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Safety Evaluation of Stay Cables of Cable-Stayed and Extradosed Bridges via Deterministic and Non-deterministic Methods

Khawaja Ali and Aleena Saleem

Abstract

Cable-stayed and extradosed bridges are thought to be identical structures because both bridges use stay cables for reinforcement. However, the safety factors of their stay cables are stipulated differently in many international standards, i.e., Japanese specifications suggest the safety factors of 2.5 and 1.67 for the design of cable-stayed and extradosed bridges, respectively. In this chapter, a parametric study is carried out for the evaluation of safety factors of stay cables by employing the deterministic and nondeterministic methods at limit states. As a result, it is found that the safety factors in the range of 2.3–2.5 and 1.67 are indispensable for the safe design of cable-stayed and extradosed bridges, respectively, to satisfy the conditions of limit states and target reliability index.

Keywords: cable-stayed bridge, extradosed bridge, stay cable, safety factor, reliability, fatigue, limit state

1. Introduction

The extradosed bridge is thought to be a special form of cable-stayed bridge because both bridges use inclined stay cables for supporting the girder load elastically at points along its length in order to increase the span of girder without intermediate piers [1]. The dead and live loads on girders are transferred to towers by axial action of stay cables. Thus, the safety of these kinds of flexible structures is mainly dependent on the safety of stay cables, which is usually assured by introducing a safety factor to provide a margin between theoretical strengths (R) and load effects (S). For instance, the allowable stress (σ_{all}) at serviceability limit state (SLS) as per the Japan Prestressed Concrete Engineering Association's Specifications, may be determined as 0.4 σ_{UTS} and 0.6 σ_{UTS} (where σ_{UTS} is ultimate tensile strength) for the design of cable-stayed and extradosed bridges, respectively [2]. In that context, Ali et al. [3] estimated an optimum value of safety factor for stay cables of a cable-stayed bridge under ultimate and fatigue limit states by considering the effects of various unexpected events. However, the problem of how much σ_{all} should be used for the stay cables of extradosed bridges is still controversial because these cables are considered as external cables arranged outside the box girder. Moreover, the safety factors of these cables have not been verified against

extreme loading and unexpected damage conditions. Besides this, the stress range in a stay cable due to live load is one of the most important considerations for the design of stay cables against fatigue failure [4]. Owing to the variations in live loads, it is difficult to precisely examine the safety of these kinds of flexible structures through an evaluation method comprising safety factors based on experience. Therefore, it seems to be reasonable to conduct safety and reliability assessment using a nondeterministic reliability method which takes into account the effects of all kinds of uncertainties [5–7].

In this paper, a parametric study is carried out to evaluate the safety factors of stay cables of cable-stayed and extradosed bridges by employing the deterministic and nondeterministic methods at limit states. The effects of various parameters, i.e., cable loss and deterioration of cables due to corrosion, on demand to capacity ratio (DCR) of stay cables are also considered in this study. Finally, it is found that the safety factors in the range of 2.3–2.5 and 1.67 are essential for the safe design of cable-stayed and extradosed bridges, respectively to satisfy the conditions of limit states and target reliability index.

