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Static Bending Test of Hybrid CFRP-Concrete Bridge Superstructure

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ABSTRACT

The objective of this study is to examine the proposed Hybrid CFRP-Concrete bridge superstructure experimentally, which consists of CFRP girders with a trapezoidal cross section and precast concrete slab wrapped by additional carbon fiber sheets. Bending tests are carried out in order to assess its failure mechanism and strength. It is understood from the loading tests that the proposed structural system shows a good performance; namely, the filled concrete layer prevents the local deformation of CFRP and the failure can be categorized by (a) compressive failure of concrete, (b) adhesive failure between concrete and CFRP, (c) shear failure between CFRP members and (d) buckling of the CFRP upper flange. A comparison of weight and life-cycle cost is also made between the proposed Hybrid CFRP-Concrete bridge superstructure and the ordinary Steel-Concrete bridge superstructure. It concludes that as for the total weight of superstructure, drastic reduction is observed, and that this significant weight reduction leads to the shortening of construction period as well as the simplification of substructures.

Keywords: Composite Girder, Bending, Strength, Buckling

1 INTRODUCTION

Most of civil infrastructures constructed extensively in the 20th century have been getting older, and eventually many maintenace works for such structures have been increasingly required in the cycle of routine inspections, assessment of structural integrity and necessary rehabilitations. Even for renewals or reconstructions, focused are advanced technologies not to affect current social activities. In addition, construction technologies in civil infrastructures have to face with global economical as well as environmental problems including the shortage of experienced engineers and natural resources, so that advanced and epoch-making materials somehow are demanded. Being to be equal to existing structural materials such as steel and concrete, the creation of new materials that can have potentials to change the current design and construction method is the frontier for civil engineers.

One of the advanced materials developed in the late 20th century was “Fiber Reinforced Polymers (FRP)”, and those have been successfully applied to main structural elements in aerospace and related engineering fields as shown in Fig. 1, particularly transportation industries. However, it is understood that even though the amount of 0.3 million metric tons have been used in the infrastructure’s applications as shown in Fig. 2, those were not applied to primary structural members so far. Under these circumstances, CONMAT(The High-Performance CONstruction MATerials and System) program that looked for new structural materials and systems in the new century has started in the U.S.A.[1] where smart materials and smart structures were focused. Many footbridges and slab decks have been constructed; but less roadbridges can be found[2].

The Structural Engineering Committee of Japan Society of Civil Engineers(JSCE) has formed the technical committee on FRP bridges chaired by Prof. T. Oshima of Kitami Institute of Technology starting in 2000 for 2 years; and then consecutive technical committee chaired by Prof. K. Maeda of Tokyo Metropolitan University further summarized the state of the art of FRP bridge comprehensively published from JSCE’s structural engineering series No.14 in 2004[3]. Then the technical committee chaired by Prof. S. Yamada of Toyohashi University of Technology was further extended to promote the FRP research community and continued to develop the design specification of FRP footbridges. Besides these activities in Japan, the first stage of research by Public Works Research Institute of previous

Ministry of construction started, and eventually the first FRP bridge of Okinawa Road Park Bridge have been successfully constructed in 2000. In addition, the second FRP bridge for the bicycle pathway was completed in 2008 and more recently in 2009 another footbridge was also opened as the first truss type bridge.

The objective of this paper is to examine the Hybrid CFRP-Concrete bridge superstructure experimentally and analytically, consisting of CFRP girders with a trapezoidal cross section, precast concrete slab and Carbon fiber sheets that have been originally proposed for GFRP and assessed by KITANE, et al.[4]. In order to assess such proposed structural systems by CFRP, the followings are discussed; (1)The design concept and fabrication procedure for Hybrid CFRP-Concrete bridge structure are feasible by loading test; (2)The cost of proposed Hybrid FRP-Concrete bridge is competitive compared with that of conventional bridge.

2 OUTLINE OF STATIC LOADING TEST

2.1 CFRP-Concrete Hybrid System

(1) Cross Section and Lamination of CFRP

Although the properties of FRP can differ by the lamination, it is well known that the shear and torsional rigidity are relatively small so that special design consideration is required such as utilizing sandwich structure or closed cross section. On the other hand, among many manufacturing processes of FRP, the pultrusion developed in the 1960s has been most popular to have continuous fibers in member direction with uniform cross section by being hardened continuously in the heated die so that high strength and high stiffness can be achieved. In addition, the mass production in the automation can reduce its manufacturing cost, and it is very attractive to have various cross sectional shapes such as plate, angle, channel, H-shape, I-shape, pipes and so on.

