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Hyeong-Yeol Kim[*] Sun-Myung Kim[†]
Yoon-Koog Hwang[‡]

[*] Korea Institute of Construction Technology, hykim1@kict.re.kr
[†] Korea Institute of Construction Technology, smkim@kict.re.kr
[‡] Korea Institute of Construction Technology, ykhwang@kict.re.kr

DESIGN OF A PULTRUDED GFRP DECK FOR HIGHWAY BRIDGES

Hyeong-Yeol Kim, Research Fellow, PhD
Korea Institute of Construction Technology, 2311 Daewha-Dong Ilsan-Gu
Goyang, Gyeonggi-Do 411-712, Korea
T: +82-31-910-0582; F: +82-31-910-0578; E: hykim1@kict.re.kr

Sun-Myung Kim, Researcher, MS
Korea Institute of Construction Technology, 2311 Daewha-Dong Ilsan-Gu
Goyang, Gyeonggi-Do 411-712, Korea
T: +82-31-910-0719; F: +82-31-910-0121; E: smkim@kict.re.kr

Yoon-Koog Hwang, Research Fellow, PhD
Korea Institute of Construction Technology, 2311 Daewha-Dong Ilsan-Gu
Goyang, Gyeonggi-Do 411-712, Korea
T: +82-31-910-0129; F: +82-31-910-0121; E: ykhwang@kict.re.kr

ABSTRACT

This paper deals with the design and analysis of a GFRP deck for the highway bridges. Several cellular tube sections were assessed to obtain a viable cross-sectional profile of the deck. Two GFRP patterns were proposed and tested. Using the proposed deck profile and GFRP patterns, a GFRP deck for a prototype steel I-girder bridge was designed and presented in this paper.

INTRODUCTION

Bridge deck is a structural component that distributes and transmits the live loads to the girders. Although many different types of deck systems are currently designed and constructed, the most commonly used type of deck for the slab-on-girder systems is a cast-in-place reinforced concrete deck. A properly designed and maintained concrete deck can carry the live loads safely during many years of service. However, due to the heavy vehicle traffic and environmental attacks, the concrete deck often requires repairs, and the deteriorated one should be rehabilitated or replaced. For these reasons, the service life of the concrete decks is several times shorter than those of other primary bridge components.

At present, around 20,200 bridges are operated on our highway systems, and 30 percent of them are the slab-on-girder systems. Since potential demand for longer span bridges is high, the number of slab-on-girder bridges on our highway systems will be continuously increased. In 1999, the report of KICT (1) indicates that average service life of the cast-in-place concrete decks of the bridges owned by the Ministry of Construction and Transportation is at most 16 years, while that of girders is over 40 years. Furthermore, 15 percent of the decks have the substantial problems of cracking, corrosion of rebars, and spalling.

Therefore, the use of high-strength and -durability bridge decks in the bridge construction becomes crucial to minimize the maintenance works during the service and to increase the service life of entire bridges. Since the concrete decks are heavy and require relatively long erection period, bridge engineers seek new materials to reduce the dead load of the superstructures and to shorten the erection period. The rapid construction of decks may be beneficial to the deck replacement projects, in lowering the user costs induced by the detouring, especially for the bridge having a high traffic volume.

The FRPs (Fiber Reinforced Polymers) are relatively new materials in bridge construction. In spite of their higher initial costs, the FRPs possess several advantages over the conventional materials such as high strength to weight ratios, excellent durability, and competitive life-cycle costs. Although, significant efforts have been made in utilizing FRPs in the bridge construction including the decks, hybrid systems, tendons, and rebars, the bridge decks have received most attentions. This may be due to the fact that the use of lightweight materials is ideal for the rapid construction and reduction in dead load of superstructures. If an existing concrete deck can be replaced with a FRP deck, the load carrying capacity of the superstructure can be increased without strengthening the girders. However, the FRP decks have several shortcomings over the conventional decks that will be addressed later in this paper.

