Investigation of Design Loads and Load Combinations for Limit State Design of Long Span Cable-Supported Bridge

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Summary

For the design of long span cable supported bridge (LSCSB), the reliability based limit state design manual is under development. Statistical and probabilistic definition of the design loads and the load factors in the load combination are examined in relation to the design period and the safety level. For the purpose of investigating the reliability level of the design load combinations in the ultimate limit state and the extreme event limit state, the definitions of the variable loads are reviewed in terms of the design period and exceedance probability. An example of cable-stayed bridge is presented to show the reliability indexes of design load combinations of earthquake load.

Keywords: long-span cable-supported bridge; design life; reliability index; earthquake load; cable-stayed bridge; pylon.

1. Introduction

One of the most important matters in the design codes for bridge structures may be the criteria relating to the safety level of the design. In the ongoing project in Korea for the writing of the draft of the design manual for LSCSB, it is decided that the safety level needs to be determined in terms of probabilistic and statistical manner. Already the probabilistic and statistical concepts are used in the definition of the design loads for wind and earthquake in the domestic design standards. Also, the specific design value for the compressive strength of concrete is defined in probabilistic and statistical manner (KCI (2012)) [1]. Recently, due to the rapid advances in the field of construction technology and the accumulation of measured database, the probabilistic and statistical concepts are widely spread for defining the characteristic values of the primary design parameters.

During the process of writing a rational design manual of LSCSB, the domestic data is collected from construction sites regarding the loads and resistances and is analyzed to build the statistical database. Also, the preceding research results from other research groups as well as the experience from the past are combined to achieve a rational and economical bridge design.

Through the research so far, by considering the relative importance of the bridge structures, the target reliability indexes are differentiated in order to obtain rational and economical design. Differentiation of the target reliabilities between ordinary bridge and LSCSB are made. Also, the differentiation between structural components in LSCSB is made.

In this paper, a brief presentation of the reliability differentiation in the design manual of LSCSB between bridge structures as well as structural components is made. Also, a sample reliability analysis is shown for an example LSCSB designed by a design group of the Super Long Span Bridge R&D Center. The probabilistic and statistical analysis is made for the variable loads and the statistical properties for the earthquake load is applied in this study to show the reliability of the flexural strength of the concrete pylon of the example cable-stayed bridge.

2. Differentiation of target reliability

2.1 Importance of structure

Long-span cable-supported bridge (LSCSB) is a distinct structure compared to the ordinary bridges in terms of the size and importance of the structure. The target reliability index for the design of LSCSB can be different from that of the ordinary bridge. In this study, the target reliability index and design life for the design manual of LSCSB are proposed compared to those of the ordinary bridge design. In addition, more rational and economical design is sought by differentiating the target reliability index and design life between the structural components of LSCSB.

The design life of the ordinary bridge is 75 years in AASHTO LRFD and CHBDC. The target reliability index is 3.5 in these design codes. The recently issued Korea Bridge Design Code – Limit State Design method (MLTM (2012)) [2] defines design life for the ordinary traffic road bridge of 100 years based on the period used for the determination of the traffic live load model. The target reliability index of KBDC-LSD is 3.72 which corresponds to the probability of failure of 10^{-4}. The target reliability index of a design code is usually represented by the reliability index of the live load combination of the ultimate limit state acting in gravitational direction.

The design manual of LSCSB adopts limit state design format and follows the basic concept of the KBDC-LSD. The design life of LSCSB is assumed as 200 years compared to 100 years for the ordinary bridge in KBDC-LSD. In order to compare the reliability indexes with different design life, the reliability index based on 1 year is obtained. If the target reliability index is assumed as 3.72 for 200 years design life, the corresponding probability of failure in 1 year is 5.00×10^{-7} as shown in Table 1. The corresponding 1 year probability of failure for 100 year design life is 1.00×10^{-6} which is twice that of 200 years. Therefore, the probability of failure is reduced by half by increasing the design life from 100 years to 200 years while maintaining the target reliability index the same. In other words, the effect of increasing the design life to 200 years from 100 years is the safety increase of about twice in terms of 1 year probability of failure.