Therefore the prototype of superstructure as shown in Fig. 3 is considered because of high torsional rigidity of the closed section, and flexibility in structural dimensions by adding simple module structures and high strength of compressive elements by concrete slab on the top. As for the simple module structure of CFRP box member with trapezoidal cross section, each module is manufactured by sheet winding instead of pultrusion, where CF sheet with elastic modulus of 230(kN/mm^2) and tensile strength of 3400(kN/mm^2) is used and hardened by epoxy resin with the elastic modulus of 8.5(kN/mm^2) and tensile strength of 40(kN/mm^2). Although the volume fraction of fibers is fixed to be 60%, only 70% of fibers is located in the member direction and the rest is located in 45 degree as listed in Table 1. This test specimen is designed as about 1/20 scaled model.

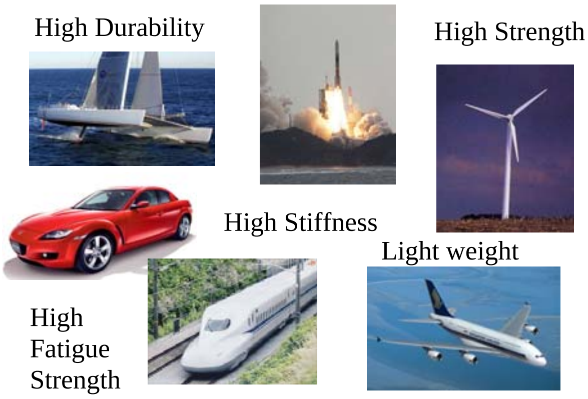


Figure 1: Applications of FRP materials

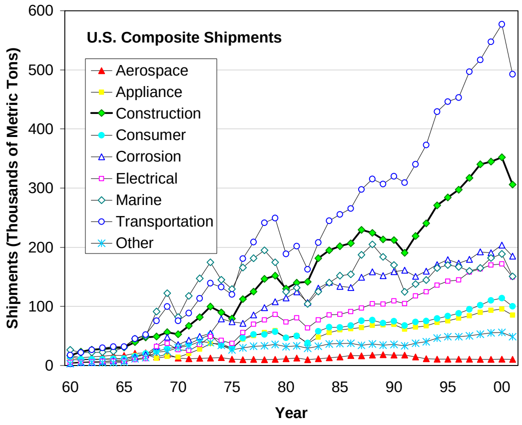


Figure 2: Market trend of GFRP Material

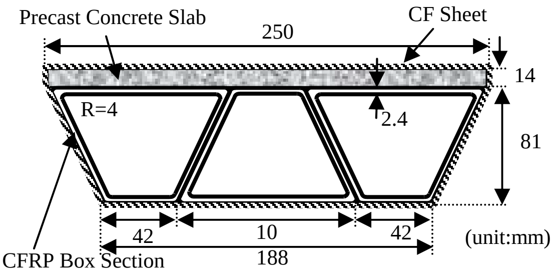


Figure 3: Hybrid Cross Section

Table 1: Nominal Effective Elastic Modulus of Laminated CFRP Plate

Mat.	Volume of 45 Fiber	E_1	E_2	G_{12}	E_1/G_{12}
M1	50(%)	87.2	24.4	17.4	5.0
M2	30(%)	106.4	18.5	19.6	5.4
Steel	—	206	206	79	2.6

注) E_1 : Elastic Modulus in fiber direction(kN/mm^2)
E_2 : Elastic Modulus in the direction perpendicular to fiber direction(kN/mm^2)
G_{12}: Shear Modulus(kN/mm^2)

(2) Fabrication Process

The fabrication process is illustrated in Fig. 4. The web surfaces of CFRP box members are attached side by side, by using an epoxy glue with tensile elastic modulus of 3.29(kN/mm^2), tensile strength of 53(kN/mm^2), compressive strength of 0.167(kN/mm^2), shear bond strength of 19.6(kN/mm^2) and tensile bond strength of 7.7(kN/mm^2). After assembling CFRP girder with multi-cells, the precast concrete plate is placed on the CFRP girder with block type shear connectors at 8 locations. In order to prevent a separation of CFRP girder from concrete slab, CF sheets of two layers(each thickness is about 0.167mm) are wrapped over CFRP girder and concrete slab.

