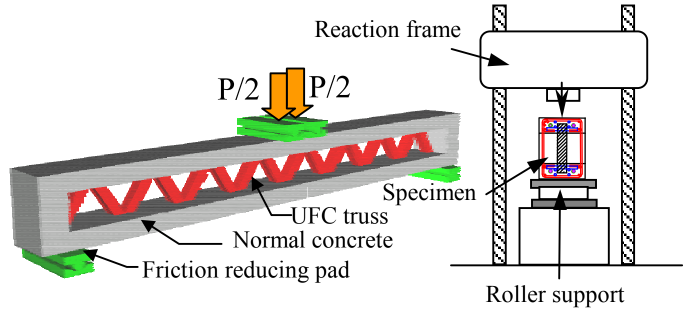


Figure 3 Flexure-shear test of PC composite beams

Table 2 Mix proportion of UFC [kg/m^3]

Water	Premix	Steel fiber	Superplasticizer
180	2254	157	26

Table 3 Properties of specimens

Specimen name	60A	60B	40B
Joint method	A	B	B
Thickness of truss (b_w) [mm]	60	60	40
Effective depth [mm]	340	350	350
Shear span to effective depth ratio	4.41	4.29	4.29
Longitudinal reinforcement ratio[%]	1.89	1.86	1.86

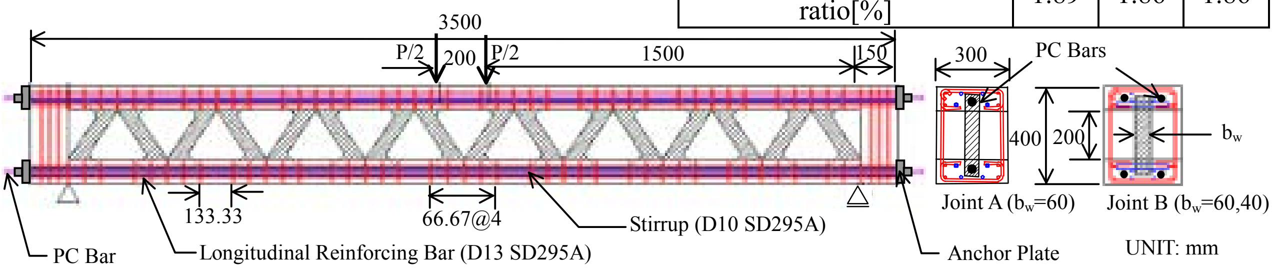


Figure 4 Outlines of experiments

Table 4 Mix proportion of concrete

Maximum size of coarse aggregate [mm]	Water-cement ratio [%]	Sand aggregate ratio [%]	Unit weight [kg/m^3]				
			Water	Cement	Fine aggregate	Coarse aggregate	Superplasticizer
15	30.0	53.3	170	567	871	765	9.1

(SBPR1080/1230; f_y = 1243MPa, E_s = 201GPa) were applied to both upper and lower flanges (two bars per each flange). The longitudinal reinforcement ratio was set to be 1.86%. For all the specimens, the stirrup (D10 SD295A, f_y = 349MPa, E_s = 206GPa) was used as the shear reinforcement in both upper and lower flanges. The shear reinforcement ratio was 0.59%.

Table 4 tabulates the mix proportion of concrete used in the flange. Before casting of concrete into the flange, the precast UFC truss web members were arranged and connected with each other by using epoxy glue. After casting the flange part, the specimens were cured for 7 days. Then, the prestressing force was applied to both upper and lower flanges in order to generate 3MPa and 5MPa in compression as the upper and lower fiber stresses, respectively. For all the specimens, grouting of cement paste was performed. After that, specimens were cured for another 7 days, thus curing period of concrete in the flange was totally 14 days before loading.

2.2 Comparison of joint methods

As the first step, the comparison of joints A and B was made. Table 5 shows the results of experiments. From the experimental results of 60A and 60B, the first peak loads, P_m (not the maximum loading capacities), were 92.5kN and 115kN, respectively. Figure 5 illustrates the load-deflection curve of beams with joint A and joint B. According to Figure 5(a), from the beginning, the curves rise up to the first peak load, P_m. It should be noted that the values of P_m of the two beams show the different results. After that the loads dropped until it reached the stable condition, and then gradually increased again. After the deflections of beams reached 13mm, the behavior of 60A and 60B was the same.

