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Sensitivity Analysis by Parametric Study of Load Factor for a Concrete Box Girder Railway Bridge Using Limit State Design

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Abstract

Reliability based limit state design method is replacing traditional deterministic designs such as allowable stress design and/or ultimate strength design methods in world trends. European design code(Eurocode) has adopted limit state design, and Korea road bridge design standard has also recently been transferred to limit state design method. In this trend, Korea railroad design standard is also preparing for adopting the same design concept. While safety factors are determined empirically in traditional design, load combinations as well as load factors are determined by solving limit state equations. General partial safety factors are evaluated by using AFORM(Advanced First Order Reliability Method) in the reliability based limit state design method. In this study sensitivity analysis is carried out for a dead load factor and a live load factor. Relative precisions of the dead load and the live load factors are discussed prior to the AFORM analysis. Furthermore the sectional forces of design and the material quantities required by two different design methods are compared for a PSC box girder railway bridge.

Keywords: *Railway bridge, Reliability based design, Limit State Design, Sensitivity analysis, Load factor,*

1. Introduction

1.1 Design methods

Allowable stress design(ASD) and ultimate strength design(USD) methods have been widely used for structural design as a deterministic design concept. The ASD is based on the elastic analysis in which a structural member shows elastic behavior under service loads. Because the elastic behavior is assumed in the ASD method, the principle of proposition is valid. Member stresses are evaluated for each predicted load. The most unfavorable combination stress should be below the allowable stress. The ASD method is usually used for steel structures that show elastic behavior. The stress-strain curve is assumed to be linear and the tensile bending stress of concrete is ignored for the reinforced concrete structure.

In the USD method, load factors as well as strength reduction factors are used to determine a proper section of a structure. The load and the strength reduction factors represent the statistical uncertainty of the action and the resistance in some degree. The design strength, that is the multiplied value of the nominal strength and the strength reduction factor, should be larger than the required strength which is the multiplication of the load factor and the service load. The strength reduction factor and the load factor reflect an uncertainty of the material property and the overload, respectively. The USD is usually used for concrete structures.

The ASD concept is simple but it may not be inadequate to account for the variability. Different load factors can be used in the USD depending on uncertainty the load, but it is more complicated than the ASD. For concrete railway bridges the USD is generally applied while the design is checked by the ASD afterwards.

Since 1980's there has been a great deal of research effort for developing the limit state design(LSD) method. The LSD adopts a reliability based design concept that explicitly accounts for the uncertainties safer and more economical designs compared with the traditional deter-

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ministic designs. The LSD has been recently adopted in Europe as a typical design concept replacing with the traditional ASD and USD. The reliability based design method such as LSD or LRFD(Load and Resistance Factor Design) has also been recently applied for design of road bridges as well as concrete and steel structure in Korea.

1.2 Limit state deign method

Traditional deterministic design uses safety factors to assess the safety. Because the structural resistance and the load are evaluated by the deterministic method, the safety factors in the traditional design method are determined empirically. In most cases, deterministic design can lead to not only an uneconomical design but also occasionally unsafe designs. The reliability based design method is Load and Resistance Factor Design(LRFD) developed in North America, and the LSD in Europe.

Load and resistance factors in the reliability based design method are developed from current statistical information or data on loads and structural performance and calibrated through the theory of reliability. A limit state in the design method is a specified structural condition, beyond which a structure or a component of a structure ceases to satisfy its intended design function. There are four limit sates in the AASHOTO LRFD, each with a corresponding set of load combinations.

- Service limit state that provides restrictions on stress, deformation and crack width
- Fatigue and fracture limit state that controls crack growth under repetitive load
- Strength limit state that provides strength and stability, locally and globally
- Extreme event limit state that ensures structure survival from an earthquake or other rare-occurrence events

For each load case in the four limit states, the following equation must be satisfied;

$$\sum \eta_i \gamma_i Q_{ni} \leq \phi R_n \tag{1}$$

Where,

R_n : nominal resistance

ϕ : resistance factor

Q_{ni} : nominal load effect

γ_i : load factor

η_i : load modifier

Limits states are classified into ultimate limit states and serviceability limit states in the Eurocode. The ultimate limit states concern the safety of people and the structure. The limit states that concern the functioning of the structure or structural members under normal use, the comfort of people, and the appearance of the construction works, shall be classified as serviceability limit states Design for limit states shall be based on the use of structural and load models for relevant limit states.

