Reliability Analysis on Flexural Behavior of FRP Bridge Decks

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ABSTRACT

Design codes for the design of FRP bridge decks shall be established to promote the use of such innovative materials. For the purpose of preparing code provisions, reliability analyses were conducted to evaluate proper levels of safety and serviceability. Based on the results, several guidelines on design codes are suggested.

INTRODUCTION

Bridge decks are one of the main structural components that are most suitable for utilizing the advantages of FRP materials. In Korea, a long-term project named 'Development of Durable and Economical Bridge Decks' using FRP Materials has been under way. The project consists of the work scopes including material design and test, optimization for deck profiles and materials, module design, fabrication, detailed design such as deck-to-girder connections, installation, and monitoring for maintenance. It is essential to establish design codes for the design of FRP bridge decks, which will also be the foundations for performing the project.

At present, design codes are relatively well established for the use of FRP materials as reinforcements in concrete structures. However, design codes have not yet been provided for the structures made of FRP as a main construction material. FRP materials are quite different from the conventional construction materials such as steel and reinforced concrete, in terms of material properties. They have high strength-weight ratio, but relatively low modulus of elasticity compared with steel. Thus the critical design criteria may not be the strength but the serviceability such as deflection as opposed to steel or reinforced concrete structures.

In preparing design code provisions for FRP bridge decks, reliability analyses are to be conducted to evaluate safety and serviceability. The results of the analyses can be used as a fundamental step toward code provisions for FRP bridge decks in Korea.

This paper discusses the reliability analyses focused on the flexural behavior of FRP bridge decks, of which results will be the basis for the preparation of design codes. For the analyses, an example FRP deck was selected from KICT (1), which was designed to meet a deflection criterion. Resistance models are set up using statistical parameters of FRP materials collected through literature surveys. Load models are reasonably assumed to be identical to those specified in the current design codes for conventional reinforced concrete materials. In evaluating the target reliability, failure modes of bridge decks inherent to FRP material properties are taken into considerations. Based on the results of this study, several guidelines on design codes for FRP bridge decks are suggested.

DESIGN EXAMPLE

For the purpose of the analyses, the GFRP deck, designed and analyzed in KICT (1), is selected as an example, as shown in Figures 1 and 2. The example bridge consists of a deck width of 12 *m* and is supported by five 40 *m* long steel girders spaced at 2.5 *m*. The cross section of the FRP deck has flanges and webs with a thickness of 12 *mm* and 9 *mm*, respectively. The webs are spaced at 150 *mm*.

The design is mainly considered to meet the deflection criterion of Span/425, which is 5.9 *mm* with the span length of 2.5 *m*. The deflection limit is same as the one specified for timber bridges in AASHTO (2).

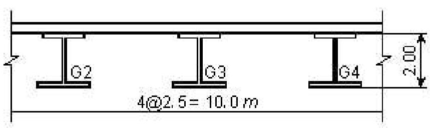

Figure 1. Bridge Cross Section

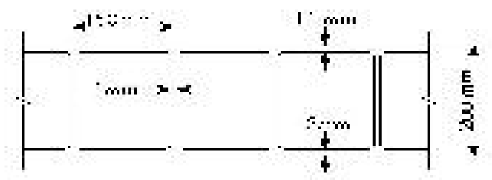

Figure 2. Cross Section of FRP Deck

This study also uses the results of structural analyses previously conducted using a general purposed FEM program and given in KICT (1). In the analyses, the live load was the standard design load DB-24 [MOCT (3)], which is approximately 1.3 times heavier than HS20 load [AASHTO (2)].

According to the results, the maximum deflection of the deck is 4.44 *mm*, which is within the allowable value of 5.9 *mm*. In addition, the results of Tsai-Hill failure analyses showed that the maximum Tsai-Hill failure index is 0.142 far below 1.0 compared to the failure strengths. The results can be interpreted that the deflection is Span/563, and the factor of safety for failure strength is a very high value of 7.0.

BACKGROUNDS OF RELIABILITY ANALYSES

Structures shall be designed to meet the requirements for safety and serviceability specified in design codes. This means that the resistances of structures shall sufficiently surpass the corresponding load effects. Resistances and load effects are random variables containing some degree of uncertainty. Thus safety is usually expressed in terms of reliability index obtained from reliability analyses based on the theory of probability.

In order to conduct reliability analyses, load and resistance models should be set up, and their statistical parameters such as means, and standard deviations are to be provided.

LOAD MODELS

In general, there are dead, live, and dynamic loads to be applied in the design of bridge decks. In this study, the dead load of FRP decks is reasonably assumed to be negligible. Live and dynamic load models are discussed as follows.