2. Finite element modeling

2.1 FE model of cable-stayed bridge (CSB)

A 3D FE model of a cable-stayed bridge, with a main span length of 460 m, is developed using a FEM software (Midas Civil). The structural configuration of the bridge model is shown in **Figure 1**. The bridge model is cambered linearly by 2%. The steel box girder is used for this model. The total width and depth of girder are 21.75 m and 3.5 m, respectively with four design lanes of each 3.5 m wide as shown in **Figure 2**. The configuration of tower is an H-shape composed of steel legs. The total height of tower is 140 m and pylon height (110 m) is taken as 1/4th of the main span length. Moreover, cable-stayed bridge model consists of 144 stay cables (Cs), arranged in a modified-fan style. The anchorage points of stay cables at the bridge deck are located at an interval of 12 m. Tower and girder are modeled as elastic beam elements (168 beams) whereas stay cables are modeled as truss elements (only tension). Fishbone modeling technique is adopted to connect the stay cables with deck spine through rigid links. Moreover, the model is supported by roller supports provided on each end of bridge and piers are assumed to be fixed into firm foundation. All bearings of main girder are movable in longitudinal direction of bridge, i.e., there is no connection between tower and girder at their intersection. The attachments of the cables to tower are pinned. Elastomeric rubber bearings are installed to connect the girder with lower transverse beam through elastic links.
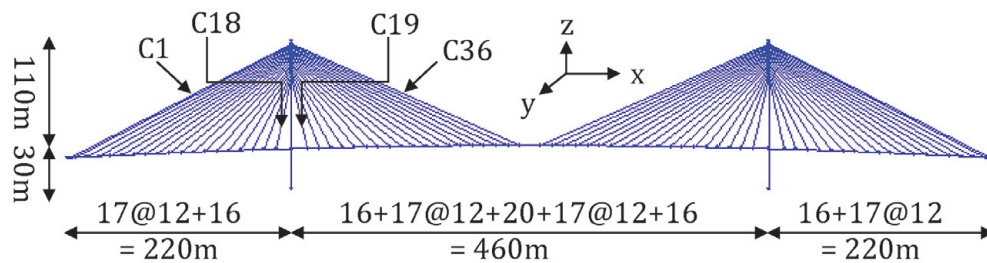
Figure 1.
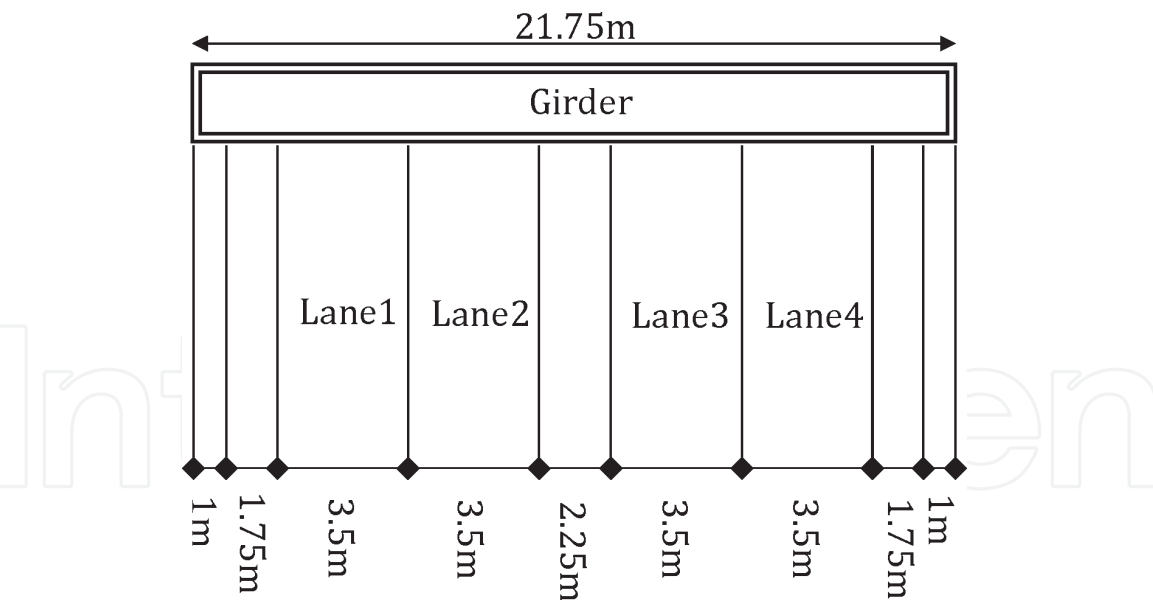*Configuration of cable-stayed bridge model.*

Figure 2.
Configuration of traffic lanes.

2.2 FE model of extradosed bridge (EDB)

Similar to cable-stayed bridge, a 3D FE model of extradosed bridge, with a main span length of 208 m and two side spans of each 100 m, is developed. The structural configuration of bridge model is shown in **Figure 3**. The total width and depth of concrete bridge girder are 21.75 m and 4.5 m, respectively with four lanes as already shown in **Figure 2**. The depth of girder is kept same at the pylon locations as well as at mid-span. The total height of the concrete tower is 40 m and pylon height (20 m) is taken as 1/10th of the main span length. The bridge girder is supported by the piers and a system of 88 stay cables (EDCs) arranged in a modified-fan style. The anchorage points of stay cables (EDCs) at the bridge deck are located at the intervals of 5 m and 6 m on side and main spans, respectively. The connection between tower and girder is assumed to be fixed and monolithic because stress range due to live load in the cables is affected by the girder stiffness and fixity of support on the piers. When the girder is stiff, the stress range in cables due to live load will be small in comparison with permanent loads. To reduce the magnitude of this stress range, girder should be fixed at the piers.