Table 1 : 1-year Probability of Failure to Guarantee the Same Reliability Level for Design Life

Based on 1-year Time Period			Based on Design Life			
			100-year Design Life		200-year Design Life	
Target Reliability	Probability of Failure	Ratio	Target Reliability	Probability of Failure	Target Reliability	Probability of Failure
4.75	1.00×10^{-6}	1	3.72	10^{-4}	3.54	2.00×10^{-4}
4.89	5.00×10^{-7}	1 / 2	3.89	5.00×10^{-5}	3.72	10^{-4}

Considering the importance of LSCSB, the target reliability index is set to 4.0 compared to 3.72 of ordinary bridge. When the target reliability index is increased from 3.72 to 4.0 for a 100 year design life, the probability of failure for 1 year is decreased by 3.16 times. If the effect of increasing the design life from 100 years to 200 years is combined, the probability of failure for 1 year of LSCSB for which the target reliability index and design life are 4.0 and 200 years, respectively, is decreased by 6.32 times compared to that of ordinary bridge for which those values are 3.72 and 100 years.

As the design of the structural component is based on the increased reliability index, the design life of the structural component is classified depending on the required performance in order to achieve a rational and economic design. The bridge components are classified as permanent component, repairable component and replaceable component. Permanent component is the structural element which lasts throughout the service life of the bridge with a minimum of maintenance and the design life is 200 years. Repairable component is the structural element for which replacement is almost impossible but repair or strengthening is appropriate for an acceptable degree of damage and the design life is 75 to 100 years. Replaceable component is the structural element which is relatively easy to be replaced and the design life is 20 to 50 years. Relatively low reliability indices can be applied for the replacement element. Appropriate details should be considered for easy replacement work.

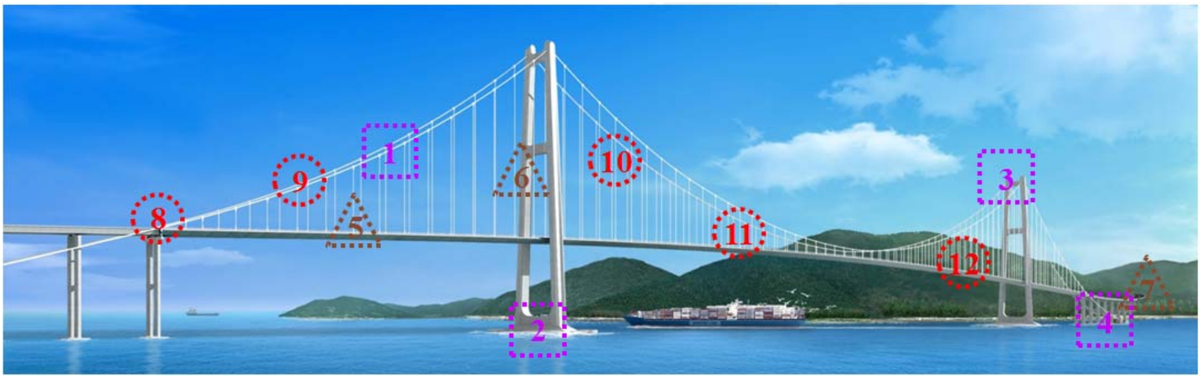


Fig. 1: Variable Design Life for Structural Components
(1. Main cable 2. Pile foundation 3.Pylon Saddle 4. Splay Saddle 5. Steel Girder 6. Concrete Pylon 7. Anchorage 8. Expansion joint 9. Cable band 10. Hanger 11.Painting 12.Pavement)

Figure 1 shows some of the typical bridge elements which can be classified according to the three categories. In the figure, numbers 1 to 4 in dotted rectangle denote the permanent component, 5 to 7 in dotted triangle denote the repairable component and 8 to 12 in dotted circle denote the replaceable component. Examples of permanent components are main cable, pile foundation, pylon saddle, splay saddle. Examples of repairable components are steel girder, concrete pylon, anchorage. Examples of replaceable components are stay cable system of cable-stayed bridge, hanger cables and main cable wraps for suspension bridge, secondary steel structures, expansion joints, bridge bearings, pavements and so on.