Live Load Model

For the analyses, the live load model is used, which was obtained from real measurements using BWIM [Kim et al (4); Nowak et al (5)]. The measurements were carried out without noticing drivers, consequently the results were proved to be quite accurate. From the results, statistical data on total weight, axle loads, and the distances between axles were obtained. In the design of bridge decks, wheel loads are used rather than total weight or axle loads.

The measured axle loads varied depending on the bridge locations, and the mean values were in the range of 40 to 55 *kN*. The maximum axle loads were measured at 13 locations, and they varied from 95 to 220 *kN*. The mean of maximum axle loads is about 200 *kN*, and the C.O.V is 0.12. An axle is usually composed of four wheels, thus a wheel load is 0.25 of the axle load. The mean value of a wheel load is 50 *kN*, and that of two wheels is 100 *kN*.

Dynamic Load Model

For the analyses, the dynamic load model is used, which was obtained from a numerical simulation model [Hwang and Nowak (6)]. The model was proved to agree well to the test results. Dynamic loads are considered as equivalent static loads combined with live loads. Based on the results, Nowak (7) proposed that the mean of dynamic loads be 0.15 of live loads and the C.O.V be 0.8, which are used in this analysis.

Load Combinations

The load combination is done using the statistical data on live and dynamic loads. The live load model is expressed as the multiplication of static live load *L* and analytical parameter *P*. The mean and C.O.V of *P* are 1.0 and 0.12, respectively, [Kim et al (4); Nowak et al (5)]. Thus V_{LP}, the C.O.V of LP, is assessed as 0.17 using the formula (1), where V_L = 0.12 and V_P=0.12 as discussed before.

$$V_{LP} = \sqrt{V_L^2 + V_P^2} \quad (1)$$

The mean of maximum live plus dynamic load (=LP+I) is 1.15 times of the live load, and the standard deviation (= σ_{LP+I}) of LP+I can be assessed from the formula (2). Then C.O.V (= V_{LP+I}) of LP+I is obtained as 0.21 using the formula (3).

$$\sigma_{LP+I} = \sqrt{\sigma_{LP}^2 + \sigma_I^2} \quad (2)$$

$$V_{LP+I} = \frac{\sigma_{LP+I}}{m_{LP+I}} \quad (3)$$

STATISTICAL PARAMETERS OF FRP MATERIALS

The flexural behavior of FRP bridge decks is influenced by not only section properties such as the moment of inertia and section modulus, but also material properties. FRP decks are formed with orthotropic material of which important properties are the modulus of elasticity, tensile strength, and Poisson's ratio in both parallel and perpendicular to fibers. Such statistical data of E-Glass/Epoxy produced in Korea are given in Table 1.

The data in accordance with KS show variations a little larger than those by other two test methods. In any case, the variations are small and consistent enough to show good quality control. Furthermore, it turns out to be possible that FRP producers can achieve a quite high target quality if ordered specifically, in Korea.

Table 1. Statistical Data on Material Properties Parallel with Fibers

Properties \ Test		ISO	ASTM	KS
Elastic Modulus (E1)	Bias Factor (λ)	1.22	1.23	1.07
	Mean (MPa)	48530	49174	42370
	C.O.V (%)	2.48	3.47	8.53
Poisson's Ratio (μ)	Mean	0.3279	0.3378	0.3420
	C.O.V (%)	4.8102	4.6955	9.6778
Tensile Strength (F1t)	Bias Factor (λ)	0.98	1.01	0.74
	Mean (MPa)	1074	1109	819
	C.O.V (%)	7.83	7.45	8.14

RELIABILITY ANALYSES

The limit state function g for failure strength is set as the equation (4). If g is greater than 0, the design is satisfied.

$$g = \frac{\sigma_u}{\sigma_d} \tag{4}$$

The stress σ_d produced in FRP decks is a function of the live load and geometrical data such as sectional properties, and it can be expressed as follows;

$$\sigma_d = L \times AFS \tag{5}$$

Where L is the live load, and AFS is a constant representing all the other factors that influence the stress calculations. AFS includes size and shape of sections, span of girders, etc. which are reasonably assumed to be deterministic. They are also random variables, but the variations are considered insignificant. Then AFS can be assessed from the condition of exact design in which the nominal stress is same as the allowable one as indicated in the equation (6). In calculating the stress, it is reasonably assumed that the stress is not affected by the modulus of elasticity contrary to the deflection.

$$(\sigma_d)_{nominal} = L_{nominal} \times AFS = \sigma_\alpha \tag{6}$$

From the equation (6), the constant AFS can be expressed as follows.

$$AFS = \frac{\sigma_\alpha}{L_{nominal}} \tag{7}$$

The allowable stress σ_a is determined by dividing $(\sigma_u)_{\text{nominal}}$ with the safety factor of FS as the formula (8).