2.2 Material Test Results

Test specimens for material properties of CFRP are prepared by cutting small pieces from fabricated CFRP box member with length of 2.1(m) as shown in Fig. 5. Three test pieces are fabricated for each type of test specimens.

As for concrete slab, the cylinder specimens with diameter of 10(cm) and height of 20(cm) are tested and the elastic modulus, compressive strength, tensile strength and poisson's ratio of 0.19 are obtained.

(1) Tensile Test Results

The tensile test is carried out with loading rate of 1(mm/min) and strains are evaluated by strain gages glued on both sides of test specimens. The test results are summarized in Table 2. It is understood that the measured elastic modulus is in good agreement with the theoretical one by lamination theory, but that the shear properties by Type 3 is little smaller than theoretical one because of the discontinuity of fibers. Consequently, it is concluded that the fabrication of CFRP box members are made properly as designed. As for a reference, the failure mode of tensile test specimens are shown in Fig.6.

(2) Compression Test Results

The compressive elastic modulus obtained by stub column test is 90.28(kN/mm^2), which is about 10% lower compared with that in tension. Generally speaking, compressive properties of CFRP are relatively smaller than tensile properties so that concrete slab in the compressive side of hybrid girders could be very effective. The compressive strength of 138.2(kN), which is calculated to be 0.18(kN/mm^2) as the working stress over the cross section. This is very small because the failure of CFRP box member is buckling in the wider flange plate with width of 104(mm). It is also observed that at the 60% stress level of compressive strength the local plate buckling occurred.

(3) Bending Test Results of CFRP Box Member

As shown in Fig. 8, the bending response of CFRP member is examined by three points bending. During the test, the deflection at the middle of the member and the bending strain distribution at the quater point of the span are measured and compared with the theoretical response in Figs 9 and 10 respectively. It is understood that the flexural rigidity of CFRP member is significantly small compared to that by the simple beam theory. However, it can be well predicted by including shear deformation. In Fig, 9, FEM represents the result by using shell elements which can consider the shear deformation in conjunction with the proper shear modulus of

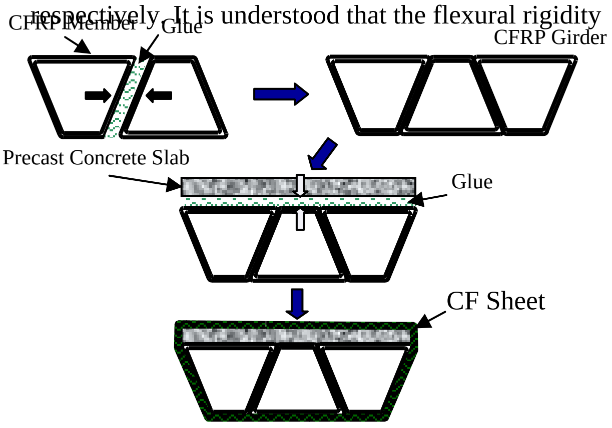
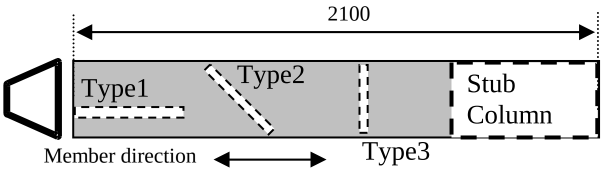
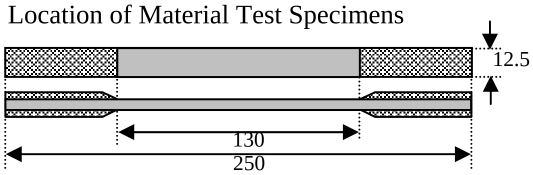