A large number of FRP decks are already in service worldwide. Within a decade, over 80 FRP decks have been built, and several projects are currently underway [Godwin (2)]. Earlier works and recent accomplishments are well summarized in the references by Bakis *et al.* (3), Karbhari (4), DARPA (5), and Luke (6). Since the major demonstration projects have already been completed, current efforts on the FRP decks have been focused on the developments of the design guidelines, deck-to-girder connections, and bridge details [FHWA (7), Moon II *et al.* (8), Zhao (9), Demitz *et al.* (10), and Qiao *et al.* (11)].

This paper presents the design and analysis of a pultruded GFRP deck for highway bridges. The primary objectives of this project are to gain the fundamental understanding of the material behaviors, design and analysis techniques for FRP structures; to design a FRP bridge deck and details for practical applications; and to provide the necessary information and background for the bridge engineers and researchers in utilizing FRPs.

SCOPE AND METHODOLOGY

To accomplish the primary objectives of the project, several work tasks have been established. A concise flow of the overall work task of the project is illustrated by a flowchart shown in Figure 1. This paper presents the achievements of the first year study performed at KICT [KICT (12)]: literature review; pattern design and material test; preliminary design of a GFRP deck for a prototype bridge; and establishment of future work tasks to be performed.

The design of a FRP structural component involves both the material and structural design. In this study, basically two GFRP (Glass Fiber Reinforced Plastics) stacking patterns with different composition of constituents are designed for the deck profile. GFRP plates are fabricated and tested to determine the material properties of each pattern. In order to design a viable cross-sectional profile of the deck, the structural characteristics of several cellular tube sections are analyzed, and the profile is finally optimized to reduce the fabrication cost.

To date, no consensus is made on the design criteria for FRP decks. Excepting the design provisions specified in the Specifications by MOCT (13), the criteria suggested in the FHWA's Advisory [FHWA (7)] have been used. Using the proposed cross-sectional profile and GFRP patterns, a GFRP deck for an example bridge is designed and presented in this paper. This paper also presents the proposed deck-to-girder connection.

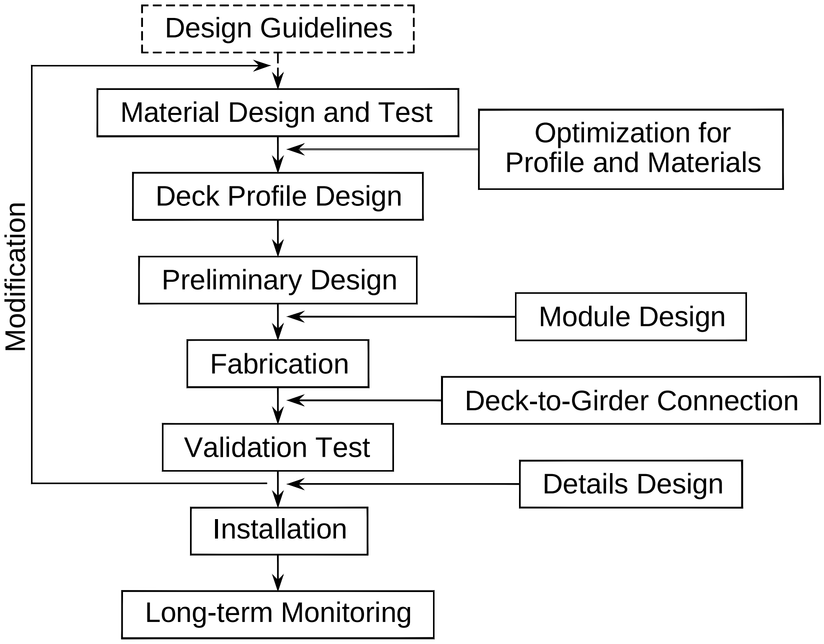

Figure 1. Flowchart for Overall Work Task

MATERIAL DESIGN AND TEST

Based on our preliminary investigation, the materials, fabrication method, and design method to be used in this study are selected. The main constituents of FRP are the fibers and matrix. Currently various types of fibrous materials are used for the deck fabrications. By considering the initial costs and FRP markets in Korea, E-glass fibers and vinylester were chosen as the main constituents for the proposed deck system. Although sandwich and hybrid types of FRP decks have also been introduced in several demonstration projects, most currently designed and commercially available FRP deck is an adhesively bonded pultruded type. Therefore, the pultrusion method of fabrication was chosen.

