Design Life and Reliability-based Design Concept for Long-Span Cable-Supported Bridge

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Summary

The basic design concepts for the limit state design code under development in Korea for the long-span cable-supported bridge are presented. Considering the importance of the structure, higher target reliability level and longer design life are defined compared to those of the ordinary bridges. In deciding the amount of safety increase, the construction cost and the consequence of structural failure are examined. Safety factors including the importance factor which is multiplied to the design strength of the structural member are calibrated through reliability analysis of the actual design examples. It is also shown that the nonlinear analysis of the cable-supported bridge yields higher reliability index of the main cable than that obtained by the linear analysis.

Keywords:long-span cable-supported bridge; design life; reliability index; construction cost; safety factor format; importance factor; nonlinear analysis.

1. Introduction

In this paper, the safety concept of the long-span cable-supported bridge (LSCSB) design is discussed. With higher target reliability and longer design life, the design load models and the load combinations for the design of the LSCSB are under proposing in Korea. The enhanced safety is taken into account by multiplying the modification factor to the load factors in the design load combination. The safety factors in the proposing code are determined after conducting probabilistic study. The statistical properties for the loads and the resistances are based on the domestic field data as well as the relevant references. The safety level of the design load combinations for the strength limit state and the extreme event limit state are under examination and a brief result is shown in this paper.

In addition, depending on the importance of the structural members such as the main cable, the pylon and the stiffened girder, the member importance factor is multiplied to the design strength of the member. For the purpose of classifying the member importance factor, the actual design works of the cable-stayed bridges and the suspension bridges are collected. The relative safety levels of the current design are calculated and the reliability indexes along the entire length of the main members are presented.

It is also presented by numerical example that the nonlinear analysis of the cable-supported bridge yields higher reliability index than that obtained by the linear analysis with the same safety factor for the design of the main cable.

2. Determination of target reliability

2.1 Importance of structure

In order to determine a proper safety level for the design of long-span cable-supported bridges, the definition of the relative importance and the design life among different structural types is required. In this research, the probabilistic and statistical definition of the safety level of structural design is reviewed. In addition, a background study is conducted to come up with a rational safety level for the design life of the LSCSBs.

The design life of structures is well summarized in the designer's guide to Eurocode [1]. Ordinary building structures and civil engineering structures are categorized to select the reliability level corresponding to the consequences of failure in the guide. Structures can be classified in 3 levels according to the importance as well as the reliability. The target reliability level of 1 year for the ultimate limit state(ULS) can be assigned and the corresponding target reliability index for the design life of the structure, 50 years, for example, could be defined.

In AASHTO LRFD Bridge Design Specification [2], the design life is defined for the statistical derivation of transient loads and is based on 75 years. The design formula for the limit state involves the importance factor which is multiplied to the load side among other safety factors. The importance factor for the important bridges may be 1.05 compared to 1.00 for ordinary bridges. The basic value of the target reliability index for the specification is 3.5 for the strength limit state and the effect of 5% increase in the safety factor results in the increase of the reliability index to 3.8, approximately.

The recently issued bridge design code in Korea (KBDC (2012)) [3] is also based on 75 years of design life and the target reliability level of 3.5 for the ordinary short or middle span bridges. Considering the importance and the budget involved in the construction and the operation of the LSCSBs, the required reliability level as well as the design life should be reasonably determined.

An example is shown in Table 1 in which the reliability index can be selected as 4.0 for LSCSB compared to 3.5 for the ordinary bridges. Also, the design life can be increased up to, for example, 100, 150 or 200 years of time period compared to 75 years. The outcome of the decrease in the yearly probability of failure is approximately by the amount of 1/10, 1/15 or 1/20, respectively.

Table 1 : Example Target Reliability Index and Design Life of Long-Span Cable-Supported Bridges

Bridge Type	Target ReliabilityIndex β	Design Life (year)	Probability of Failure based on		
			Design Life	1 year	Ratio
Ordinary Bridge	3.5	75	2.33×10^{-4}	3.10×10^{-6}	1
Long-Span Cable-Supported Bridge	4.0	100	3.17×10^{-5}	3.17×10^{-7}	1 / 9.79 ≒ 1 / 10
		150	3.17×10^{-5}	2.11×10^{-7}	1 / 14.7 ≒ 1 / 15
		200	3.17×10^{-5}	1.58×10^{-7}	1 / 19.6 ≒ 1 / 20

* Ratio of 1 yr. probability of failure of Long-Span Cable-Supported Bridges to that of ordinary bridges.