1.3 Reliability based design method

Both the LSD and LRFD use structural reliability based design concept. Structural reliability is the application of probabilistic principles to an evaluation of acceptable and unacceptable structural performance. Safety can be measured in terms of the probability of uninterrupted operation under a given set of conditions. In Korea, reliability based design method has been recently introduced in world trends. The deterministic steel and concrete structure design standards were replaced by reliability based design. The reliability based limit state design method was released as a Korea road bridge design criteria in 2012, and it is supposed to be used as an obligatory regulation for road bridge design from 2015. Especially the Eurocode adopts the reliability based limit state design for railway bridges as well as road bridges. The Eurocode consolidates the two design standards of road and railway into one. EN 1991(Eurocode 1) only defines actions on structures according to transportation system. Such unified criteria may be reasonable because both bridge types have similar shapes, forms, functions, and materials except for live load. Therefore, if the statistical parameters of railway live load are evaluated, the reliability based limit state design method for railway bridges can be established.

While the safety factor in the ASD determined empirically, the reliability based design method, the safety factor based on the probability of failure. It is defined using of the probability of failure(or the reliability index). It is possible that the reliability based design secures an uniform safety for structures and their components. Uncertainties of various design parameters are considered by their statistical data. Because individual partial safety factors can be determined according to characteristics of each design variables, it is essential to provide the statistical data. In this view, the statistical data of train live loads are required to establish the reliability based limit state design standard for railway bridges.

1.4 Evaluation procedure of reliability based load-resistance factors

Defining limit states is the first step in the establishment of reliability based design. Limit states can be classified into ultimate limit states and serviceability limit states as previously mentioned. A target reliability index is then determined for the limit states. Load and resistance factors shall finally be determined statistically such that the reliability of each case complies with the target reliability.

The target reliability index is determined in the range of 3.5~3.8 as a level of ultimate limit state(or strength limit state) in the Eurocode and the AASHTO LRFD, respectively. The reliability index is evaluated by Level II in which the statistical distribution of variables is assumed as independent normal distribution, and the index is estimated by the mean and the variation. In case that the statistical variables do not have normal distribution, Rackwiz-Fiezzler transform can be applied to transform the non-normal variable to the normal variable. In general, reliability index of 3.72 means failure probability of 1/10,000. The partial safety factors(resistant and load factors) can then be evaluated by AFORM(Advanced First Order Reliability Method) to assure the target reliability index. With the bias factor of individual design variable determined, the individual partial safety factor can be calculated, the bias factor means the ratio of mean value to nominal value.

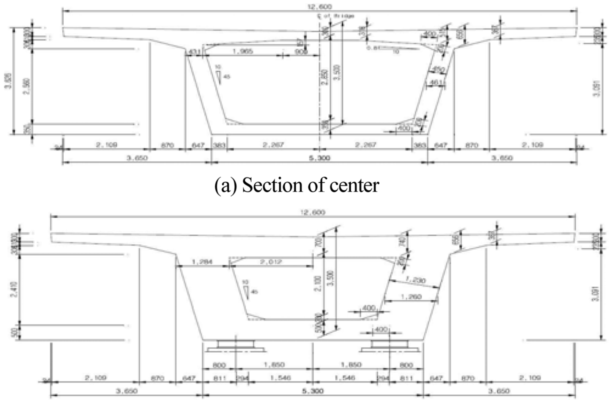
1.5 Objective of the Paper

The reliability based limit state design method has recently been adopted as structural design standards in Korea. The design standard for road bridges has been changed to the limit state design standard. In light of this trend in design criteria, the reliability based design method is expected to be introduced for rational and economic railway bridge design. Some specific steps are required to develop the reliability based design method for railway bridges.

- Generate load combination according to limit states
- Develop reliability based load and resistance factors
- Investigate the need for a new live load model
- Develop separate factors for load rating or modify the developed design factors
- Calibrate against existing simulated railway bridge designs

Load factors should be determined based on the statistical properties of loads in Korea. Prior to the preparation of full-fledged limit state design method for railway bridges, sensitivity of load factor is investigated to each load combination of the limit states in this paper. The results can be used to determine load factors adequate for domestic circumstances in Korea.