Pattern Design

The stiffness, strength, and cost may be the major factors of consideration in the pattern design. It is obvious that infinite combinations of constituent composition and fiber orientation are possible to achieve the material properties of a FRP structural component required by the structural aspects.

Figure 2 shows the stacking sequences for the patterns considered in this study. The constituents are the unidirectional E-glass roving, continuous strand mat, woven fabric, and vinylester. The pattern shown in Figure 2(a) is designated for the flanges of the deck profile. On the other hand, the pattern shown in Figure 2(b) is reinforced by +45°/-45° woven fabrics, and designated for the webs.

Based on the stacking sequences shown in Figure 2, the material properties of moderately thick GFRP plates having various material compositions of constituents were predicted by using the classical lamination theory. As provided in Table 1, finally total five different types of material composition and constituents for the patterns were chosen for the fabrication and material test.

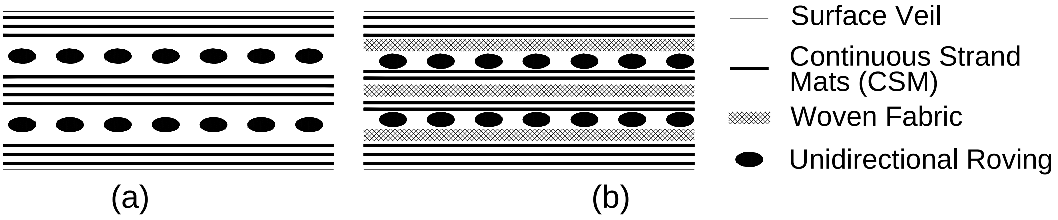

Figure 2. Stacking Sequences for GFRP Patterns: (a) Flange; and (b) Web

Table 1. Material Composition and Constituents for Specimens

Constituent	Specimen Type				
	I	II	III	IV	V
Unidirectional Roving (%)	35	30	25	25	20
Continuous Strand Mat (%)	10	10	10	10	10
Woven Fabric (%)	0	0	0	5	10
Vinylester (%)	55	60	65	60	60

A veil was used as the protective coating, and a small amount of aluminum hydroxides, 10 percent of vinylester by weight, was used as the filler. The elastic moduli of the E-glass fibers and vinylester were 72.1 *GPa* and 3.84 *GPa*, respectively. It is noted that relatively low fiber volume ratio was assumed for the pattern design. This is to assure the quality control in the fabrication by considering the capability of fabricator in our country.

Material Tests

For each specimen type in Table 1, a GFRP plate having the width of 60 *mm* and thickness of 15 *mm* was pultruded. The material tests have been performed on the coupon specimens that were cut from the pultruded plates. 20 coupon specimens for each pattern were tested for the compression, tension, shear, and flexure. The coupon dimensions, testing methods, and test results were summarized in the report by KICT (12).

Table 2 provides the highlight of the test results. The results indicate that, as expected, Type I provides high strength and high stiffness for the extension and flexure tests, while Type V shows high shear stiffness. Therefore, Types I and V were selected as the patterns for the flange and web of the proposed deck system, respectively.

Table 2. Test Results for Coupon Specimens (Units: *GPa*)

Type	Tensile		Compressive		Shear		Flexural
	Strength	Modulus	Strength	Modulus	Strength	Modulus	Strength
I	0.427	25.01	0.411	30.60	0.087	4.10	0.438
II	0.414	24.42	0.400	28.05	0.088	3.93	0.405
III	0.351	21.28	0.336	24.23	0.081	3.63	0.305
IV	0.354	19.61	0.345	22.26	0.112	4.32	0.312
V	0.343	20.30	0.337	21.97	0.106	4.88	0.262

DESIGN OF DECK PROFILE

Since the FRPs are relatively expensive materials than the conventional ones, thin-walled and cellular structural shapes are usually employed for the deck profiles. Although, moderately complex shapes of deck profile can be efficiently pultruded nowadays, most typical cross-sectional shapes are the rectangular, triangular, and trapezoidal shapes. In this study, the structural characteristics of these sections were assessed to design a viable cross-sectional profile of the deck.