Figure 6 shows the crack patterns of specimens. First cracking loads of 60A and 60B were 69kN and 78kN, respectively. However, crack patterns of each specimen were similar (Figures 6(a) and (b)). In both cases, crack propagated in tension members of UFC truss on the left side and the failure was asymmetric. After that, cracks occurred in compression members because of the bending as a result of sliding of upper and lower flanges as shown in Figure 7.

Because the specimen 60B showed the higher loading capacity, this joint method is suitable to pursue in the study of the influence of UFC truss thickness for 40B.

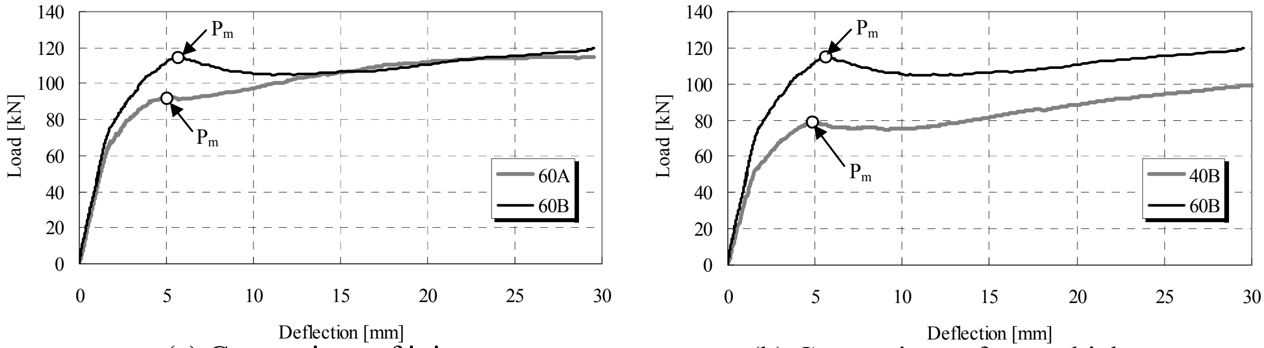
2.3 Influence of thickness of UFC truss

By comparing the thickness of UFC truss, when the cross sectional area of UFC truss used in 60B was decreased one-third of its cross sectional area, the first peak load, P_m of PC composite beam (specimen 40B) decreased about one-third of its P_m as shown in Figure 5(b). This implies that the first peak load depends on the thickness of truss.

From Figsure 6(b) and (c), there was not much difference on crack patterns between specimens 40B and 60B. The influence of thickness of UFC truss cannot be observed. It was also noticed that the failure was asymmetric.

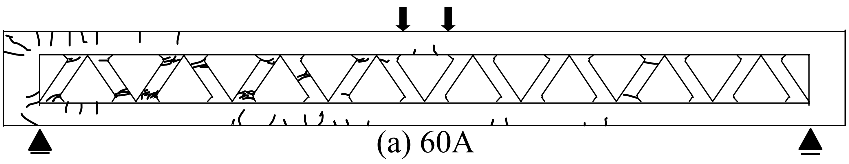
Table 5 Loading capacity of PC composite beams and material strength

Specimen	First peak load P_m [kN]	Concrete in Flange			UFC in Web		
		Compressive strength [MPa]	Tensile strength [MPa]	Young's modulus [GPa]	Compressive strength [MPa]	Tensile strength [MPa]	Young's Modulus [GPa]
60A	92.5	71.2	3.2	34.3	195.1	8.8	52.9
60B	115.0	69.1	3.5	32.9			
40B	78.8	77.3	3.1	32.3	206.7	7.6	53.3