Table 2 : Target reliability for Design Life by Classification of Structural Components

Class	Structural Component	Based on 1-year Time Period		Target Reliability Based on Design Life				
		Target Reliability	Probability of Failure	20 year	30 year	50 year	100 year	200 year
(Ref.)	Ordinary Bridge (100 year)	4.75	1.00×10^{-6}	4.11	4.01	3.89	3.72	3.54
1	Replaceable Components (20 year)	4.66	1.58×10^{-6}	4.00	3.90	3.78	3.60	3.42
	Replaceable Components (30 year)	4.74	1.05×10^{-6}	4.10	4.00	3.88	3.71	3.53
	Replaceable Components (50 year)	4.85	6.32×10^{-7}	4.21	4.12	4.00	3.83	3.66
2	Repairable Components Permanent Components	5.11	1.58×10^{-7}	4.52	4.43	4.32	4.16	4.00

The target reliability index of 4.0 is basically applied to all members of LSCSB and the reduced design lives for the replaceable components are applied. The design lives of the replaceable components are 20, 30 and 50 years depending on components. Table 2 shows the target reliability index converted to 1 year time period. The corresponding reliabilities for 1 year are 4.66, 4.74 and 4.85 for the design lives of 20, 30 and 50 years, respectively. These values of reliability are similar to 4.75 of the ordinary bridge. Thus the safety levels of the replaceable components are similar to that of the ordinary bridge.

The current design for the cable components follows the allowable stress design method in Korea. But the design manual for LSCSB is being written by adopting the limit state design method, the design method for the cable components needs to be changed to the limit state design method, too. The safety factor for the cable components in the current allowable design method has been strongly based on the past experience. The target reliability index of the cable component in the limit state design has been determined corresponding to the safety factor in the allowable stress design. The reliability index corresponding to a safety factor of 2.5 in the current allowable stress method for the main cable of a suspension bridge ranged from 13.25 to 13.70. Similarly, the reliability index corresponding to a safety factor of 2.2 for the stay cable of a cable-stayed bridge ranged from 9.41 to 9.50.

The safety factor for the design of the cable component is getting decreased recently. This is partly due to the increase in main span length which increases the weight proportion in the load. As the dead load is more accurate than the variable loads to estimate, it reduces the uncertainty and increases the safety level. Also, considering the accumulation of the construction experience and the development of the technology in the field of analysis, design, construction and material, the target safety level is lowering in these days. The draft of the design manual is based on the safety factor of 2.2 for suspension bridge and the corresponding reliability index of 12. Also, the basic safety factor is 2.0 for cable-stayed bridge and the corresponding reliability index is 8.5. By summarizing the above discussion the target reliability indexes for the structural components of LSCSB can be classified as in Table 3.

Table 3 : Target reliability for Design Life

Structural Component		Based on 1-year Time Period		Target Reliability Based on Design Life				
		Target Reliability	Probability of Failure	20 year	30 year	50 year	100 year	200 year
Replaceable Components	Stay cable & Hanger Rope	9.09	4.74×10^{-20}	8.76	8.72	8.66	8.58	8.50
	Other Components (20 year)	4.66	1.58×10^{-6}	4.00	3.90	3.78	3.60	3.42
	Other Components (30 year)	4.74	1.05×10^{-6}	4.10	4.00	3.88	3.71	3.53
	Other Components (50 year)	4.85	6.32×10^{-7}	4.21	4.12	4.00	3.83	3.66
Repairable & Permanent Component	Main Cable	12.43	8.88×10^{-36}	12.19	12.16	12.11	12.06	12.00
	Other Components	5.11	1.58×10^{-7}	4.52	4.43	4.32	4.16	4.00

3. Safety level of design manual

3.1 Statistical properties of design loads

In the writing of the design manual of LSCSB, it is required to determine the target reliability index and the appropriate safety factors. The safety factors are calibrated using the statistical properties of the loads and resistances. For the calibration process, it is very important to define the design loads in statistical manner. Especially, the variable loads which depend on time such as live load, wind load and earthquake load are defined based on statistics and probability.

In order to define the target reliability index during the design life of the bridge, the definition of the variable loads should be defined for the design life of the bridge. The study for the definition of the variable loads by applying the domestic load data available is in progress. In this paper the intermediate results of the ongoing research for the determination of the statistical properties of the design earthquake load are presented and applied for the analysis of the reliability of the example LSCSB design.