Design Load and Criteria

Although many researches have been conducted to establish the design criteria for the FRP bridge systems, currently no official specifications are available for the design of the FRP bridge systems. Based on the results of preliminary study performed in this study, following design load and criteria were tentatively employed for the design process.

Standard design load DB-24 [MOCT (13)] with tire contact area shown in Figure 3 was assumed for a design live load. A DB-24 truck load is approximately 1.3 times heavier than AASHTO's HS20 truck load [AASHTO (14)]. Deflection limit of *L*/800 and ultimate safety factor of five that provided in the FHWA's Advisory [FHWA (7)] were employed. Since the local buckling is not a failure mode, safety factor of two was employed against local buckling.

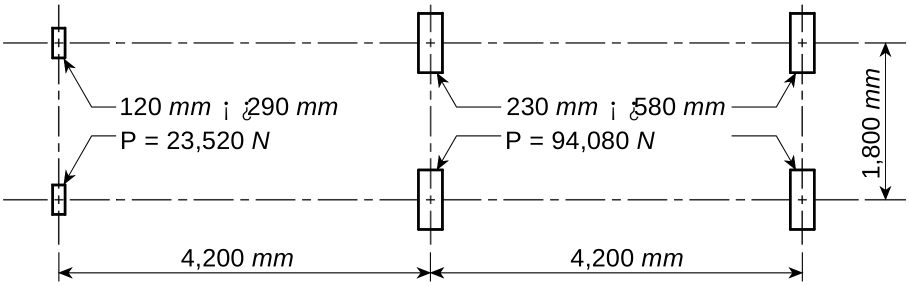

Figure 3. DB-24 Truck Load and Tire Contact Area

Structural Characteristics of Deck Profiles

In order to assess the structural characteristics of deck profiles, a simply supported beam subjected to single wheel load shown in Figure 4 is considered. For the given geometry and loading conditions of the beam, a flexural rigidity (*EI*) of the beam should be greater than 976,875 *GPa*-cm^4/m to satisfy the deflection limit of *L*/800. By assuming a longitudinal elastic modulus of FRP as 25 *GPa,* minimum required second moment of area (*I*) becomes 39,075 cm^4.

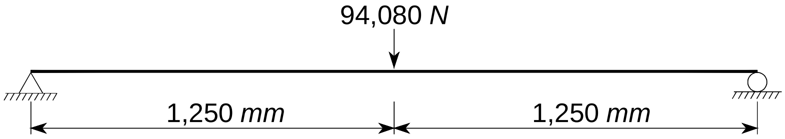

Figure 4. Loading and Boundary Conditions for a Simple Beam

One the other hand, a simple Fortran program was coded for the one-dimensional deflection analysis of the beam having the cellular cross-sectional profiles shown in Figure 5. Using this code, structural analysis was carried out for the profiles having various combinations of thickness of flanges and web, and space of web. In the analysis, the width and depth of the deck were assumed as 1.0 *m* and 0.2 *m*, respectively. Table 3 provides the minimum sectional properties required for each deck profile satisfying the deflection limit requirement.

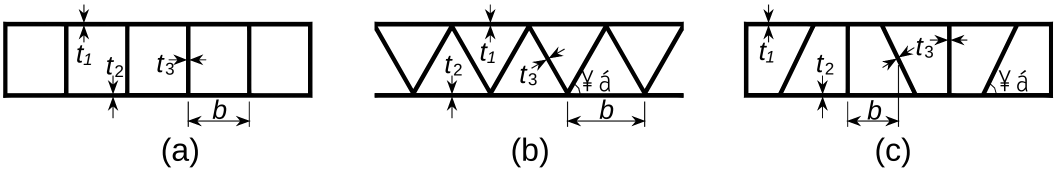

Figure 5. Cross-sections: (a) Rectangular; (b) Triangular; and (c)

Trapezoidal

Table 3. Dimensions and Sectional Properties of Deck Profiles

Section Shape	t_1 (mm)	t_2 (mm)	t_3 (mm)	α (°)	b (mm)	I (cm^4)	A (cm^2)
Rectangular	22.00	22.00	18.27	90	163	39,075	639.45
Triangular	20.56	20.56	10.00	60	200	39,075	688.36
Trapezoidal	22.00	22.00	17.13	60	163	39,075	639.46

Besides one-dimensional deflection analysis discussed above, an extensive three-dimensional structural analysis has been performed to assess the structural behaviors of deck profiles, and results were summarized in the report by KICT (12). The results indicate that, overall, the deck profile having a rectangular-shaped cellular profile gives favorable structural performance than others. Therefore, a rectangular profile was chosen for a preliminary design of a GFRP deck.