$$\sigma_\alpha = \frac{(\sigma_u)_{nominal}}{FS} \tag{8}$$

Then by plugging the formula (8) into (7), AFS is obtained as the equation (9).

$$AFS = \frac{(\sigma_u)_{nominal}}{(FS)L_{nominal}} \tag{9}$$

Then the designed stress is expressed as the equation (10).

$$\sigma_d = L \times \frac{(\sigma_u)_{nomial}}{(FS)L_{nominal}} \tag{10}$$

Therefore, the limit state function g is expressed as the formula (11);

$$g = (FS)\frac{\sigma_u}{(\sigma_u)_{nominal}}\frac{L_{nominal}}{L} \tag{11}$$

Where the material strength σ_u and live load L are random variables, and the other nominal values are deterministic constants. In the case of FRP decks, live load means the rear wheel load.

As can be expected, the formula (11) clearly shows that the reliability index increases as the safety factor FS increases. In addition, the limit state functions for stresses are identical regardless of their types such as flexural, shear, or bearing stress.

By taking *log* at both sides of the formula (11), the following equation is obtained.

$$g = \ln(FS) + \ln\sigma_u - \ln(\sigma_u)_{nominal} - \ln L + \ln L_{nominal} \tag{12}$$

The limit state function (12) is a linear combination of normal distribution functions. Thus the reliability index β can be assessed as follows;

$$\beta = \frac{\ln(FS) + \overline{\ln\sigma_u} - \ln(\sigma_u)_{nominal} - \overline{\ln L} + \ln L_{nominal}}{\sqrt{(\sigma_{\ln\sigma_u})^2 + \sigma^2_{\ln L}}} \tag{13}$$

Where $\overline{\ln\sigma_u}$ and $\overline{\ln L}$ are the means of σ_u and *L*, and $\sigma_{\ln\sigma_u}$ and $\sigma_{\ln L}$ are the standard deviations of σ_u and L, respectively. Statistical data for the analyses, such as the bias factors and C.O.V's, are presented in Table 2.

From the formula (13), reliability indices are assessed, and indicated in Figure 3, which shows the variation of reliability index with respect to the ratio of allowable stress to nominal strength of the FRP material. For instance, if the ratio of allowable stress to strength is 0.5, equivalent to a safety factor of 2.0, then the reliability index is approximately 3.0. If the stress induced by loads is 20 % of the strength, equivalent to a safety factor of 5.0, then the reliability exceed over a very high value of 7.0. In the case of design example, the stress ratio is 0.142, thus the corresponding reliability is over 8.0, as shown in Figure 4. This proves that deflection criterion, rather than strength failure, governs the design.

In general, reliability analyses are performed to assess the safety for ultimate states, and the serviceability criteria are checked later. However, the deflection limit is the main concern in the design of FRP bridge decks, reliability analyses on deflection were also attempted. In the analyses, it is considered that the live load and elastic modulus are random variables, and other design factors are deterministic constants for simplicity.

Reliability analyses were performed using Rachwitz and Fiessler method, which can deal with nonlinear limit state functions and non-normal distributions. The statistical data for the analyses are taken from Table 2.

The main purpose of this analysis is not to determine the design criterion on deflection, but to compare with the reliability on the strength safety. The detailed procedure is not presented in this paper. Instead, the final results are shown in Figure 4.

As expected, in case the designed deflection is same as the allowable deflection, the reliability index is very low with a value of about 0.2. This means that the probability of exceeding the allowable deflection is very high. In the case of design example, the deflection is about 75% of the allowable value, thus the corresponding reliability is close to 2.0, as shown in Figure 4.

Table 2. Statistical Data for Reliability Analyses

Variation	λ	C.O.V	Distribution
Elastic modulus E	1.07	0.0853	Normal
Rear wheels L	1.05	0.20	Lognormal
Failure Strength	1.00	0.08	Lognormal

Figure 3. Reliability vs. Stress Ratio

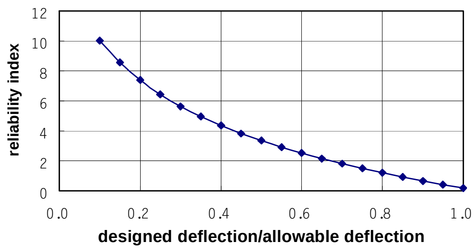

Figure 4. Reliability vs. Deflection Ratio

EVALUATION OF THE ANALYTICAL RESULTS

The level of safety specified in the design code is determined by the target reliability, which is theoretically the most optimum value considering the relationship between cost and reliability. In reality, it is difficult to determine such theoretical target values. Instead, the target reliability is established based on failure experiences and performances of existing structures. However, FRP structures lack such data due to the short history in the construction field.