The statistical definition of the earthquake load is based on the data used in the domestic research (MLTM (1997)) [3]. Also, the research results by Korea Atomic Energy Research Institute (2012) [4] on the determination of the ground acceleration for the evaluation of earthquake safety are used. The statistical properties of the peak ground acceleration (PGA) for domestic sites are estimated by applying optimization process for those of the preceding research results. The statistical distribution of the PGA is assumed to follow an extreme distribution. The optimization process follows the generalized extreme value (GEV) distribution method which uses Von-Mises form to find the best-fit distribution. Von-Mises form encompasses three extreme distributions of Gumbel, Frechet and Weibull distribution. It is estimated that the PGA of the domestic data follows Frechet distribution. The optimized results for the design life of 50 years, 100 years and 200 years are shown in Figure. 2.

By applying the statistical properties of the parameters that are included in the determination for seismic loads presented in the reference [5], the statistical properties of the earthquake load for the domestic construction sites are estimated after combined with those of the PGA.

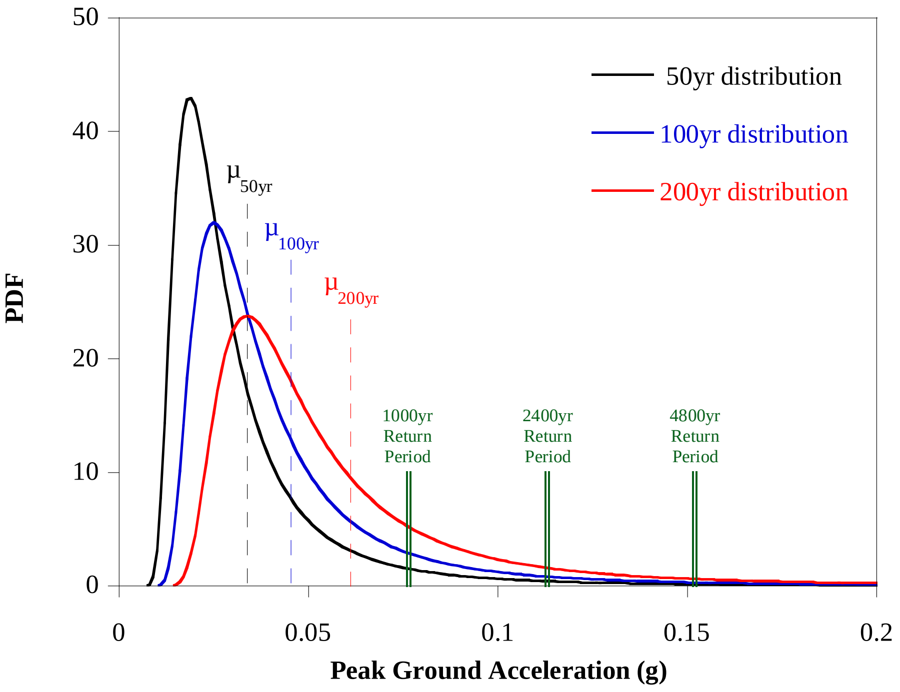
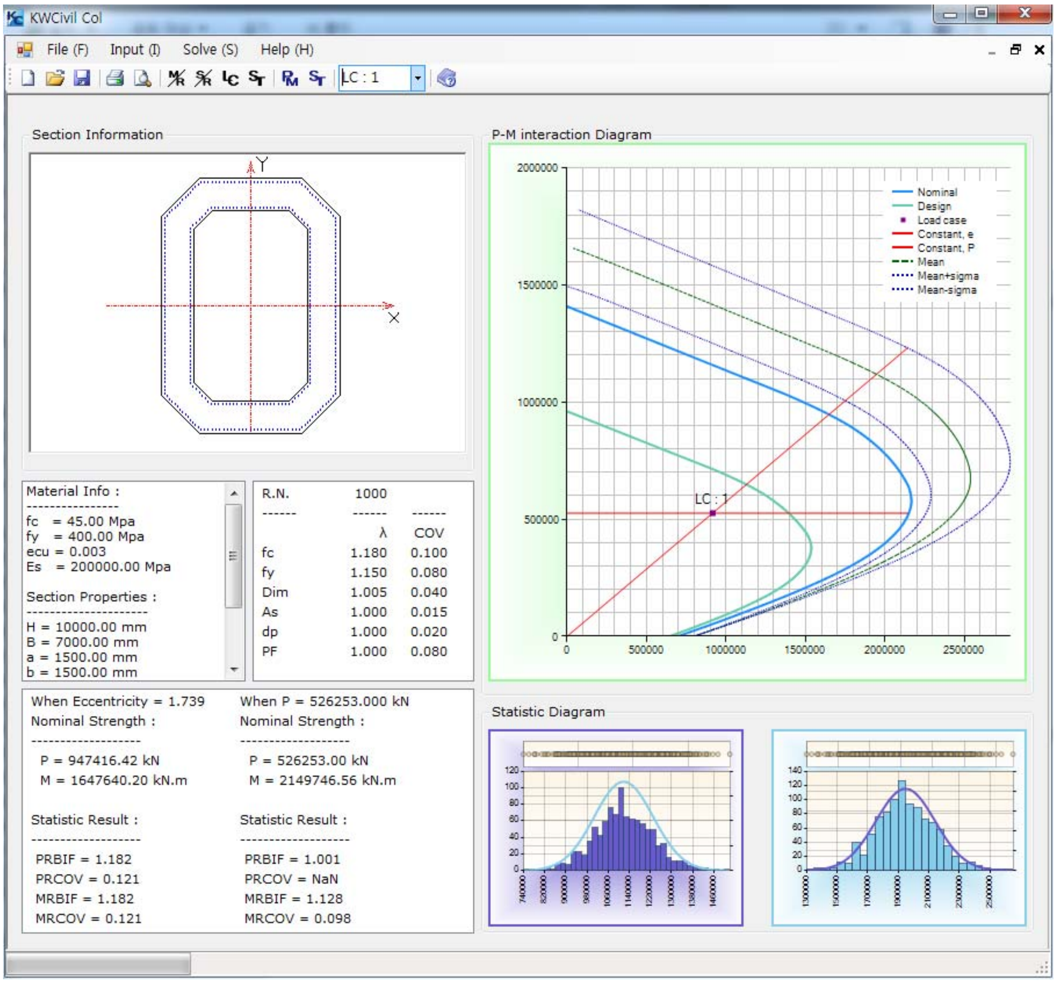