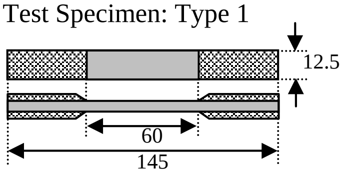
Figure 4: Manufacturing Process of Hybrid Superstructure



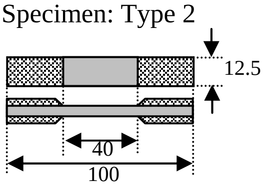
(a) Location of Material Test Specimens



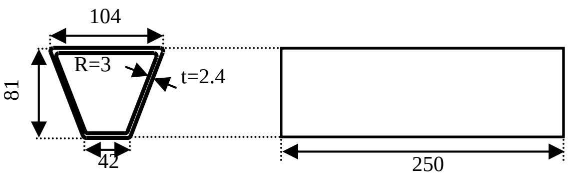
(b) Tensile Test Specimen: Type 1



(c) Tensile Test Specimen: Type 2



(d) Tensile Test Specimen: Type 3



(e) Stub Column Test Specimen under Compression

Figure 5: Preparation of Material Tests(unit:mm)

CFRP lamination. It is also understood from Fig. 10 that the bending strain distribution satisfy the Bernoulli-Euler

Table 2: Material Test Results

Specimens	Elastic Modulus (kN/mm^2)	Tensile Strength (kN/mm^2)	Strain at Breakage
Type1	99.2 (106.4)	1.87	0.0172
Type2	17.0 (18.50)	0.057	0.0051
Type3*	12.95 (19.6)	0.211	0.0207

The values in ( ) are theoretical based on lamination theory.
*This is evaluated as a shear property

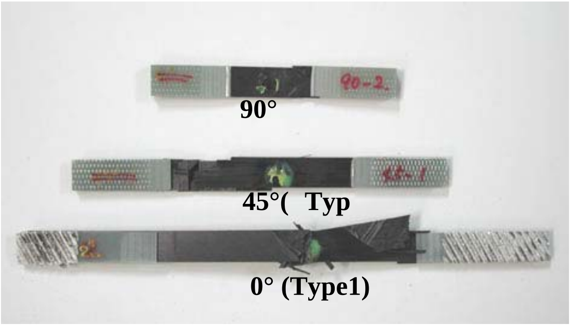


Figure 6: Failure Modes in Tension Test

Figure 7: Failure Mode in Compression Test

hypothesis. Furthermore the compressive strain in upper flange started to be reversed when it reached at about 1000 microstrains, and CFRP member failed by the buckling of upper flange near loading point. It is in good agreement with the stub column test under compression.

3 EXPERIMENTAL RESULTS

3.1 Preliminary Loading Test on Hybrid Girder

In order to assess the initial rigidity of hybrid girder, two types of loading were carried out as shown in Fig. 11, where P=5(kN) was applied.

The relation of the deflection at the midspan of the hybrid girder to applied load is shown in Fig. 12. It is understood that the deflection can be predicted by the simple beam theory, not like the response of CFRP member. In addition, it is observed that the bending strain distribution satisfy the Bernoulli-Euler

