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Differentiation of Target Reliability and Design Life in Design of Long-span Cable-supported Bridges

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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 (LSCSB) are presented. Considering the importance of the structure, higher target reliability level is defined compared to that of the ordinary bridges. Regardless of design life, the target reliability index is only defined by importance class. But the difference in design life makes the difference in the 1-year probability of failure when the target reliability index with respect to the corresponding design life is fixed. For the repairable or replaceable components, the target reliability of them could be guaranteed during their service life even if the target reliability is applied relatively low with respect to the design life of the bridge. The target reliability indices for cable elements are determined with reference to the results of reliability assessment.

Keywords: long-span cable-supported bridge; limit state design; importance class; design life; probability of failure; reliability index; target reliability

1. Target reliability according to the importance class and design life

Five importance classes for structure are suggested with reference to the Eurocode EN 1990. Table 1 shows the details with respect to the five importance classes for structure. For the general cable-supported bridges, the importance class is 3 and the corresponding target reliability is 3.7. On the other hand, for significant cable-supported bridges, the importance class is 2 and the corresponding target reliability is 4.0. The long-span cable-supported bridges are generally classified as highly significant structures, but the importance class can be decided by the owner, responsible organization or designing engineer.

Table 1 : Importance Class of Structures

Importance class	Degree of importance	Examples of buildings and civil engineering works	Values for β (Ultimate Limit State)	Reference (Eurocode EN 1990)
Class 5	Low	Agricultural buildings, Green houses	3.09 (P_F=10^{-3})	CC1
Class 4	Medium	Residential and office buildings	3.42 (P_F=3.16×10^{-4})	Geometric mean of CC1 & CC2
Class 3	High	Public buildings, Ordinary bridges, **Cable-supported bridges**	3.72 (P_F=10^{-4})	CC2
Class 2	Very High	**Significant cable-supported bridges**	4.00 (P_F=3.16×10^{-5})	Geometric mean of CC2 & CC3
Class 1	Extremely high	Nuclear power reactors, Major dams and barriers	4.26 (P_F=10^{-5})	CC3

2. Target reliability for replaceable or repairable components

The target reliability for the secondary component needs not be as high as that for the primary component, and the target reliability for the repairable or replaceable with respect to the design life needs not be as high as that for the permanent components. Table 2 shows the target reliability differentiation for components according to the element classification and design life in case that the class 2 cable-supported bridge for which the design life is 200 years.

Table 2 : Target Reliability for Components (Class 2 bridge for which the design life is 200 years)

Element Classification		service life	Values for β (Ultimate Limit State)						
			1 year reference period		reference period				
			β	P_F	20 year	30 year	50 year	⋯	200 year
Primary components	Permanent components	200 year	5.11	1.58×10^{-7}	-	-	-	-	**4.00**
	Replaceable or Repairable components	20 year	4.66	1.58×10^{-6}	**4.00**	⋯	⋯	⋯	**3.42**
		30 year	4.74	1.05×10^{-6}	-	**4.00**	⋯	⋯	**3.53**
		50 year	4.85	6.32×10^{-7}	-	-	**4.00**	⋯	**3.66**
Secondary components	Replaceable or Repairable components	20 year	4.42	5.00×10^{-6}	**3.72**	⋯	⋯	⋯	**3.09**
		30 year	4.50	3.33×10^{-6}	-	**3.72**	⋯	⋯	**3.21**
		50 year	4.61	2.00×10^{-6}	-	-	**3.72**	⋯	**3.35**

3. Target reliability for cable elements

The reliability assessment for the cable elements is carried out with respect to three bridges. Table 3 shows the results of the reliability assessments for the cable elements. The target reliability indices for the stay cable of cable-stayed bridge and that for the main cable of the suspension bridge are determined 6.0 and 7.0, respectively.

Table 3 : Reliability indices for cable elements

		Stay cable of cable-stayed bridge	Main cable of Suspension bridge	
		Incheon Bridge	Yi Sun Sin Bridge	Ulsan Bridge
Design resistance		9.25	7.85	8.18
Required resistance	S.F.=2.5	-	7.51	7.36
	S.F.=2.2	6.19	6.51	6.39
	S.F.=2.0	5.43	5.77	5.67
	S.F.=1.8	4.58	-	-

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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 (LSCSB) are presented. Considering the importance of the structure, higher target reliability level is defined compared to that of the ordinary bridges. Regardless of design life, the target reliability index is only defined by importance class. But the difference in design life makes the difference in the 1-year probability of failure when the target reliability index with respect to the corresponding design life is fixed. For the repairable or replaceable components, the target reliability of them could be guaranteed during their service life even if the target reliability is applied relatively low with respect to the design life of the bridge. The target reliability indices for cable elements are determined with reference to the results of reliability assessment.