Fig. 2: Probability Density Function of Peak Ground Acceleration for Determination of Statistical Properties of Design Earthquake

3.2 Reliability of an example bridge

An example LSCSB designed by the prototype bridge design team [6] are used for the reliability calculation of the application of design load combination of the proposed design manual. The example cable-stayed bridge is shown in Figure 3. The total span is 2,240m and the middle span is 1,200m. The height of pylon is 283.5m.



```
Material Info :
----------------
fc   = 45.00 Mpa
fy   = 400.00 Mpa
ecu  = 0.003
Es   = 200000.00 Mpa

Section Properties :
---------------------
H = 10000.00 mm
B = 7000.00 mm
a = 1500.00 mm
b = 1500.00 mm
```

```
R.N.        1000
------      ------   ------
                 λ      COV
fc          1.180    0.100
fy          1.150    0.080
Dim         1.005    0.040
As          1.000    0.015
dp          1.000    0.020
PF          1.000    0.080
```

```
When Eccentricity = 1.739      When P = 526253.000 kN
Nominal Strength :             Nominal Strength :
-------------------            -------------------
  P = 947416.42 kN               P = 526253.00 kN
  M = 1647640.20 kN.m            M = 2149746.56 kN.m

Statistic Result :             Statistic Result :
-------------------            -------------------
 PRBIF = 1.182                  PRBIF = 1.001
 PRCOV = 0.121                  PRCOV = NaN
 MRBIF = 1.182                  MRBIF = 1.128
 MRCOV = 0.121                  MRCOV = 0.098
```

Fig. 3: Output of PM Diagram and Statistical Characteristics for RC Pylon

The statistical properties of the primary loads comprising the load combinations as well as the structural resistances are determined by using domestic statistical data. The reliability index of concrete pylon of the example cable-stayed bridge is estimated for the earthquake design load combination. The applied load combination is **1.25DC+1.50DW+0.5L+1.0EQ+1.0Q**, in which DC and DW are dead load of structural component and wearing surface, respectively, L is live load, EQ is earthquake and Q is sum of water pressure, buoyancy and wave pressure.

Six different sections shown in Figure 5 (b) of the pylon are checked in the design. The moment in the transverse direction is studied and the results are shown in Figure 5 (a). The reliability index of the example bridge pylon is denoted as R_{real} and is between 2.50 and 2.84. The reliability index with the minimum required strength required by the design load combination of the design manual is denoted as R_{min} and is between 2.34 and 2.61.