2.3 Design considerations for cable-stayed and extradosed bridges

Bridge design loads are referred to Japanese specifications for highway bridges [4] as shown in **Table 1**. Dead loads are applied uniformly on entire spans whereas
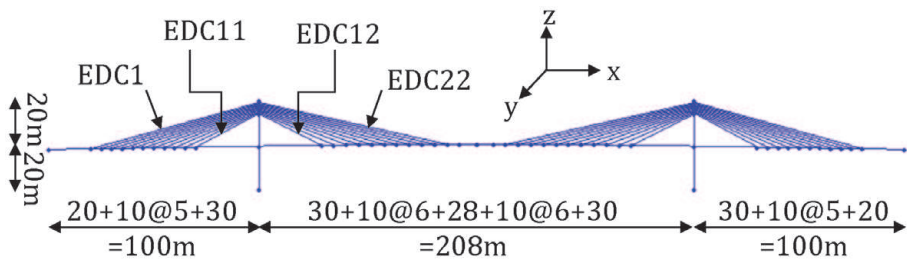

Figure 3.
Configuration of extradosed bridge model.

Dead load, DL_{CSB} (kN/m)	Self-weight of deck	w_{DC1}	48.5
	Pavement loads	w_{DW}	34.2
	Additional loads	w_{DC2}	4.85
Dead load, DL_{EDB} (kN/m)	Girder self-weight	w_{DC1}	335
	Pavement loads	w_{DW}	34.2
	Additional loads	w_{DC2}	4.85
Live load, LL (kN/m)	Concentrated load	P_1	97.5
	Uniformly dist. Load	P_2	29.3
	Pedestrian load	PL	10

Table 1.
Design loads.

B-live loads (concentrated live load: P_1 and uniformly distributed load: P_2) are applied only on main spans of both bridges. The material and sectional properties of bridge components are also shown in **Tables 2** and 3, respectively.

2.4 Stay cables of cable-stayed bridge (Cs)

Preliminary design of stay cables of cable-stayed bridge (Cs) is carried out by assuming a safety factor of 2.5 against σ_{UTS} following the allowable stress design

Properties	Stay cables of CSB	Stay cables of EDB
σ_{UTS} (MPa)	1860	2000
σ_y (MPa)	1302	1400
σ_{all} (MPa)	744	1200
E (GPa)	195	195
ν	0.3	0.3
γ (kN/m^3)	77	77

Table 2.
Material properties of stay cables.

	Members	Deck	Pylon	Pier	Transverse beam
CSB	A (m^2)	0.59	1.11	1.11	0.55
	I_{xx} (m^4)	14.73	7.96	7.96	2.61
	I_{yy} (m^4)	5.13	6.24	6.24	2.14
	I_{zz} (m^4)	29.03	4.72	4.72	1.52
EDB	A (m^2)	13.54	6	12	6
	I_{xx} (m^4)	168.62	4.7	19.44	4.7
	I_{yy} (m^4)	54.22	4.5	16	4.5
	I_{zz} (m^4)	683.84	2	9	2

Table 3.
Sectional properties of bridge components.

(ASD) method. An optimization technique of finding unknown load factors is applied to find the initial pretension forces (PS) through an iterative process in order to achieve the balanced state of bridge under its own weight. Subsequently, the cross-sectional areas of stay cables are calculated and shown in **Figure 4**. In addition to that, stay cables are designed in such a way that axial stresses in stay cables are about 50–60% of σ_{all} under dead loads and less than 95% of σ_{all} under dead plus live loads.