Keywords: long-span cable-supported bridge; limit state design; importance class; design life; probability of failure; reliability index; target reliability

1. Introduction

In recent years, the design codes for bridges, such as Eurocode EN 1990 [1] and AASHTO LRFD [2], are adopting the limit state design method instead of the allowable stress design method. In Korea, extensive researches have been conducted by Korea Bridge Design Research Center in order to introduce the limit state design method to the bridge design code. As a result, *Highway Bridge Design Code (Limit State Design Method)* [3] is enacted and it is in the stage to be applied to the actual design of bridge nationwide.

In the ongoing project by the Super Long Span Bridge R&D Center in Korea, it is decided that the safety level needs to be determined in terms of probabilistic and statistical manner and various researches are performed for the writing of the draft of the design manual for LSCSB.

In this paper, the target reliabilities of the structures are differentiated by the importance and the design life. And the differential application of target reliability is shown for the repairable or replaceable components. In addition, the reliability assessment for cable element is shown for three cable-supported bridges in Korea and the target reliability indices for cable elements are presented with reference to the results.

2. Design philosophy relating to design life

In order to determine the target reliability of long-span cable-supported bridge (LSCSB), the philosophical consideration about the design of bridge is needed. Eurocode EN 1990 [1] is a representative design specification in which design philosophy is described in detail. In Eurocode the design life is indicated and the class of the structures is recommended for the consequence of failure and the cost of construction. In the code the reliability differentiation for the class of structure is made based on the 1 year reference period.

In Eurocode EN 1990, the design (working) life of structure is defined as "assumed period for which a structure or part of it is to be used for its intended purpose with anticipated maintenance but without major repair being necessary", and the design life of 50~100 year is indicated with respect to the building or the bridge.

Eurocode EN 1990 defines quantitatively three consequence classes (CC) according to the consequences of failure or malfunction of a structure. And three reliability classes (RC) are defined by the reliability index concept, associated with the three consequences classes. The higher class number represents the more critical structures. Eurocode EN 1990 defines the 1-year probability of failure ($P_{F(1)}$) of the structures according to the CC and RC. Then, it calculates the probability of failure during the design life of 50 years ($P_{F(50)}$) using the equation (1), and determines the target reliability index corresponding to probability of failure using the equation (2).

$$P_{F(N)} = (P_{F(1)})^N \tag{1}$$

$$\beta_{(N)} = \Phi^{-1}[1 - P_{F(N)}] \tag{2}$$

Table 1 is an example in Designers' Guide to EN 1990 [4] that the target reliability of structure is given by consequence class and reliability class. It shows a link between consequence classes, reliability classes and values for the reliability index β.

During the development procedure of the design manual for long-span cable-supported bridge (DMCB), the basic philosophy of the Eurocode is adopted. But the changes are made on the basic reference period for the differentiation of the reliability class as the design life of the LSCSB can be extended further to 200 years. Table 2 shows the target reliability indices for the design life of 100 years and 200 years, calculated by the equation (1) and (2). As it can be seen from Table 2, the target reliabilities for the CC2 and RC2 structure are determined as 3.89, 3.72 and 3.54 for the design life of 50, 100 and 200 year, respectively following the concept of Eurocode EN 1990 based on 1 year reference period. An important point to note is that the target reliability index is determined lower in spite of the longer design life. This is because the target probability of failure and the reliability index are determined as constant value with respect to 1 year reference period, then the target reliability index with respect to the design life varies. The probability distribution of the design load is defined as exceedance probability (or non-exceedance probability) for the whole design life, and so is the target reliability index. Therefore, it is reasonable that the target reliability for the structure is determined with respect to the whole design life rather than 1 year.