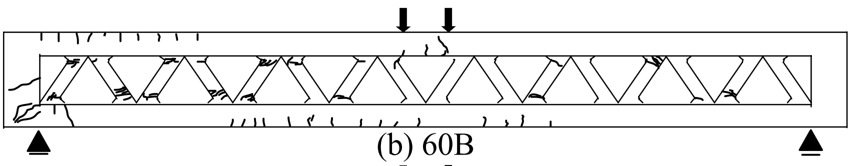


(a) Comparison of joint (b) Comparison of truss thickness

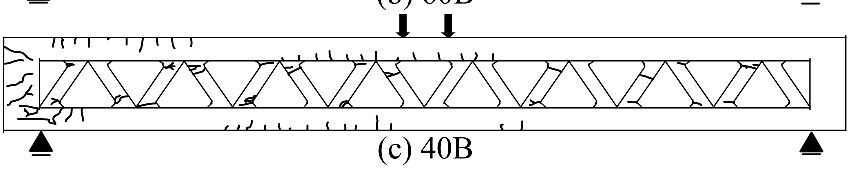
Figure 5 Load-deflection curve



(a) 60A



(b) 60B



(c) 40B

Figure 6 Crack patterns

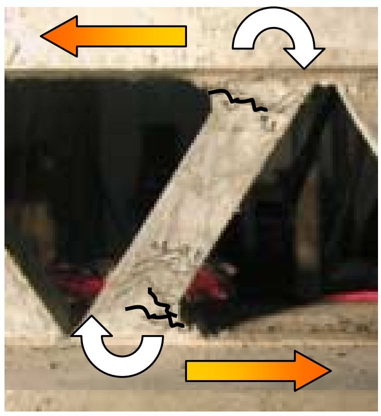


Figure 7 Cracks of compression member

3 Nonlinear FEM analyses

3.1 Analytical procedures

(1) Analytical model

For the analysis, a two dimensional nonlinear FEM tool, DIANA was applied. Figure 8 shows the mesh division. Four nodes isoparametric plane stress elements were adopted for concrete and UFC. The embedded reinforcement element was employed for reinforcements and PC bars. In consideration of asymmetry of failure, a whole of specimen was analyzed.

(2) Constitutive models

For crack model of concrete and UFC, the rotating crack model was used. For UFC, from experimental results in previous work by Kakei et al. (2003), constitutive models as shown in Figure 9 were applied. For concrete, Thorenfeldt's model was applied in compressive area (Figure 10(a)) and in tension area, concrete behaves as an elastic body with the elastic modulus, E_c, until it reaches the tensile strength, f_t. In the post peak region, Hordijk's model was applied (Figure 10(b)). Reinforcements and PC bars were assumed to be elastic bodies with elastic modulus, E_s, until it reaches yield stress, f_y, and then the stress increases gradually with $0.01E_s$ after it reaches f_y as shown in Figure 11.

(3) Characteristics of materials

Experimental results were applied to concrete and UFC. The yield strength, f_y, of PC bars is 1250 MPa and f_y of SD295A is 340MPa. Tensile strength, f_t, of UFC on the right side is assumed to be slightly higher than that of the left side by 0.5MPa.

3.2 Results and discussions

(1) Load-deflection curve

Figure 12 illustrates load-deflection curves obtained by experiments and analyses. In case 60B,