A high-speed railway bridge, which was designed in the past according to the Korean Railway Bridge Design Code(KRBDC), has been redesigned by using the limit state design method of the Eurocode in this paper. The total weight decrement of rebar in the redesign is evaluated, and the sensitivity of each load factor is then analyzed



(a) Section of center

(a) Section of support

Fig. 1 Girder sections by the current design specification

Table 1 Load factors in the KRBDC

Load case	D	PS	L	W	T
LC 1	1.4	1.0		1.4	
LC 2	1.45	1.0	1.45		
LC 3	1.8	1.0	1.80		
LC 4	1.4	1.0	2.33		1.4
LC 5	1.4	1.0	1.4	1.4	1.4

Table 2 Load factors in the Eurocode

Load case	D	PS	L	W	T
ULS1	1.35	1.0	1.45		
ULS 2	1.35	1.0	1.45		0.9
ULS 3	1.35	1.0		1.5	
ULS 4	1.35	1.0	1.45	1.5	0.9
ULS 5	1.35	1.0	1.45	1.4	0.9

2. Comparison of Design Sections by Two Design Methods

2.1 Bridge for analysis

The object of the high speed railway bridge in this study is a representative PSC-box girder-bridge on the Ho-nam high speed railway line. Its span length, width, and height are 35 m, 12.6 m, and 3.5 m, respectively. Fig. 1 shows the cross sections of a simply supported girder bridge designed according to KRBDC.

The design compressive strength of concrete, design yield strength of rebar, and the design yield strength of tendon are 40 MPa, 400 MPa, and 1,880 MPa, respectively.

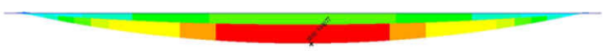
Table 1 and 2 show prescribed load cases in the KRBDC and the Eurocode, respectively. Because main sectional force is induced vertically and the girder is single span, thermal load(T) and wind load(W) do not affect the girder behavior. Midas Civil, a structural analysis software was used for structural design. Applied loads(live load, self-weight, secondary dead load, wind load, thermal load) are identical as those used in the design for Honam high speed railway line.

Five dominant load cases are considered for strength design criteria of PSC box girder in the KRBDC. In the Eurocode, combination factors are considered for ultimate limit states of permanent action, leading variable action, accompanying variable action. Load factors are shown in Table 1 and 2 for the KRBDC and the Eurocode, respectively. The limit sectional moment and shear force are evaluated for normal design state load factors.

2.2 Material quantity comparisons by two design methods

Fig. 2 and Fig. 3 show the bending moment and shear force diagrams for a 35 m-long simply supported girder, respectively. It can be seen that the ultimate sectional forces by the KRBDC are approximately 20% larger than those by the Eurocode. The reason for this difference is that the load factors in KRBDC are larger than those in the Eurocode. Because combination factors are determined using the reliability based statistical method, it is regarded that combination factors by the Eurocode are rational and efficient. The number of tendons can be reduced due to the reduction of the ultimate sectional forces by the Eurocode. Furthermore, the quantity of concrete also can be reduced by controlling sectional thickness.

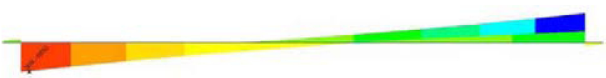
The required quantity of rebar is calculated by lateral investigation for each section at the center and support. The required quantity of main reinforcement is reduced by



(a) Application of the KRBDC (M_u=148.0 MN m)

(b) Application of the Eurocode (M_u=113.8 MN m)

Fig. 2 Bending moment diagrams



(a) Application of the KRBDC (V_u=18.7 MN)

(b) Application of the Eurocode (V_u=15.7 VN)

Fig. 3 Shear force diagrams

11% in design of the Eurocode compared with that in the KRBDC. The required quantity of main reinforcement is evaluated as 63.91 ton and 56.97 ton for the application of the KRDBC and the Eurocode, respectively.

3. Sensitivity Analysis of Combination Factors

3.1 Considered parameters

Sensitivity analysis is performed study how the uncertainty of each combination factor in the Eurocode can be apportioned to sectional force by load combinations in each ultimate limit state. The target reliability index (β_t) is established considering the design life time of each member. After establishing β_t, coincidental load factor and resistance factor are evaluated. The combination factor as a partial safety factor can be evaluated by AFORM to guarantee β_t, so it cannot be an integer but an infinite decimal. However, a partial safety factor of simple form is needed to use for practical design. Because even a small change of the factor can control billions of construction cost, it may be meaningful to analyze the sensitivity of load according to load factor. Since the structure analyzed in this paper is a simply supported box girder, factors only for dead load and live load are selected for this sensitivity analysis. Therefore, Eq. (1) can be transformed to Eq. (2)

$$\gamma_D Q_D + \gamma_L Q_L \leq R_r \quad (2)$$

Where,

R_r : factored resistance

Q_D : modified dead load effect

Q_L : modified live load effect

γ_D : load factor for dead load

γ_L : load factor for live load

3.2 Effect of each parameter

As shown in Table 2, the load factors are 1.35 and 1.45 for dead load and live load of ultimate limit state in the Eurocode, respectively. These values are selected as a reference in this study. The change of sectional force is evaluated according to ±20% independent change for each load factor from the reference values. Fig 4 shows the analysis results. The vertical and the horizontal axes represent sectional force and self-normalized load factor(1.35 for Dead load and 1.45 for Live load), respectively.