Table 1 : Consequence and reliability Classes, and values for the reliability index β [4]

Consequence Class	Reliability Class	Values for β					
		Ultimate Limit State		Fatigue		Serviceability	
		1 year reference period	50 year reference period	1 year reference period	50 year reference period	1 year reference period	50 year reference period
CC3	RC3	5.20	4.3				
CC2	RC2	4.75	3.8	(3.0-4.7)	1.5-3.8	2.9	1.5
CC1	RC1	4.26	3.3				

Table 2 : 100 year and 200 year reliability index β based on 1 year reference period

Consequence Class	Reliability Class	Values for β (Ultimate Limit State)			
		1 year reference period	reference period of design life		
			50 year	100 year	200 year
CC1	RC1	4.2 (P_F=10^{-5})	3.29 (P_F=5.00×10^{-4})	3.09 (P_F=10^{-3})	2.88 (P_F=2.00×10^{-3})
CC2	RC2	4.7 (P_F=10^{-6})	3.89 (P_F=5.00×10^{-5})	3.72 (P_F=10^{-4})	3.54 (P_F=2.00×10^{-4})
CC3	RC3	5.2 (P_F=10^{-7})	4.42 (P_F=5.00×10^{-6})	4.26 (P_F=10^{-5})	4.11 (P_F=2.00×10^{-5})

3. Differentiation of Target reliability for Long-span Cable-supported Bridge

3.1 Target reliability according to the importance class and design life

During the calibration study [5] five importance classes for structure are suggested with reference to the Eurocode EN 1990. As the lower number in the bridge classification represents the more critical structure in Korea, the order of the structural class is reversed as compared to that of Eurocode. Table 3 shows the details with respect to the five importance classes for structure.

In DMCB the target probability of failure and reliability indices are defined with respect to the whole design life, which is different from Eurocode where the classification is based on 1 year probability of failure. The target reliability indices for the class 5, class 3 and class 1 in Table 3 are determined with reference to the CC1, CC2 and CC3, respectively, in Table 2 which is obtained based on 1 year concept in Eurocode EN 1990. And those for the class 4 and class 2 are calculated by the geometric mean values. The values of the target reliability with respect to the whole design life which is assumed as 200 years for LSCSB are determined based on 100 year target reliability based on 1 year concept as shown in Table 2.

The public buildings and the ordinary bridges are classified as class 3 in DMCB corresponding to CC2 of Eurocode EN 1990, and the nuclear power reactors and major dams are classified as class 1 corresponding to CC3 of Eurocode EN 1990. The importance of the cable-supported bridges is set to be separated by the two classes. For the general cable-supported bridges, the importance class is 3 and the corresponding target reliability is 3.7. On the other hand, for significant cable-supported bridges, the importance class is 2 and the corresponding target reliability is 4.0. The long-span cable-supported bridges are generally classified as highly significant structures, but the importance class can be decided by the owner, responsible organization or designing engineer.

Table 3 : Importance Class of Structures

Importance class	Degree of importance	Examples of buildings and civil engineering works	Values for β (Ultimate Limit State)	Reference (Eurocode EN 1990)
Class 5	Low	Agricultural buildings, Green houses	3.09 (P_F=10^{-3})	CC1
Class 4	Medium	Residential and office buildings	3.42 (P_F=3.16×10^{-4})	Geometric mean of CC1 & CC2
Class 3	High	Public buildings, Ordinary bridges, **Cable-supported bridges**	3.72 (P_F=10^{-4})	CC2
Class 2	Very High	**Significant cable-supported bridges**	4.00 (P_F=3.16×10^{-5})	Geometric mean of CC2 & CC3
Class 1	Extremely high	Nuclear power reactors, Major dams and barriers	4.26 (P_F=10^{-5})	CC3

Table 4 : 1-year probability of failure indices according to the Importance Class & Design Life

Importance class	Design life	Values for β (Ultimate Limit State)					
		1 year reference period			reference period of design life		
		β	P_F	Ratio	50 year	100 year	200 year
Class 3	50	4.61	$\mathbf{2.00\times10^{-6}}$	1/0.5	**3.72**	-	-
	100	4.75	$\mathbf{1.00\times10^{-6}}$	1	3.89	**3.72**	-
	200	4.89	$\mathbf{5.00\times10^{-7}}$	1/2	4.06	3.89	**3.72**
Class 2	50	4.85	$\mathbf{6.32\times10^{-7}}$	1/0.5	**4.00**	-	-
	100	4.98	$\mathbf{3.16\times10^{-7}}$	1	4.16	**4.00**	-
	200	5.11	$\mathbf{1.58\times10^{-7}}$	1/2	4.32	4.16	**4.00**