2.2 Construction and recovery costs of bridge

2.2.1 Construction costs of bridge

When the long-span cable-supported bridge is constructed instead of the ordinary bridge in the same site, the construction costs requires more. When viewed simply in terms of construction costs, the probability of failure of the long-span cable-supported bridge should be lower than that of the ordinary bridge.

Table 2 and 3 show the construction costs per unit slab section of the ordinary bridges and those of the long-span cable-supported bridges, respectively. Although there are differences depending on the type of bridge, the average construction costs per unit slab section required 2.3 million won for the ordinary bridges and 9.6 million won for the long-span cable-supported bridges(suspension bridge : 10.8 million won, cable-stayed bridge : 8.3 million won). The construction costs per unit slab section of long-span cable-supported bridges are around four times those of the ordinary bridge. Thus the probability of failure of the long-span cable-supported bridges should be one fourth of that of the ordinary bridge.

Table 2 : Average Construction Costs per Unit Slab Section($1m^2$) of Ordinary Bridges

[unit : 10^3 KRW]

Bridge Type	PSC Beam	Steel Girder	Composite Girder	Rahmen
Costs	1,685	2,307	2,636	2,702

Table 3 : Average Construction Costs per Unit Slab Section($1m^2$) of Long-Span Cable-Supported bridges

[unit : 10^3 KRW]

Bridge Type	Suspension Bridge		Cable-stayed Bridge	
	Ulsan Bridge (1,150m)	LeeSunShin Bridge (1,545m)	Handol Bridge (500m)	Bukhang Bridge (540m)
Costs	11,380	10,570	8,070	8,590

2.2.2 Recovery costs of bridge

The bridge collapse causes a huge loss to human life and property. Assuming a situation when the long-span cable-supported bridge collapses, the recovery costs concerning the damage to human lives and properties are expected to be much larger than those of the ordinary bridges. In view of the recovery costs, the probability of failure of the long-span cable-supported bridge should be lower than that of the ordinary bridge. The targeting span lengths of the ordinary bridge design specifications are usually less than 200m. If the length of the main span is longer than 1000m for the long-span cable-supported bridge, the probability of failure should be about one-fifth of that of the ordinary bridge because the recovery costs due to the damage to human lives and properties are expected to be more than five times those of the ordinary bridges.

2.2.3 Target probability of failure of long-span cable-supported bridge

It was referred that the probability of failure of the long-span cable-supported bridges should be one-fourth and one-fifth of that of the ordinary bridge considering the construction cost and the recovery cost, respectively. The target probability of failure for 1-year reference period of LSCSB is suggested based on the above consideration.

2.3 Safety factor format

The safety factor format for the design of the LSCSBs adopts similar concepts to the recently issued domestic bridge design code, KBDC (2012) [3] and is shown in equation (1).

$$\sum \gamma_i Q_i \leq \phi_{imp} R_r \quad (1)$$

in which γ_i is the load factor, Q_i is the load effect, ϕ_{imp} is the importance factor and R_r is the design resistance. Note that the design resistance $R_r = R\{\phi_k X_k\}$ for the concrete member is obtained by applying the material resistance factors ϕ_k to the characteristic values of the material strength X_k. The partial factor format which includes the material resistance factors are well explained in the Model Code 2010 [4]. The design resistances of other members $R_r = \phi R_n$ are obtained by applying the member resistance factor ϕ to the nominal member strength R_n. Note also that the importance factor in Eq. (1) is applied to the resistance side instead of the load side as is in the KBDC (2012).

The safety factors applied in Eq. (1) are being calibrated and some of the results are presented in this paper. For the main cable, the stiffened girder and the concrete pylon, the reliability indexes for the dominant load combinations for the design of each member are calculated and the effect of applying the importance factor is examined. The information for the analysis models of the example cable-supported bridges which were proposed to the design projects are obtained from the domestic design offices.