2.5 Stay cables of extradosed bridge (EDCs)

Similar to cable-stayed bridge, the preliminary design of stay cables of extradosed bridge (EDCs) is also carried out by using a safety factor of 1.67. For the calculation of initial pretension forces (PS) of stay cables, the continuous beam method is applied. Hit and trial method is used to find the ideal and balanced state of extradosed bridge under dead loads. Many iterations are performed to optimize the bending moment and cable forces, and cross-sectional areas of stay cables are calculated accordingly as shown in **Figure 5**. In extradosed bridge, the prestress force (Pi) is also applied to the concrete girder. Full pre-stressing of the girder is not feasible. Since only concentric pre-stressing can be used locally in the girder (eccentric pre-stressing causes a secondary bending moment as large as the primary bending moment), a prestress force (Pi) of 200,000 kN is required at main span and some portion of side span to keep the girder un-cracked. Pi is required to

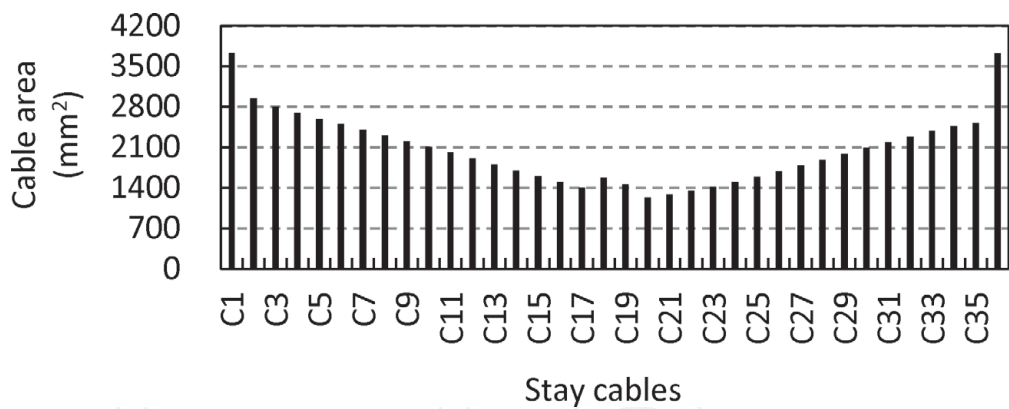**Figure 4.**
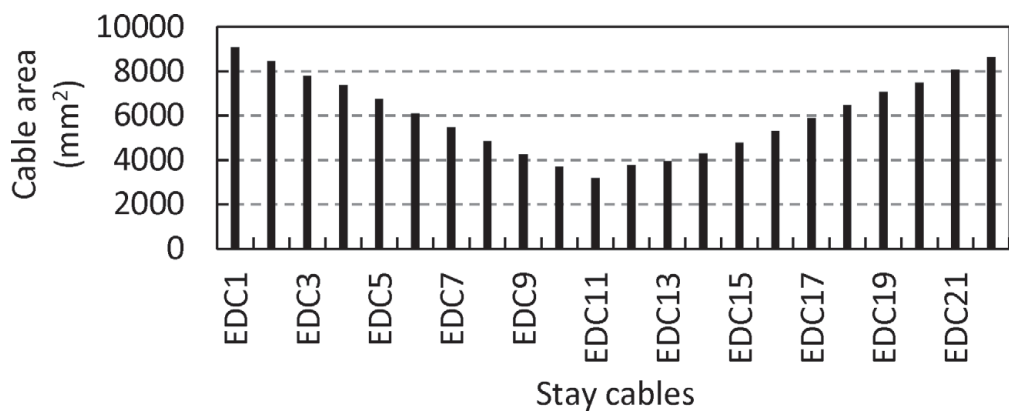*Cross-sectional areas of stay cables of cable-stayed bridge.*

Figure 5.
Cross-sectional areas of stay cables of extradosed bridge.

minimize the deflection and to resist the bending moments due to long-term effects and live loads.

2.6 Effects of nonlinearity

Nonlinearity effects including cable sag effect due to self-weight of stay cables and P-Delta effects due to interaction of deck and tower are also considered in the analysis of both bridge types. Reduced or equivalent modulus of elasticity of stay cables is determined by:

$$E_{eq} = \frac{E}{1 + \frac{(wL)^2 AE}{12T^3}} \tag{1}$$

Eq. (1) is known as Ernst' formula in which E_{eq} is equivalent modulus of elasticity, E is effective material modulus of elasticity, A is cross-sectional area of stay cable, w is cable weight per unit length, L is horizontal projected length and T is tensile force in stay cable.