Fig. 4 shows that the rate of change in sectional force is influenced by permanent load factor more than live load factor, which implies that the dead load factor can have more influence to the construction cost of railway bridges compared with the live load factor. This means that the permanent load factor provides more sensitive effect to

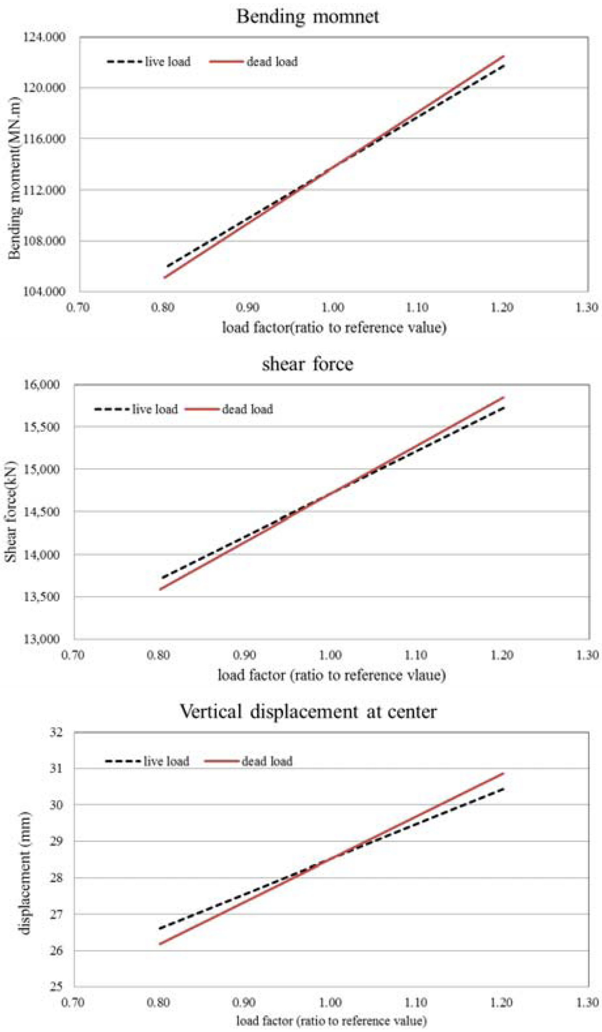


Fig. 4 Sensitivity of sectional force to load factors

sectional force than live load factor. Most of permanent load(or dead load) is the girder self-weight, which has generally increased reliability among various loads.

Sensitivity of dead load factor is 11% and 9% larger than that of live load factor for moment and shear force, respectively. Sectional force has effect on economics of structure by decision of girder size. Dead load governs the economic design of structure under ULS compared with live load. Load factors are determined by AFORM with reliability analysis under the target reliability. The resultant values can be evaluated according to the variability and reliability. This paper shows that the precision of dead load factor should be higher than that of live load. When the reliability based limit state design method is introduced, the precision of load factor for each limit state should be decided by sensitivity analysis for more rational factors hereafter.

4. Conclusion

A girder section was designed conforming to KRBDC for railway bridges on the Honam high speed railway line. The girder section designed by the Eurocode was compared with the section by KRBDC. It was shown that the sectional force and required main reinforcement can be reduced by approximately 20% and 11%, respectively. This implies that the reliability based limit design method can provide more economic design than the current KRBDC.

Sensitivity analysis also revealed that the dead load factor was about 10% more sensitive than the live load factor for sectional forces. This implies that the dead load factor should be more precise than the live load factor. Because the dead load can be more reliably predicted than the live load, the dead load factor can be lower than the live load factor, as shown in Table 2. The live load factor is usually determined based on a great deal of measured data, but it should be noted that the dead load factor also should be determined with more measured data collection accordingly to the sensitivity analysis, in this paper.

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