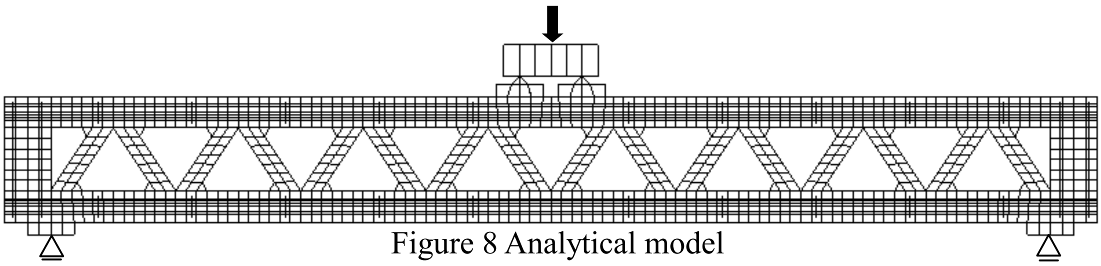
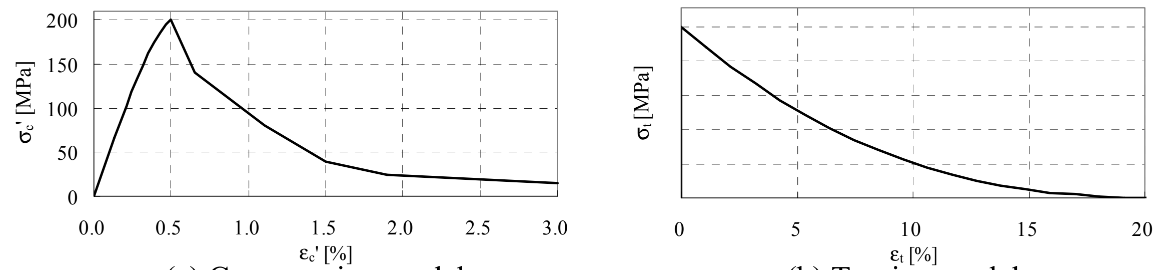
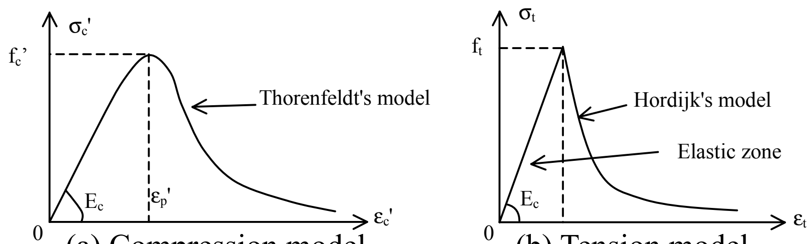


Figure 8 Analytical model



(a) Compression model (b) Tension model

Figure 9 UFC model



(a) Compression model (b) Tension model

Figure 10 Concrete model

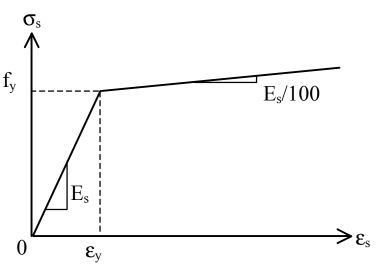
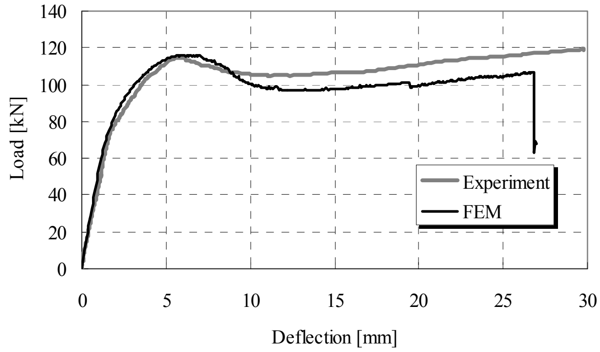


Figure 11 Model for steel bar

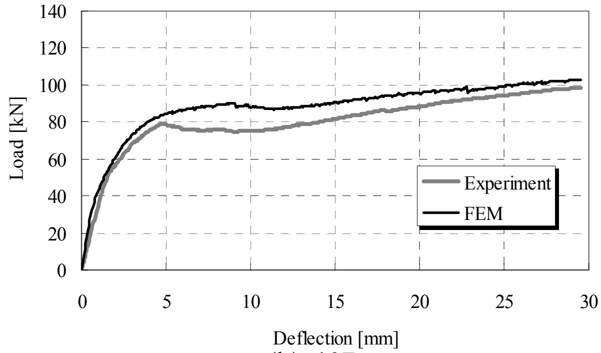
ultimately the compressive failure of concrete under the loading plate occurred in the analysis. However, the analysis expressed the behavior after the load fell until it reached the stable condition, and then gradually increased. Especially, the analytical first peak load, P_m, was almost consistent with the experimental one. By the way, in FEM analysis of this study, the joint between web and flange was completely bonded. Consequently, based on the agreement of value of $P_{m,}$ joint B on the experiment yields the high performance of bond. For case 40B, the load-deflection curve from analysis also expresses a good prediction compared with the experimental results as shown in Figure 12(b).

(2) Crack patterns from analysis

Figure 13 shows analytical crack patterns. For all cases, it is found that cracks propagated in tension members of UFC truss on the left side similar to the experimental results. That means the failure was asymmetric. Because the compression member received bending force due to sliding of a flange member, cracks occurred in compression members like those obtained in the experiments. Therefore, it can be said that, in all cases, the analyses provide adequately predicted results compared with the experimental results.