3. Safety evaluation of stay cables by deterministic method

3.1 Fatigue limit state

For the evaluation of safety factor of stay cables at fatigue limit state, moving load analysis is performed by applying fatigue design load (T-load: 200 kN) to the cable-stayed and extradosed bridge models. Then, influence line diagrams (ILDs) of axial forces in stay cables are drawn by using Breslau Muller Principle and maximum and minimum design variables are calculated. **Figure 6** shows the ILDs of axial forces of stay cables (C1 and EDC1) of cable-stayed and extradosed bridges, respectively. It is observed that the area under ILD of C1 is larger than that of EDC1 under the same fatigue load which indicates that extradosed bridge is less influenced by fatigue load as compared to cable-stayed bridge. Subsequently, cable reversal stresses and design stress range $(\Delta\sigma_d)$ values are determined by considering the cyclic loads of constant amplitude and fully reversed nature as per the guidelines of fatigue design recommendations for steel structures [8]. To assess the safety factor at fatigue limit state based on equivalent stress range theory, following equation should be satisfied [9]:
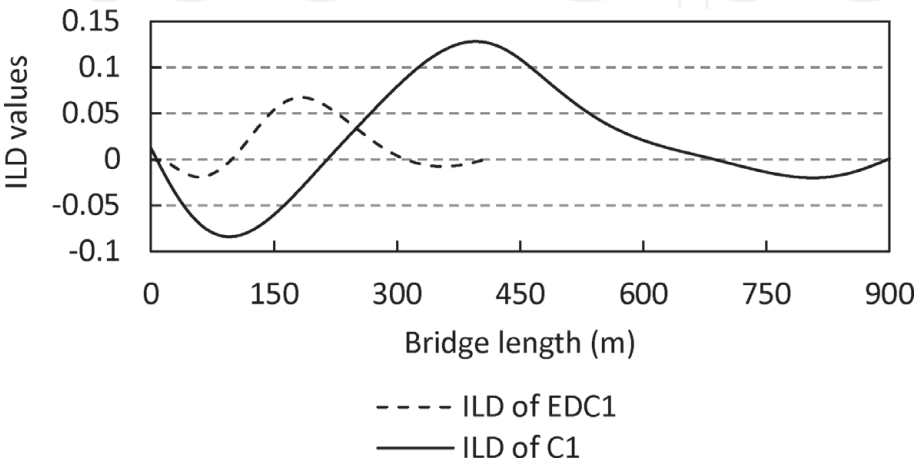
Figure 6.
ILDs of axial forces of stay cables C1 and EDC1.

$$\gamma \left(\frac{\Delta \sigma_d}{\Delta \sigma_R} \right) \leq 1.0 \tag{2}$$

where γ is safety factor equal to 1.2 based on redundancy and importance of structure, $\Delta \sigma_d$ is design stress range also known as maximum stress range and $\Delta \sigma_R$ is allowable stress range which can be found by using Eq. (3):

$$\Delta \sigma_R = \Delta \sigma_{CE} \times C_R \tag{3}$$

where $\Delta \sigma_{CE}$ is the basic allowable stress range or cut off limit for constant amplitude stress which is taken as 270 MPa and 200 MPa for parallel wire strand type stay cables of cable-stayed and extradosed bridges, respectively at 2 million load cycles based on the standard SN or Wohler's curves of cables and C_R is correction factor for mean stress which can be calculated as:

$$C_R = 1.3 \left(\frac{1-R}{1.6-R} \right) \text{ for } R \leq -1 \tag{4}$$

$$C_R = \frac{1-R}{1-0.9R} \text{ for } R > -1 \tag{5}$$

which R is the stress ratio defined as the ratio of minimum stress ($\sigma_{\min}$) to maximum stress ($\sigma_{\max}$) in stay cables.

Figures 7 and **8** compare the fatigue stress demand to capacity ratios (DCRs) of stay cables of cable-stayed and extradosed bridges, respectively. In case of cable-stayed bridge, stay cable C15 shows maximum DCR under fatigue design load and there is a hefty variation in DCR of stay cables depending on their locations with respect to tower-deck intersection. From **Figure 7**, it can be concluded that a minimum safety factor of 2.2 is necessary to satisfy the fatigue limit state.