The target reliability in current codes is approximately to be 3.0 for building structures and 3.5 for bridges. These levels of safety are based on the fact that failure modes are ductile, and materials are well proved to be safe through long-term uses. However, the reliabilities are much higher for brittle failure modes even in conventional materials and constructions. For instance, timber structures have reliabilities with a range of 3.5-6.5 [AASHTO (2)], and brittle connections may also have reliabilities over 6 or 7.

It is expected that higher target reliability index shall be used for FRP structures, considering the brittle failure modes and the degradation of material properties for long-term uses. In order to consider the degradation effect, it has been recommended to use 0.65 as a durability factor [FHWA (8)]. Based on such evaluations, it is suggested that the target reliability index for FRP bridge decks be at least 7.0, approximately equivalent to a safety factor of 5.0 as shown in Figure 3.

The main goal of the deflection limit is to provide comfortable use of bridges against vibrations due to live loads. The criterion for pedestrians is more severe than that for the drivers of vehicles because of the vibration absorbing system of vehicles [Demitz et al (9)]. In current design codes, deflection criteria are not specified for the bridge decks between girders, but specified for the girders between piers or abutments. The reasons seem to be that the deflection of bridge decks is small, and that pedestrians use sidewalks rather than decks, when they pass a bridge.

As deflection criteria, Korean Bridge Code specifies Span/800 for girders [MOCT (3)]. ASSHTO also specifies Span/800 for steel and reinforced concrete bridge girders, and L/425 for timber bridges [AASHTO (2)]. For FRP bridge decks, the deflection, not yet addressed in current codes, is tentatively recommended to be within the limit of Span/800 by FHWA (8).

Deflection criteria are expected to be required to FRP bridge decks, because deflection can be significant due to their low stiffness. Furthermore, the vibration frequency may become higher due to their reduced self-weight. The allowable amplitude shall be decreased as the frequency increases, because persons get more sensitive and uncomfortable to higher frequencies.

As in the case of degradation in strength, degradation of material properties shall also be considered for long-term use. Based on these evaluations, it is recommended that the deflection limit for FRP bridge decks be in the range of Span/600 to Span/800. At present, Span/800 seems to be conservative, however the value can be selected as the deflection criterion, until the long-term uncertainties turn out to be in the safe side.

CONCLUSIONS

Reliability analyses have been conducted on a design example of FRP bridge deck. The design is mainly considered to meet a deflection criterion of Span/425, which is 5.9 *mm* for the span length of 2.5 *m*. Structural analyses reveal that the maximum deflection of the deck is 4.44 *mm*. In addition, the results of Tsai-Hill failure analyses show that the maximum Tsai-Hill failure index is 0.142.

Regarding the design example, the reliability index is over a very high value of 8.0, which corresponds to the ratio of stress to failure strength having 0.142. The deflection is about 75% of the allowable value, and the corresponding reliability is close to 2.0. This proves that deflection criterion, rather than strength failure, governs the design of FRP bridge decks.

Design criteria on the failure strength shall consider not only the brittle failure modes but also the degradation of material properties for long-term use. Deflection criteria are expected to be required to FRP bridge decks, because deflection can be significant due to their low stiffness. Furthermore, the vibration frequency may become higher due to their reduced self-weight. The allowable amplitude shall be decreased as the frequency increases, because people feel more sensitive and uncomfortable to higher frequencies.

Based on such evaluations, it is suggested that the target reliability index for FRP bridge decks should be at least 7.0, approximately equivalent to a safety factor of 5.0. It is also recommended that the deflection limit on FRP bridge decks should be in the range of Span/600 to Span/800. At present, Span/800 seems to be conservative, however this can be selected as the deflection criterion, until the long-term uncertainties turn out to be in the safe side. This needs more research in the future.

NOTATION

FRP: Fiber Reinforced Plastics or Polymers
GFRP: Fiber Reinforced Plastics or Polymers
BWIM: Bridge Weigh-In-Motion
C.O.V: Coefficient of Variation (=Ratio of standard deviation to mean)
L: Live Load
P: Analytical Parameter in the Statistical Live Load Model
V_{LP}: C.O.V of the Multiplication of Live Load and Analytical Parameter
KS: Korean Standard
g: Limit State Function
AFS: Constant Representing Factors for Stress Calculations
σ_d : Designed Stress
σ_a : Allowable Stress
σ_u : Ultimate Strength
FS: Factor of Safety (=σ_u / σ_a)
β : Reliability Index
λ: Bias Factor, Ratio of Mean to Nominal Value
μ: Poisson's Ratio

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KEY WORDs

FRP bridge deck, Reliability, Deflection, Design Codes, Safety Factor, Ultimate Strength, Statistical Data, Vibration