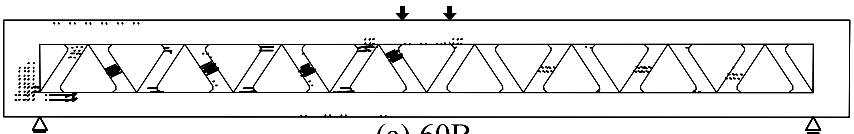


(a) 60B



(b) 40B

Figure 12 Load-deflection curve


(a) 60B

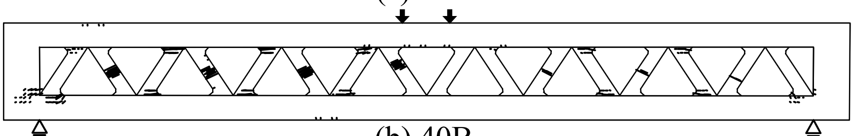
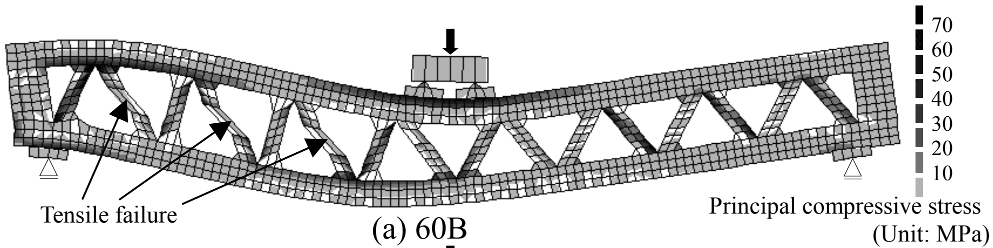
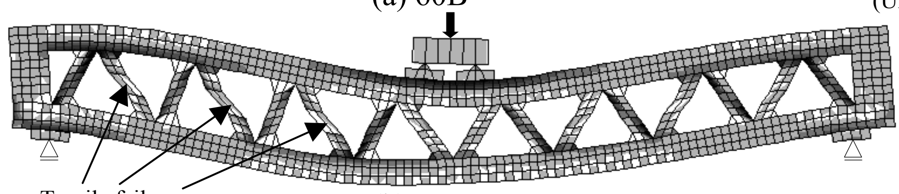

(b) 40B

Figure 13 Crack patterns from FEM



(a) 60B



(b) 40B

Figure 14 Principal compressive stress patterns and deformations

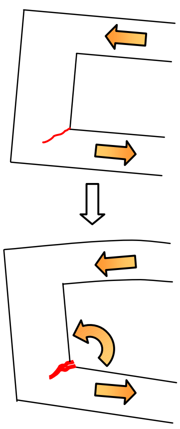


Figure 15 Mechanism of deformation at the corner of concrete frame

(3) Principal compressive stress patterns and deformations

Figure 14 shows the principal compressive stress and deformations obtained by the analysis. Deformations are exaggerated by 10 times. For all cases, from the deformations, it is shown that the tension members of UFC truss on the left side of a specimen are completely failed. However, the tension members on the right side were hardly damaged. It is found that the portion at the far left of upper flange was bended up. Moreover the compressive stress concentrated in the lower part of the upper flange. The possible reasons are as follows: (1) the edge of a concrete member was pushed by the upper flange and pulled by the lower flange, (2) in the lower corner of concrete frame, cracks occurred and opened, and (3) the upper flange member was bended (Figure 15).

From principal compressive stress patterns, for all cases, it was seen that the compressive stress of compression members of UFC truss on the right side was higher than that of the left side.

4 Comparison with RC beams

4.1 Design of RC beams

RC beams which have the same load carrying capacity as the PC composite beams (case 60B and 40B) were designed in order to examine the level of weight reduction of a web member. The characteristics of RC beams are the same as in the PC composite beams as tabulated in Table 6 and the outlines of RC beams are shown in Figure 16. The shear reinforcement ratio of RC beams was set to be 0.30%. This value is specifically the upper limit.