The load combinations and the resistance factors for the proposed design manual for the LSCSB are based on those of the KBDC (2012). The load combination for live load is $1.25D_1 + 1.5D_2 + 1.8(L+I)$ in which D_1 is the dead load, D_2 is the weight of the wearing surface, L is the live load and I is the impact. The wind load combination is $1.25D_1 + 1.5D_2 + 1.4W$ in which W is the wind load. The earthquake load combination is $1.0D + 1.0EQ$ with EQ denotes the earthquake load.

The resistance factors are shown in Table 4. For the steel and cable members, the member resistance factors are defined and the material resistance factors are set to unity. On the contrary for the concrete members, the material resistance factors are defined and the member resistance factors are set to unity.

Table 4 : Resistance Factors for the Ultimate Limit State

Type	Member Resistance Factor ϕ		Material Resistance Factor ϕ_k	
Steel	Flexure	1.00		1.00
	Shear	1.00		
	Compression	0.90		
Cable		1.00		1.00
Concrete		1.00	Concrete	0.65
			Rebar or PS tendon	0.90

The importance factors are defined as shown in Table 5 according to the structural type of cable-supported bridges. The target reliability level for the steel girder and the concrete pylon is 4.0 which is larger than 3.5 of ordinary bridge members. The target reliability for the main cable of the suspension bridge is 8.8 and that for the stayed cable for the cable-stayed bridge is 7.8. The importance factors are selected in order to achieve the corresponding target reliability level of the major structural component for the LSCSB. The safety factor sets as defined in Tables 4 and 5 are applied to the example cable-supported bridges and the reliability level obtained is reviewed in the next section.

Table 5 : Structural Importance Factor

Structure Type	Importance Factor ϕ_{imp}
Steel Girder	0.95
Main Cable for Suspension Br.	0.58~0.68
Stay Cable	0.67~0.73
RC Pylon	0.85

3. Safety level of design load combination

3.1 Statistical properties of design parameters

The statistical characteristics for the material strength are obtained by collecting the material test data from domestic construction sites and steel manufacturing companies [5].The compressive strength of concrete and the tensile strength of cables for the suspension bridge, the cable-stayed bridge and the pre-stressing tendon are collected and statistically analysed. The mean value and standard deviation are calculated for the material strengths and the goodness-of-fit tests such as the Chi-square test and the Anderson-Darling test are performed in order to find the proper distribution type for the data. Most data satisfy the normal distribution and lognormal distribution.

The strength and the statistical properties of RC pylon section are calculated by writing a computer program. Typical shapes of the pylon section can be analyzed by assigning the information of the sections and the statistical properties of the design parameters involved. Fig. 1 is an example of the program output window.