Table 4 shows the 1-year probability of failure according to the importance class and the design life, which are calculated by the inversion of equation (1). If the design life is fixed, the 1-year probability of failure for class 2 is 3.16 times higher than that for class 3, as the difference between the probabilities of failure with respect to the design life. This shows that the difference between the probabilities of failure is due to only the difference in importance class. If the importance class is fixed, the 1-year probability of failure for the design life of 100 year is 2 times higher than that for the design life of 50 year and 0.5 times lower than that for the design life of 200 year. This implies that the difference in design life also makes the difference in the 1-year probability of failure when the target reliability index with respect to the corresponding design life is fixed.

3.2 Target reliability for replaceable or repairable components

The structural components constituting the cable-supported bridge can be separated by the primary components and the secondary components according to the importance of their structural behaviour. And they can also be separated by the permanent components and the repairable or replaceable components according to the possibility of repair or replacement. For example, the main cables can be classified as the primary and permanent component, and the expansion joints can be classified as the secondary and replaceable component. Some examples of replaceable components and repairable components in suspension bridge are shown in figure 1.

The target reliability for the primary component is 3.7 or 4.0. The target reliability for the secondary component needs not be as high as that for the primary component, because the failure of the secondary component does not lead to the collapse of the entire bridge system and does not affect a significant impact to the bridge to carry out its functions.

Similarly, the target reliability with respect to the design life of the cable-supported bridge is 3.7 or 4.0. The target reliability for the repairable or replaceable components whose service life is shorter than the design life is not required to be guaranteed with respect to the design life. The target reliability of them should only be guaranteed during their service life, so the target reliability for the repairable or replaceable with respect to the design life needs not be as high as that for the permanent components.

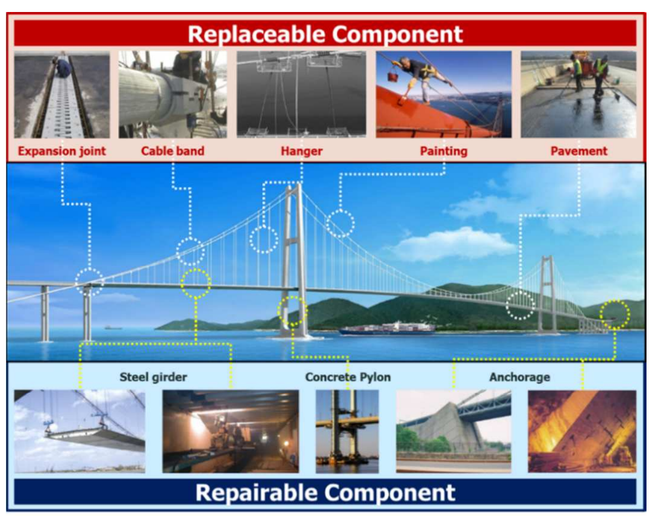

Fig. 1: Replaceable Components and Repairable Components in Suspension Bridge

Table 5 : Target Reliability for Components (Class 2 bridge for which the design life is 200 years)

Element Classification		service life	Values for β (Ultimate Limit State)						
			1 year reference period		reference period				
			β	P_F	20 year	30 year	50 year	⋯	200 year
Primary components	Permanent components	200 year	5.11	1.58×10^{-7}	-	-	-	-	**4.00**
	Replaceable or Repairable components	20 year	4.66	1.58×10^{-6}	**4.00**	⋯	⋯	⋯	**3.42**
		30 year	4.74	1.05×10^{-6}	-	**4.00**	⋯	⋯	**3.53**
		50 year	4.85	6.32×10^{-7}	-	-	**4.00**	⋯	**3.66**
Secondary components	Replaceable or Repairable components	20 year	4.42	5.00×10^{-6}	**3.72**	⋯	⋯	⋯	**3.09**
		30 year	4.50	3.33×10^{-6}	-	**3.72**	⋯	⋯	**3.21**
		50 year	4.61	2.00×10^{-6}	-	-	**3.72**	⋯	**3.35**

Table 5 shows the target reliability differentiation for components according to the element classification and design life in case that the class 2 cable-supported bridge for which the design life is 200 years. The values of the target reliability 4.0, corresponding to class 2, is given to the primary components. But the values of 3.7, corresponding to class 3, is given to the secondary components considering the importance of their structural behaviour. The values of the target reliability for the replaceable or repairable components are adjusted to lower than the values of 4.0 and 3.7 for permanent components considering their service life.