The shear carrying capacity, V_u, of RC beams can be obtained from the following Eqs. (1), (2), and (3) (JSCE code 2002).

$$V_u = V_c + V_s \tag{1}$$

$$V_s = \frac{A_w f_{wy} jd(\sin\alpha + \cos\alpha)}{s} \tag{2}$$

$$V_c = 0.2(f_c')^{1/3}\left(\frac{1000}{d}\right)^{1/4}(100p_w)^{1/3} b_w d \tag{3}$$

where, A_w: cross sectional area of stirrup [mm^2], f_{wy}: yield strength of stirrup [MPa], j: 1/1.15, d: effective depth [mm], α: inclined angle of stirrup to axis of RC beam (=90˚), s: spacing of stirrup [mm], f_c': compressive strength of concrete [MPa], p_w: longtudinal reinforcement ratio ($=A_s/(b_w \cdot d)$) [%], and b_w: web thickness of RC beams [mm].

Table 6 Characteristics of RC beam and its materials

Compressive strength (f_c')	[MPa]	60
Shear span (a)	[mm]	1500
Effective depth (d)	[mm]	350
Cross sectional area of longitudinal reinforcement (A_s)	[mm^2]	1058
Yield strength of longitudinal reinforcement (f_y)	[MPa]	1250
Cross sectional area of stirrup (A_w)	[mm^2]	142.6
Yield strength of stirrup (f_{wy})	[MPa]	295

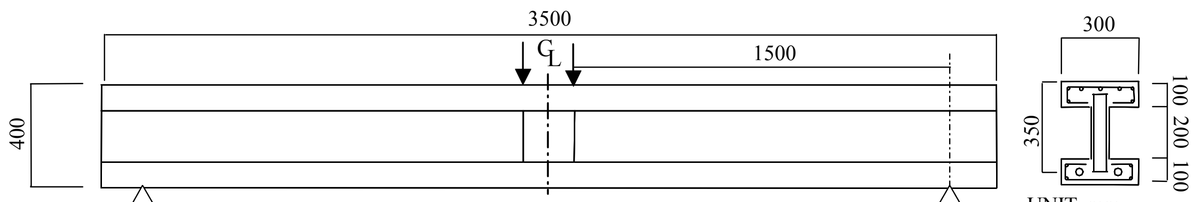


Figure 16 Outline of RC beam

Table 7 Designed results of RC beams

Specimen	Maximum load [kN]	Thickness of web of RC beam [mm]	Weight of web in PC composite beam [kg]	Weight of web in RC beam [kg]	Weight reduction rate [%]
60B	119.5	70.4	33.0	112.6	70.7
40B	99.4	55.5	22.0	88.8	75.2

By setting the value of $2V_u$ to be corresponding to the maximum loads of PC composite beams, b_w was determined. Here, the maximum load was obtained when deflections reached 30mm in the experiments (Figure 5(b)). From the densities of RC and UFC of 2.5t/m^3, the weights of a web member of RC beams and PC composite beams were compared.

4.2 Comparison of weight

Table 7 shows the designed results of RC beams with the same load capacity as PC composite beams. It was found that the weight of a web member can be reduced to about 70-75%. That means the PC composite girder can make a large contribution to the weight reduction of a web member.

This implies that the self weight of a web member of the PC composite girder using UFC truss is enormously reduced compared with RC girders.

5 Conclusions

The study of mechanical properties of PC composite beams using UFC truss as a web member was carried out. In addition, by the experiment and the nonlinear FEM analysis, the level of weight reduction of a web member by using UFC truss was investigated in comparison with RC beams.

The conclusions of this study are as follows:

1) From the experimental results, it is noteworthily turned out that the reinforcing bar with vertical key joint is more suitable joint method than the penetration of PC bar with key joint.
2) Based on experimental results, it is proved that, by reducing one-third of UFC volume in web, the first peak load of PC composite beams also decreased by one-third.
3) By nonlinear FEM analysis, the mechanical behavior of PC composite beams and the stress flow can be properly predicted.
4) By comparing PC composite beams with RC beams having the same resistance, the weight of a web member can be reduced about 70-75% when using the UFC truss. Therefore, the seismic performance of PC composite bridge structures using UFC truss can be enormously improved.

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