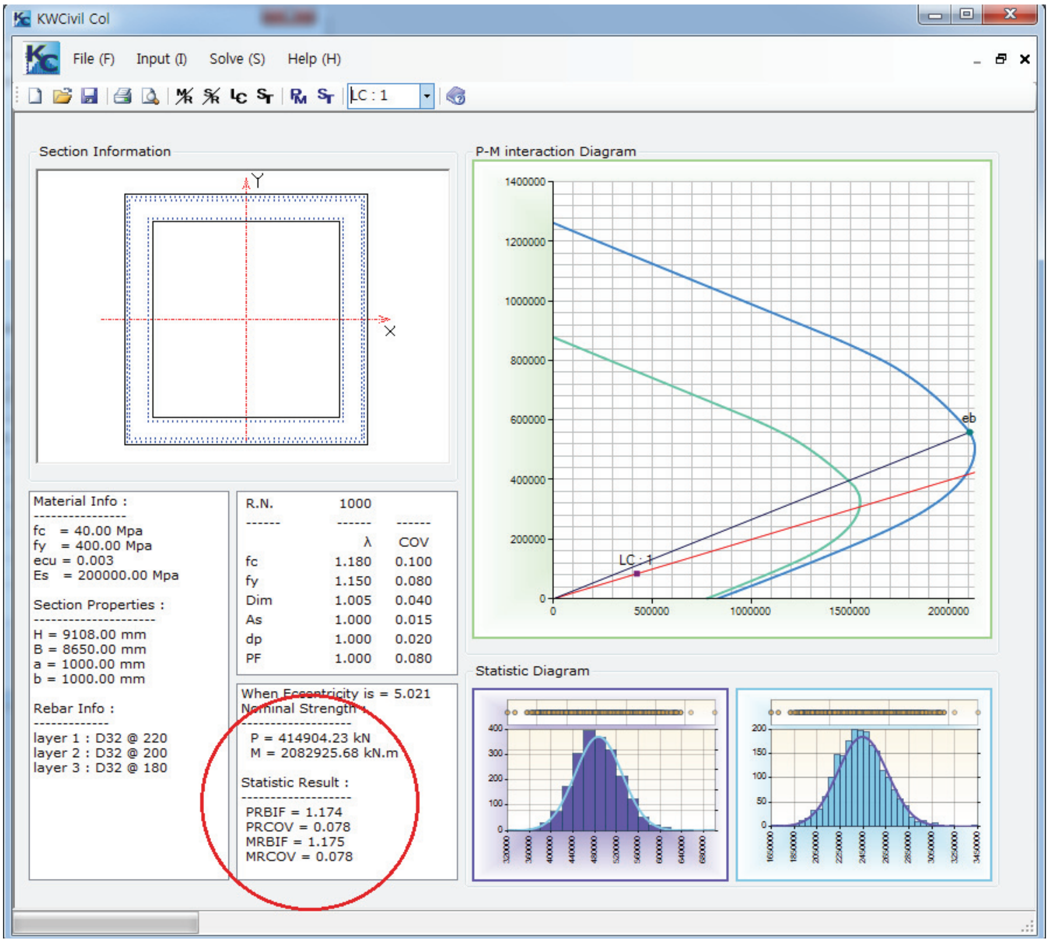


Fig. 1: Output of PM Diagram and StatisticalCharacteristics for RC Pylon

3.2 Reliability of main members

In order to determine a reasonable range of the importance factors for the main members of the LSCSB, reliability analysis is conducted. The statistical properties obtained from the statistical analysis of the available data as shown in the previous section are utilized in the analysis. Also, the relevant values for the statistical properties of the loads and the resistances are adopted from the reference [6].

The reliability level for the stiffened girder is calculated when the design live load model is applied to a real cable-supported bridge. The effect of the importance factor on the reliability index is examined by decreasing the importance factor from 1.00 to 0.85 and the result is shown in Fig. 2. As the importance factor decreases by the amount of 0.05, the results in this figure indicates that the reliability index increases approximately by the amount of 0.25. It can be observed from this result that the importance factor of 0.95 ensures the reliability index above 4.0 for the entire span.

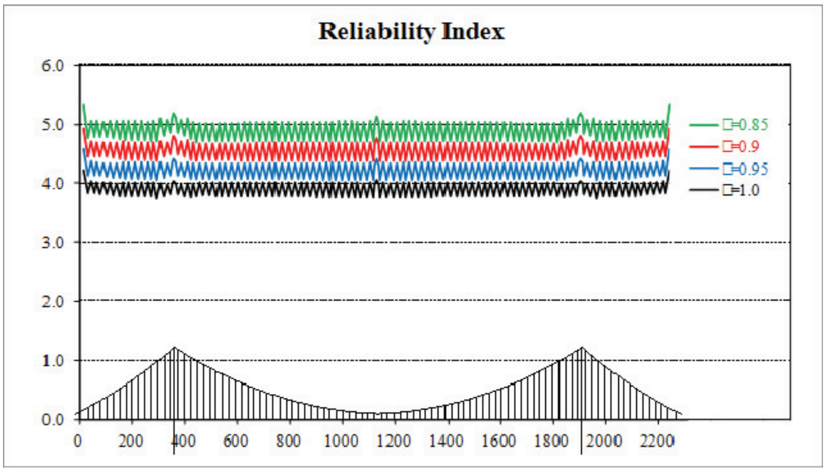


Fig. 2: Effect of the Importance Factor on the Reliability Index of Stiffened Girder

The design load combinations which control the design of the RC pylon are the wind load combination and the earthquake load combination. The reliability index for these load combination is calculated for a pylon of a real cable-supported bridge. Fig. 3 shows the reliability index at the representative sections of the pylon. The reliability index for KBDC (2012) of which the importance factor is 1.0 is the lowest and is above 3.5. When the importance factor of 0.85 for the proposed design manual for LSCSB is applied, the values of the reliability index increase by the amount of approximately 0.5 and satisfy the minimum value of 4.0. The reliability index of the real pylon design is also compared in the figure.