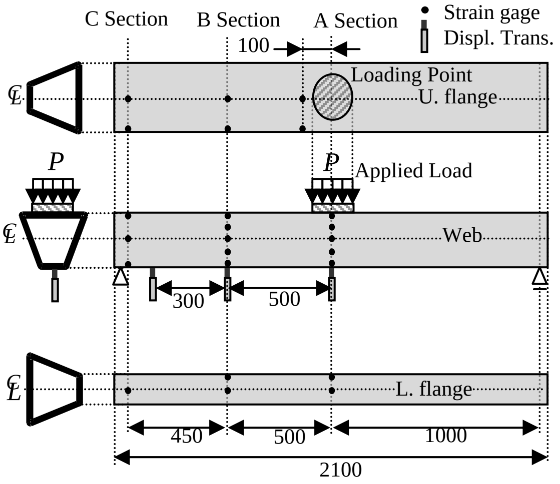


Figure 8: Setup for Bending Test of CFRP member

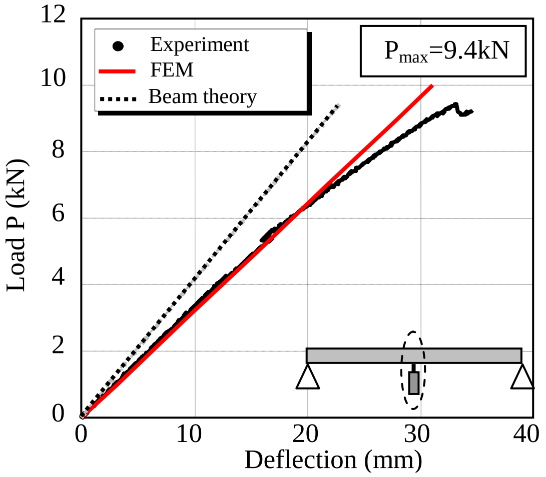


Figure 9: Relation of the Mid-deflection of CFRP Member to Applied Load

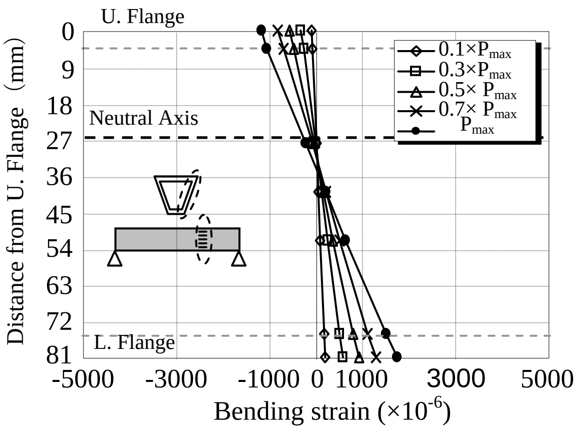


Figure 10: Bending Strain Distribution of CFRP Member in the Different Loading Levels

hypothesis. Therefore, it is concluded that the proposed hybrid girder can be treated such as steel-concrete composite girders. Particularly, special emphasis should be placed on the contribution of concrete slab which can eliminate the disadvantage of shear deformation of CFRP materials in deflection.

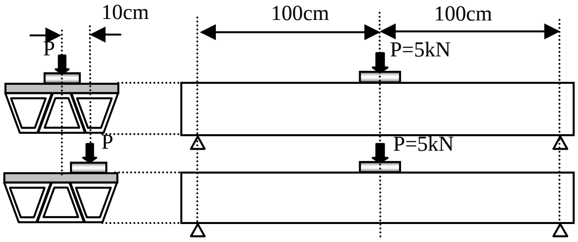
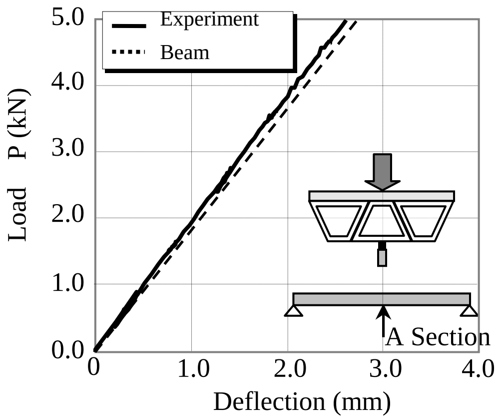
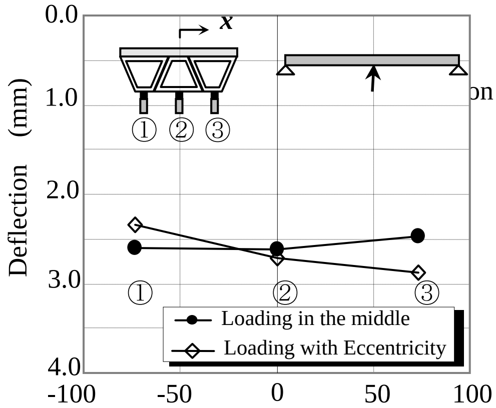


Figure 11: Loading Points for Preliminary Test



(a) Deflection by Loading in the Middle



(b) Deflection Distribution by Eccentric Loading

Figure 12: Deformation Characteristics of Hybrid Girder

3.2 Failure Mechanism of Hybrid Girder

The relation of the deflection of hybrid girder at the midspan to applied load is shown in Fig.14. It is understood that the deflection can be predicted by the simple beam theory, but the shear stress between CFRP member and concrete slab at the 1st peak is about 1.07(N/mm^2) which is much lower than the shear bond strength of glue used in the assembly, 19.6(N/mm^2). On the other hand, the tangent rigidity from the 1st peak to the 2nd peak, about 1.68×10^8(kN/mm) is close to 2.04×10^8(kN/mm) given by the layered beam of CFRP member and concrete