DESIGN EXAMPLE

Using the rectangular cross-sectional profile and FRP patterns of Types I and V, a GFRP deck for a prototype steel I-girder bridge was designed. As shown in Figure 6, the single-span bridge consists of a deck width of 12 *m* and is supported by five 40 *m* long steel girders spaced at 2.5 *m*, as provided in the Design Manuals [MOCT (15)]. The widths of the top and bottom flanges of the girder are 480 *mm* and 650 *mm*, respectively. The thicknesses of the top and bottom flanges, and web of the girder are 32 *mm*, 36 *mm*, and 12 *mm*, respectively.

In addition to a DB-24 truck load, self-weight of the superstructure including the asphalt wearing surface of thickness of 50 *mm* was considered for the dead loads.

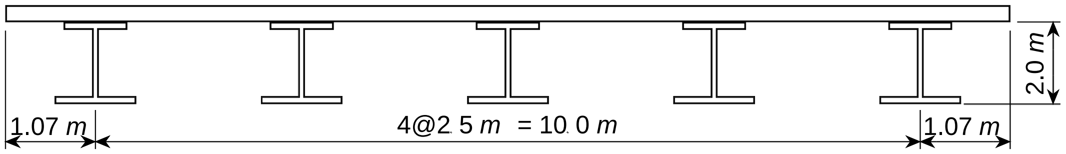

Figure 6. Front View of an Example Bridge

Material and Structural Optimizations

Using a genetic algorithm based optimization procedure, material and structural optimizations have been simultaneously performed for the proposed deck system. The solution algorithm, design variables, and constraints used in the optimization process are discussed in the reference by KICT (16). The structural computations were carried out by commercial package *ABAQUS* (17) with a 4-node shell element. As shown in Figure 7, the deck and girders were discretized by 18,775 and 960 finite elements, respectively.

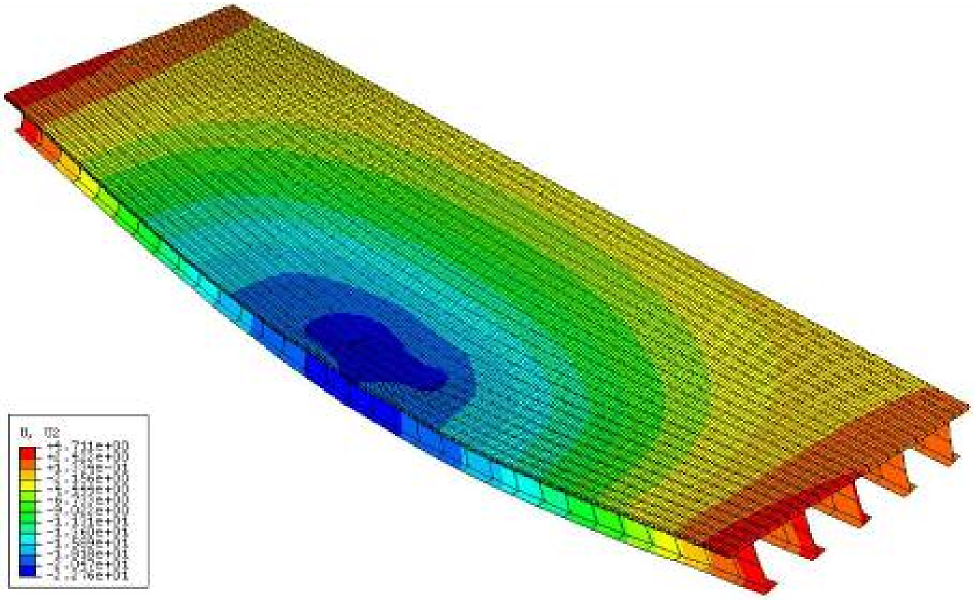

Figure 7. Finite Element Modeling for Deck System

Table 4 provides the results of material optimization along with the designed values of material properties. In the table, the materials properties used in the finite element analysis are denoted as design. The results show that, excepting E_{22} , the optimized values of material properties are slightly lower than the designed values. On the other hand, Figure 8 shows the final section of the deck profile obtained by the structural optimization.