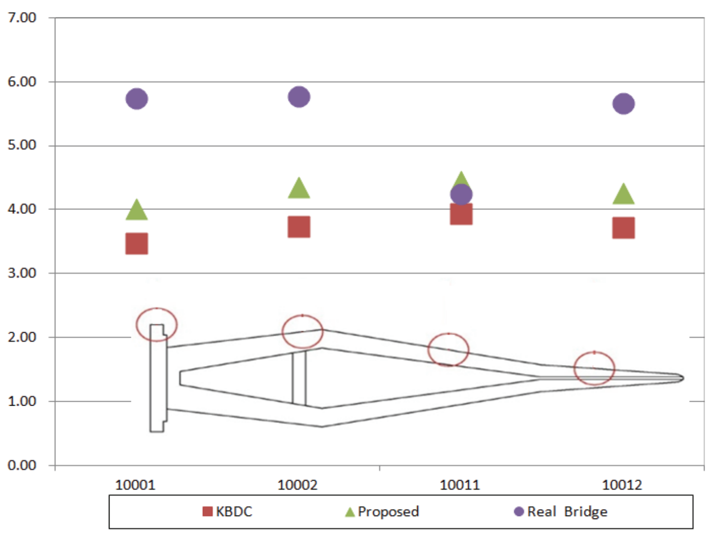


Fig. 3: Reliability Index of RC Pylon for wind load

3.3 Effect of nonlinear analysis

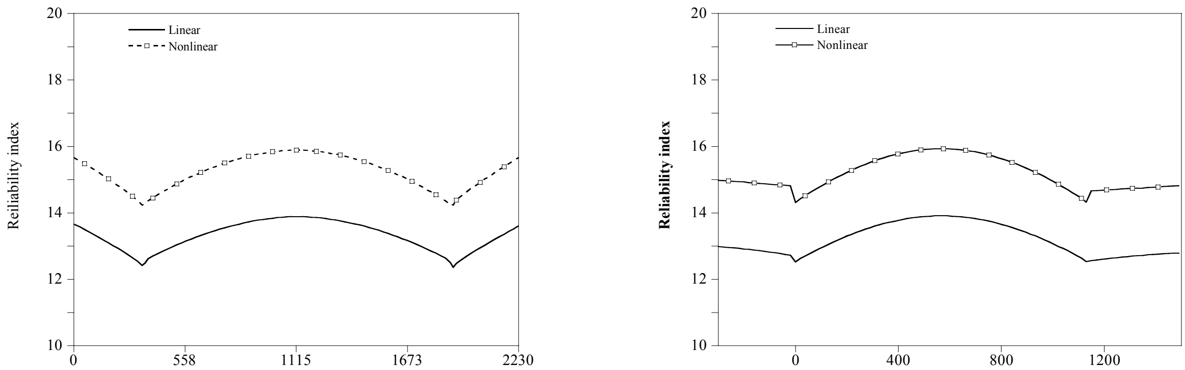
Because the cable-supported bridge shows the geometrical nonlinear behavior, the traditional reliability analysis method,which is applied to the ordinary bridge or the linear system, cannot appreciate the behavior of the cable-supported bridge sufficiently.

Table 6summarizes and compares both of the reliability analysis method for the cable-supported bridge. The reliability index could be calculated by linearization assumptions in cable members, or it could also be calculated by considering the geometrical nonlinearity of cable members, through the 'linear' or 'nonlinear' analysis method, respectively.