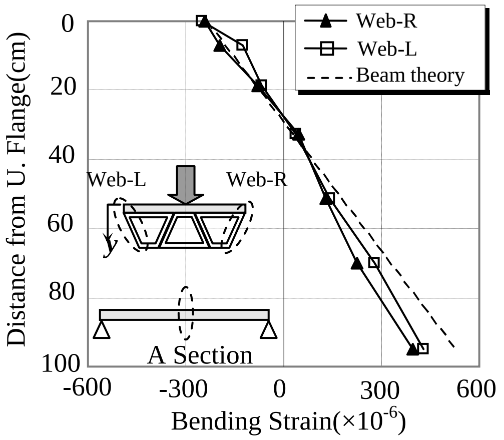


Figure 13: Bending Strain Distribution of Hybrid Girder

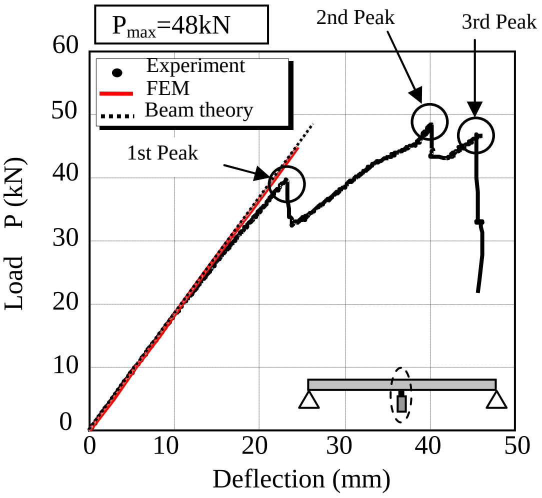
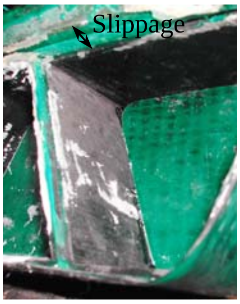


Figure 14: Load-Deflection Curves up to Failure



(a) Slippage at Girder End

(b) Deformation at the Ultimate State

Figure 15: Failure Characteristics

slab without shear stress transfer as evidenced by slippage at girder end shown in Fig. 5. After the 1st peak, excessive deflection was observed. Therefore, this premature failure is caused by the bond breakage between CFRP and Concrete. The stress between CFRP and concrete is evaluated by the detailed stress analysis by FEM(referred to Section 4), and maximum shear and normal stresses at the 1st peak load is obtained to be 7.23(N/mm^2) and 13.13(N/mm^2) respectively. Referred to the shear bond and tensile bond strength of glue used in assembly, the failure might be caused by the normal stress acting on the bond surface. Although a CF sheet was wrapped twice over CFRP member and concrete slab, this could not contribute to prevent the separation of CFRP from concrete. The shear connector used in fabrication is box-type and no resistance of such separation is expected so that this might be one of causes of failure. The deflection of each CFRP box members and bending strain distribution of hybrid girder are summarized in Figs. 16 and 17 respectively. It is understood that uneven deflection is observed after the 1st peak, and that the bending strain distribution is no longer uniform. This concludes that the interface between CFRP box members is also failed.

4 FE ANALYSIS OF PROTOTYPE BRIDGES

4.1 Analytical Model

Although the prediction of ultimate strength of proposed hybrid girders is not accurate, their initial rigidity can be well predicted by FE Modelling[5]. Based on this FE modeling, studied herein is the three spans continuous viaducts over the typical intersection of roadways as shown in Fig. 18(a). The parametric analysis is carried out focused on the height of hybrid girder, H and thickness of CFRP box member, t. Then, the applicability of CFRP-Concrete hybrid girder is assessed according to the deflection limit L/500 in which L is the span length of the bridge under the live loads specified by the Japanese Specifications for Highway Bridges[6]. The FE modeling of superstructures is shown in Fig. 19, where CFRP box members are modeled by a shell element and concrete slab is modeled by a solid element. The interface between CFRP and Concrete is assumed to be perfectly bonded and CF wrapping is not modeled in this parametric study.