Table 4. Material Properties of FRP Deck

Description		Flanges (Type I)		Web (Type V)	
		Design	Optimum	Design	Optimum
Elastic Modulus	E_{11}	25.01	22.59	20.30	18.34
	E_{22}	15.24	16.00	10.46	10.98
Poisson's	ν_{12}	0.30	0.26	0.30	0.26
Shear Modulus	G_{12} , G_{13}	4.10	3.70	4.88	4.40
	G_{23}	2.24	2.13	1.35	1.28

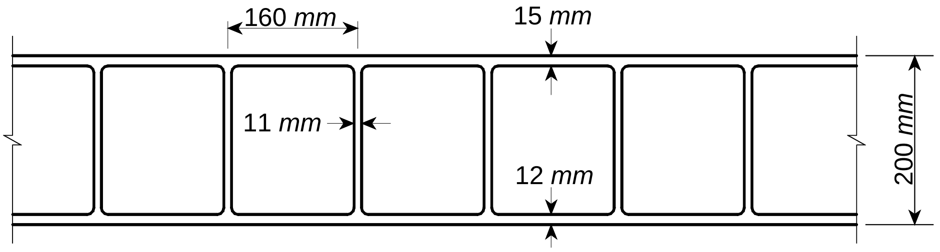

Figure 8. Cross-section of a GFRP Deck Profile

Table 5 provides the results of structural analysis for the example bridge along with the design limits. Although structural optimization gives different values for the thickness of top and bottom flanges, both were assumed as 15 *mm* to achieve the symmetry of deck. Since the ultimate strength of GFRP in the direction transverse to the fibers has not been tested in this study, this strength was assumed to be a quarter of the strength in the fiber direction.

Table 5. Results of Structural Analysis for a GFRP Deck System

Description	Design Limits	Results of	Factor of Safety
Stress in Fiber Direction (σ_{11} , *Mpa*)	392.28	67.57	5.8
Stress in Transverse Direction (σ_{22} ,	98.07	18.96	5.2
In-plane Shear Stress (σ_{12} , *MPa*)	83.36	15.27	5.5
Tsai-Hill Failure Criterion	< 1.0	0.18	5.3
Buckling Strength of Web in Shear	2,007.44	988.51	2.0
Buckling Strength of Web in Flexure	1,350.29	48.89	27.6
Buckling Strength of Flange in Flexure	71.15	35.51	2.0
Maximum Deflection of Deck (*L*/800,	50.00	21.93	2.3

The induced stresses within the deck are smaller than those of the strength limits multiplied by the safety factor of five. The compressive stresses induced in the flanges and webs are also smaller than the local buckling strengths in flexure and compression modes that were computed by using the analytical equations provided in the Handbook by EUROCOM (18). The proposed deck system has at least a safety factor of five against the material failure. As expected, the stiffness of deck was identified as a critical parameter for the design.

Proposed Deck-to-Girder Connection

The commercially available deck-to-girder connections for the FRP deck systems generally use so-called "shear pocket confinement" method of the connection. In this method, a number of shear studs are placed into a "shear pocket" prepared inside of the cellular FRP deck, and the pocket is finally grouted to provide the confinement action [Moon II *et al.* (8)]. Since the depth of typically constructed concrete decks in our country varies up to 250 *mm*, a new connection method was proposed for the deck replacement projects.

In the proposed system, a "shear pocket" will be placed beneath the FRP deck, as shown in Figure 9. If this system is employed, the existing shear studs installed in the girders need not to be removed and can be utilized for a new FRP deck system. The new shear studs shown in the figure can be used to adjust the elevation of the FRP deck installed over the existing girders. These may attribute the potential advantages of this system over the conventional methods.