Table 6 : Limit State Functions (Linear Analysis vs. Nonlinear Analysis)

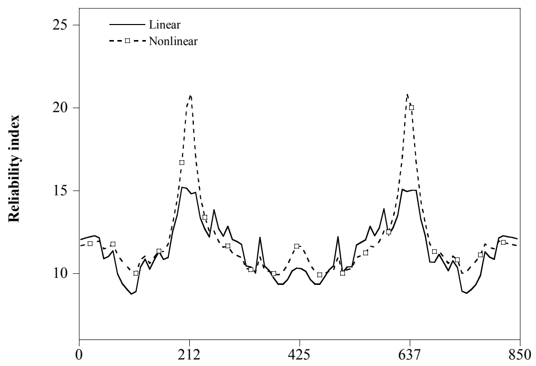
Linear Analysis	Nonlinear Analysis
- Limit State Function $g = R(f_u) - T(w_{DC}, w_{DW}, w_{VL})$ $= R(f_u) - T(w_{DC}) - T(w_{DW}) - T(w_{VL})$ where $a = \left.\frac{\partial g}{\partial w}\right\|_{\mathbf{w}=\mathbf{w}_0}$ $T(w_{DC}) = a \cdot w_{DC}$, $T(w_{DW}) = a \cdot w_{DW}$, $T(w_{VL}) = a \cdot w_{VL}$	- Limit State Function $g = R(f_u) - T(w_{DC}, w_{DW}, w_{VL})$ - Sensitivity of Response Function $\mathbf{K}_F \frac{\partial \mathbf{u}}{\partial \mathbf{w}} + \sum_e \frac{\partial \mathbf{F}_c^{\,e}}{\partial \mathbf{w}} = \mathbf{K}_F \frac{\partial \mathbf{u}}{\partial \mathbf{w}} + \sum_e (\mathbf{K}_C^{\,t})^e \frac{\partial \mathbf{u}^e}{\partial \mathbf{w}} = \frac{\partial \mathbf{P}}{\partial \mathbf{w}}$ $\frac{\partial \mathbf{u}}{\partial \mathbf{w}} = \left(\mathbf{K}_F + \mathbf{K}_C^{\,t}\right)^{-1} \frac{\partial \mathbf{P}}{\partial \mathbf{w}}$
- Sensitivity of Limit State Function $\frac{\partial g}{\partial w_{DC}} = \frac{\partial g}{\partial w_{DW}} = \frac{\partial g}{\partial w_{VL}} = -a \quad \frac{\partial g}{\partial f_u} = A_C$	- Sensitivity of Limit State Function $\frac{\partial g}{\partial \mathbf{w}} = -\frac{\partial \mathbf{T}(\mathbf{u})}{\partial \mathbf{w}} = -\frac{\partial \mathbf{T}}{\partial \mathbf{u}} \frac{\partial \mathbf{u}}{\partial \mathbf{w}} \quad \frac{\partial g}{\partial f_u} = A_C$

Two reliability indices are calculated by the linear orthe nonlinear analysis about the actual bridge design model. The results are shown in Fig.4 and 5.

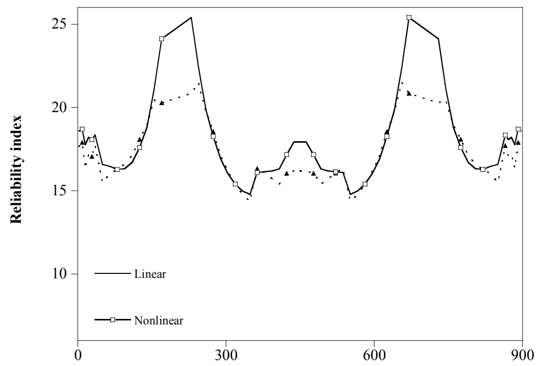


(a) LeeSunShin Bridge (b) Ulsan Bridge

Fig. 4: Reliability Index of 2 Suspension Bridges by Linear/Nonlinear Analysis



(a) HwayangBirdge



(b) Mokpo Bridge

Fig. 5: Reliability Indexof 2 Cable-stayed Bridges by Linear/Nonlinear Analysis

4. Conclusion

The ongoing research project for the development of the design manual of the long-span cable-supported bridge is presented. The target safety level is increased considering the importance of the structure and the design safety factors are calibrated by the reliability analysis. The reliability levels of the major members of the cable-supported bridge are obtained by applying to the actual cable-supported bridges and the corresponding safety factors to fulfill the required reliability could be decided. It is also presented that the nonlinear analysis of the structure results in the higher reliability index than the linear analysis.

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