3.3 Target reliability for cable elements

The bridge design specifications, such as Eurocode EN 1990 [1], AASHTO LRFD Bridge Design Specification [2] and bridge design code in Korea (KBDC (2012)) [3], are used for the design of ordinary bridges. These specifications are also very useful to determine the target reliability for the ordinary elements of cable-supported bridge, such as girder, pylon and so on, because these elements are also present in the ordinary bridge or not significantly different from the elements in the ordinary bridge.

However, there have some empirical limitations to apply the design philosophy of the aforementioned design specifications to determine the target reliability for the cable elements, because the cable elements cannot be found in the ordinary bridge and only exist in the cable-supported bridge. So, in order to determine the target reliability for the cable elements, different types of approaches are needed.

Nowadays, the cable elements are designed by the safety factor (S.F.) based on the allowable stress design (ASD). Thus, the analysis about the equivalent reliability level of the cable-supported bridges designed by ASD must be preceded to determine the target reliability for the cable elements.

The reliability assessment for the cable elements is carried out with respect to three bridges, one is cable-stayed bridge and the rest two are suspension bridges as shown in figure 2. In terms of main span length, Incheon Bridge is cable-stayed bridge in service which is the longest in Korea and the fifth-longest in the world, and Yi Sun Sin Bridge is suspension bridge in service which is the longest in Korea and the fifth-longest in the world at present. Ulsan Bridge also has a much longer main span length compared to other suspension bridges. The reliability assessment for the cable elements is performed for the real design resistance and the required resistance of the S.F. based on the ASD. The former is to know the reliability level of the present bridge and the latter is to analyse the minimum reliability level which the design specification guarantees. Table 6 shows the results of the reliability assessments for the cable elements.

(a) Incheon Bridge (main span=800m) (b) Yi Sun Sin Bridge (main span=1,545m) (c) Ulsan Bridge (main span=1,150m)

Fig. 2: Three Bridges for Reliability Assessment

Table 6 : Reliability indices for cable elements

Resistance		Reliability index, β		
		Stay cable of cable-stayed bridge	Main cable of Suspension bridge	
		Incheon Bridge	Yi Sun Sin Bridge	Ulsan Bridge
Design resistance		9.25	7.85	8.18
Required resistance	S.F.=2.5	-	7.51	7.36
	S.F.=2.2	6.19	6.51	6.39
	S.F.=2.0	5.43	5.77	5.67
	S.F.=1.8	4.58	-	-

According to the results in table 6, the reliability index for the stay cable of Incheon Bridges is above 9.0 for the real design resistance and around 6.2 for the required resistance of safety factor 2.2. The reliability indices for the main cables of two suspension bridges are around 7.8~8.2 for the real design resistance and around 7.3~7.5 for the required resistance of safety factor 2.5. The reliability of Yi Sun Sin Bridge is little higher than that of Ulsan Bridge for the same required resistance of safety factor 2.5. The difference in the reliability index is mainly due to the ratio of the dead load and live load in the tension force of main cable. The dead load vs. live load ratio in the main cable is around 88%:12% in Yi Sun Sin Bridge and 86%:14% in Ulsan Bridge, because the main span length of Yi Sun Sin Bridge is longer than that of Ulsan Bridge. As the relative proportion of live load increases, the reliability index becomes lower, because live load is more variable than dead load.

The target reliability indices for the stay cable of cable-stayed bridge and that for the main cable of the suspension bridge are determined 6.0 and 7.0, respectively. Each value is selected lower than the result of the reliability assessment, because three bridges shown in figure 2 are thought to have lower proportion of live load and higher reliability level than other cable-supported bridges whose main span length are relatively short.

4. Conclusion

The research results conducted during the writing of the design manual for LSCSB are presented. A concept about the differentiation of target reliability for design of LSCSB is suggested. The target reliability of LSCSB is determined according to the importance of structure and it can be determined not only by the unit of structure but also by the unit of component. The reliability assessment for cable element is performed and the target reliability indices for cable element are presented with reference to the results.

Acknowledgements

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