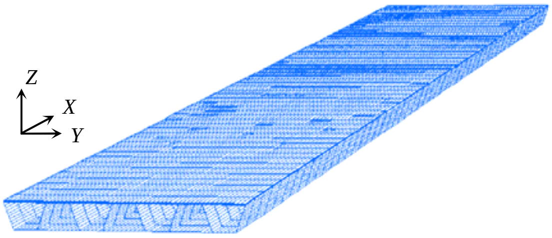


Figure 19: FE Modeling of Prototype Bridges

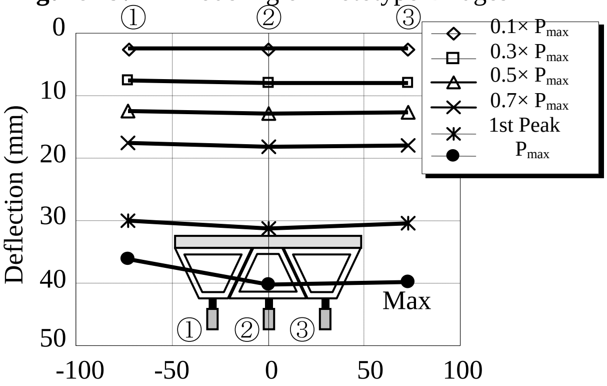


Figure 16: Deflection at the Midspan of Hybrid Girder

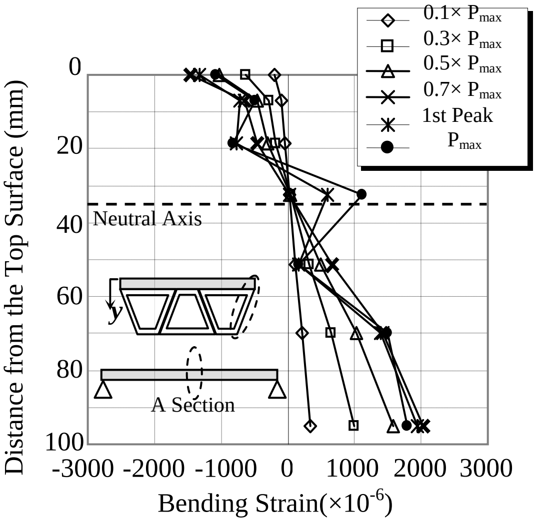
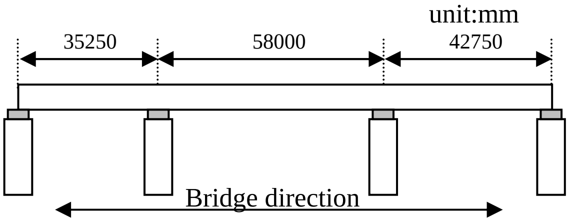
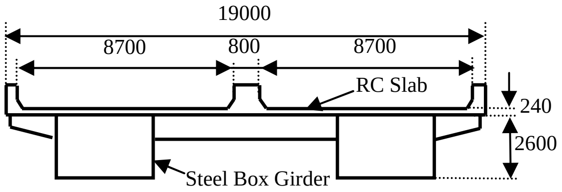


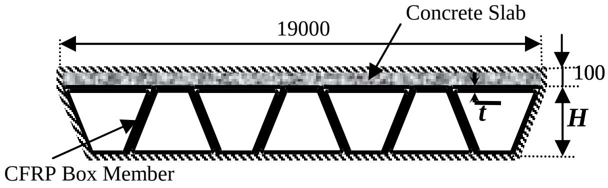
Figure 17: Bending Strain Distribution of Hybrid Girder