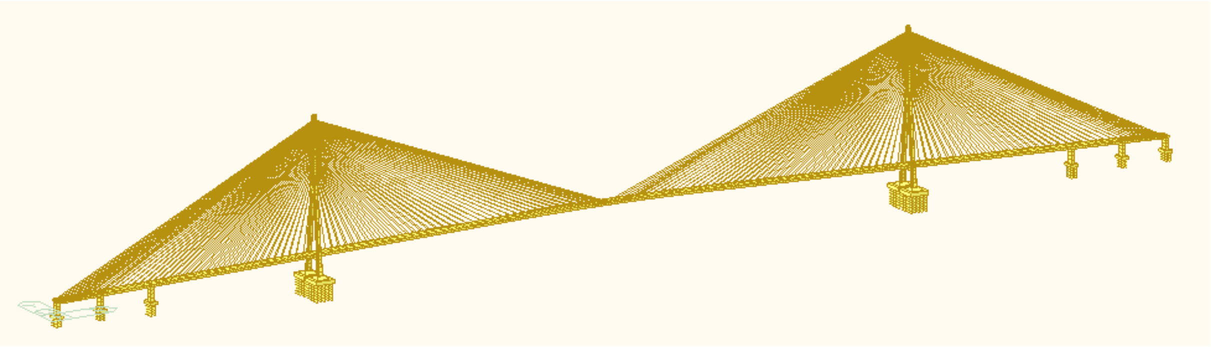
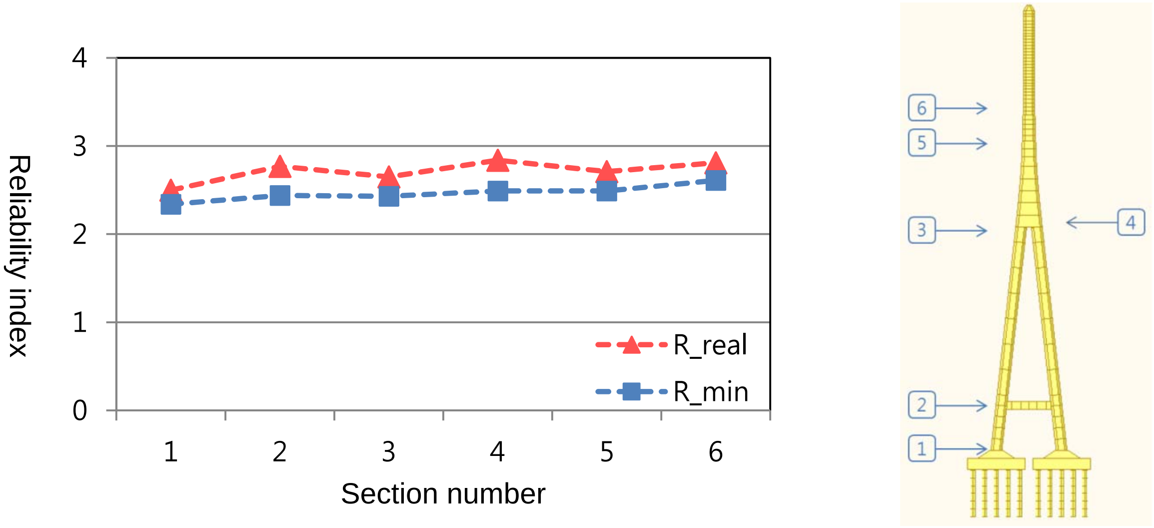


Fig. 4: Finite element modelling of an example cable stayed bridge



(a) Statistical Safety Level of Pylon

(b) Section Number for Reliability Calculation

Fig. 5: Reliability analysis of an example cable stayed bridge

4. Conclusion

A study to develop a design manual for LSCSB is underway. The safety factors for bridge design are calibrated by statistical and probabilistic analysis. The statistical properties of the variable loads such as live load, wind and earthquake are defined based on statistical concept. The statistical description of the design loads and resistances is applied to the statistical definition of the reliability index of the design load combinations for LSCSB. An example reliability analysis is conducted for the concrete pylon of a cable-stayed bridge for earthquake load. Further study is necessary for establishing the statistical relation between design loads, resistances and reliability index.

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