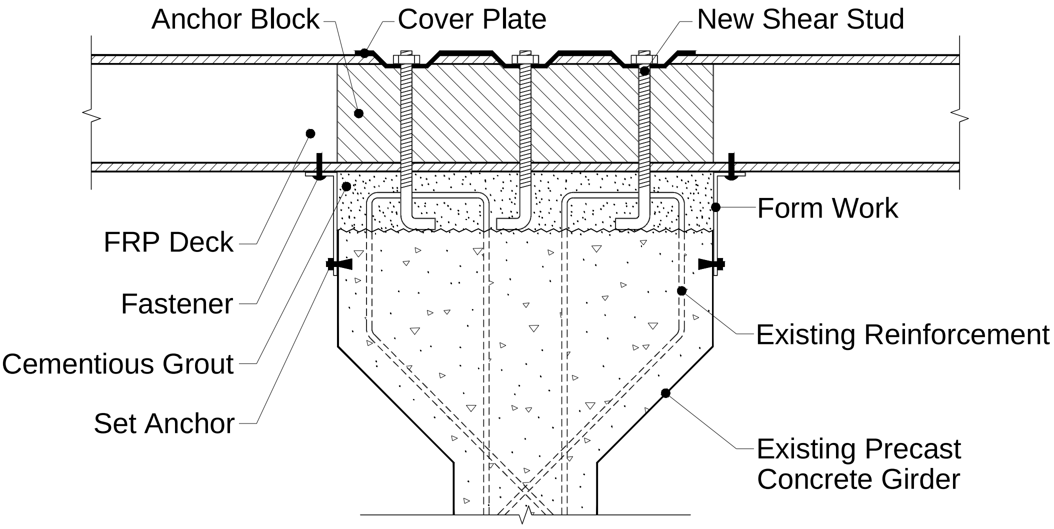

Figure 9. Schematic of Proposed Deck-to-Girder Connection

CONCLUDING REMARKS

The design and analysis of a pultruded GFRP deck system for highway bridges are briefly discussed in this paper. Based on the study outlined in this paper, several conclusions can be drawn and are summarized in the following.

In our country, typically quoted for construction of a concrete deck is about \$200/m^2, whereas roughly estimated that of a GFRP deck is \$400/m^2. Unless the life-cycle cost is considered, the use of FRP deck in bridge construction may still be a costly choice. However, for a certain circumstance, the GFRP decks may be able to compete with the conventional ones. This may be a deck replacement project of the bridge having a high traffic volume.

The FRP decks have several advantages over the conventional ones but FRPs possess several disadvantages as well. Excepting high initial costs of FRPs, one of significant shortcomings of utilizing the FRPs in bridge construction is the lack of long-term performance data. This study has been started without having a clear picture of the design criteria needed for FRP bridge decks. Establishment of the design criteria for the FRP deck systems would be one of significant and challenging tasks of this project.

Besides the establishment of the design criteria, several technical needs and contributions still remain to be made. The deck-to-girder connection and bridge details including the wearing surface, railings, and expansion joints must be developed prior to the validation test scheduled for this project. Especially, in order to double the advantage of lightweight of FRP decks, high-durability and lightweight materials for the wearing surface should be developed.

The assessments of fatigue behaviors of the deck panels and deck-to-girder connections, and durability characteristics of FRPs under the service loads and environmental attacks are the major work tasks to be performed. Furthermore, the environmental issues of FRPs, proper disposal and recycle, also need to be considered.

NOTATION

A = cross-sectional area of the deck profile;
E_{11}, σ_{11} = modulus of elasticity and stress in the fiber direction, respectively;
E_{22}, σ_{22} = modulus of elasticity and stress in the direction transverse to the fibers, respectively;
G_{12}, G_{13} = in plane shear moduli;
G_{23} = out-of-plane shear modulus;
P = single wheel load of DB-24 truck;
L = girder space or girder length;
α = angle between web tangent and bottom flange; and
ν_{12} = in plane Poisson's ratio.

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