(a) Spans of Comparative Bridges



(b) Steel-Concrete Composite Girder



(c) CFRP-Concrete Hybrid Girder

Figure 18: Cross Section of Prototype Bridges

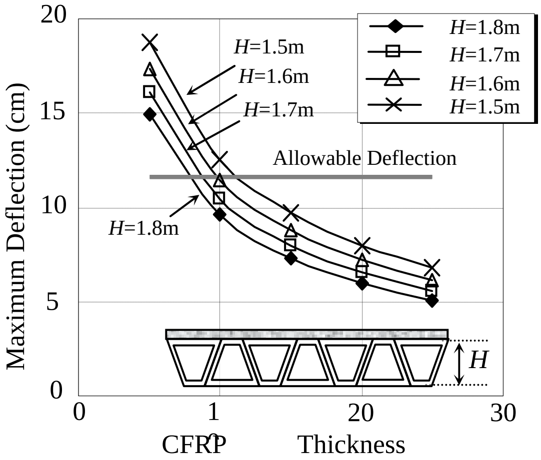


Figure 20: Deflection vs. Dimensions of CFRP Box Members, H and t

4.2 Results and Discussions

The results of FE analysis is summarized in Fig. 20. When the height of hybrid girder is in the range of 1.5 to 1.8(m), the required thickness of CFRP box member is ranging between 8 to 12(cm). In addition, the stresses in hybrid girder in the case of H=1.6(m) are tabulated in Table 3. It is understood that the stresses in CFRP box member and concrete slab are extremely small compared to those defined as failed. Particularly it is easily understood from the damage index by Tsai-Wu criterion for CFRP material in the table(the details can be referred to references[7][8]).

Table 4 summarizes the rough comparison of material cost, construction cost and maintenance cost which are the part of LCC. It is understood that the total weight can be reduced to 25% by using CFRP-Concrete hybrid girder. However, the total cost can be competitive only if no maintenance cost is needed over 100 years and the material cost could be reduced to 1/4 to 1/5 from the current manufacturing cost in the market.

5 CONCLUDING REMARKS

Examined in this study is the Hybrid CFRP-Concrete bridge superstructure, which consists of CFRP girders with a trapezoidal cross section, precast concrete slab in conjunction with Carbon fiber sheet wrapping. Bending tests are carried out in order to assess the failure mechanism and the strength of the proposed CFRP-Concrete hybrid system. It is understood from the loading tests that the proposed structural system shows a good performance; namely, the installed concrete layer prevents the local deformation of CFRP and the failure can be categorized by (a) compressive failure of concrete, (b) adhesive failure between concrete and CFRP box, (c) shear failure between CFRP boxes and (d) buckling of the CFRP upper flange. A comparison of weight and life cycle cost is also made between the proposed Hybrid CFRP-Concrete bridge superstructure and the ordinary Steel-Concrete composite bridge superstructure. It concludes that as for the total weight of superstructure, drastic reduction by using CFRP is observed, and that this significant weight reduction further leads to the shortening of construction period and the simplification of substructures.

Table 3: Typical Response of Hybrid Girders in the Case of H=1.6m

Thickness (mm)	5	10	15	20
Max. Deflection (cm)	17.33 (1/335)	11.44 (1/507)	8.79 (1/660)	7.22 (1/803)
Stress in Concrete (N/mm^2)	8.13	6.96	6.57	6.20
Damage Index of CFRP by Tsai-Wu Criterion	0.509	0.257	0.175	0.133
Volume of CFRP(m^3)	40.0	79.9	119.5	162.6

The value in ( ) is the ratio to the span

Table 4: Comparison of LCC

Items	Steel-Concrete	CFRP-Concrete	
		*65Jyen/cm^3	*20Jyen/cm^3
Girder Height (m)	2.6	1.6	1.6
Weight(ton)	2776	732.6	732.6
Material Cost (×10^3JYen)	78,000	5,200,000	1,600,000
*2 Construction of Superstructure Cost(×10^3JYen)	546,000	144,000	144,000
*3 Construction of Foundation Cost(×10^3Jyen)	257,000	129,000	129,000
*4 Maintenance Cost(×10^3Jyen)	1,040,000	0	0
LCC(×10^3JYen)	1,921,000	5,473,000	1,873,000

Assumptions:

*Cost of CFRP Material

*2 The construction cost of superstructures is proportional to the weight of superstructure

*3 As the weight of superstructure become 25%, the construction cost of foundation can be reduced to 50%.

*4 The maintenance cost for 100 years is assumed to be 130% of the initial construction cost.

6 ACKNOWLEDGEMENT

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