In case of extradosed bridge, all stay cables (EDCs) exhibit almost same DCR irrespective of their locations with respect to tower-deck intersection. **Figure 8** also
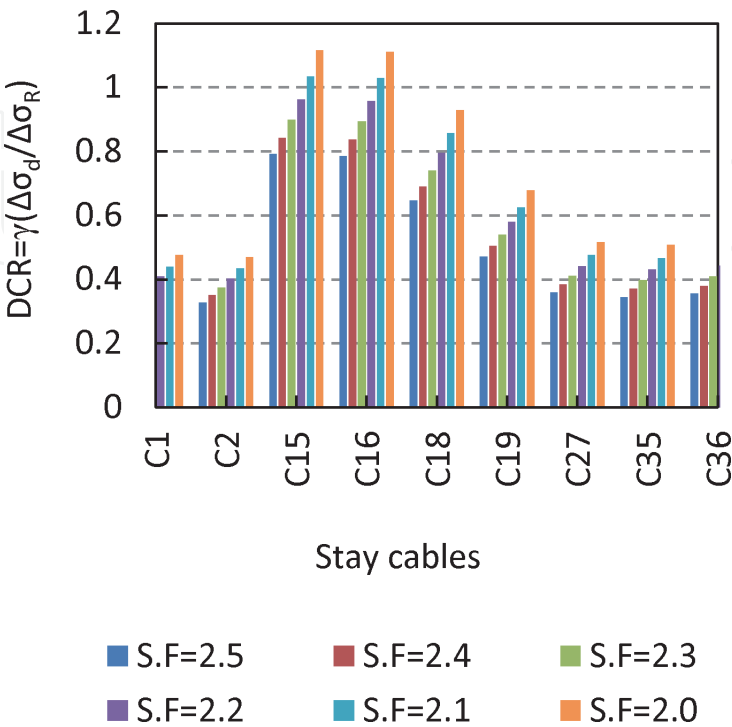
Figure 7.
Effect of fatigue load on DCR of stay cables of cable-stayed bridge.
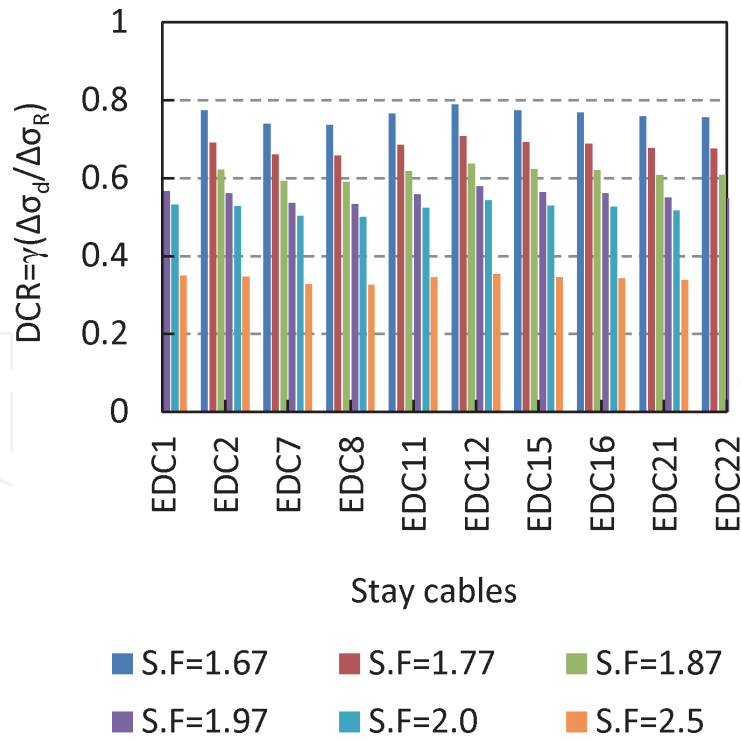
Figure 8.
Effect of fatigue load on DCR of stay cables of extradosed bridge.

shows that the safety factor of 1.67 satisfies the fatigue limit state. From probabilistic point of view, the safety of stay cables under the fatigue limit state is verified by satisfying the Palmgren-Miner hypothesis which states that fatigue failure of stay cables occurs when the accumulated damage exceeds one, $D(t) \geq 1$. Thus, if the fatigue failure time is denoted by T_f, then $P(T_f \leq t) = P(D(t) \geq 1)$. But this study is only limited to the deterministic fatigue analysis.

3.2 Ultimate limit state

After evaluation of safety factor of stay cables at fatigue limit state, the safety factor is further evaluated and verified at ultimate limit state. For that, following equation should be verified [9]:

$$\gamma_i \left(\frac{N_u}{N_{rd}} \right) \leq 1.0 \tag{6}$$

where γ_i is structural importance factor equal to 1.0, N_{rd} is equivalent design resistance of stay cables and N_u is ultimate axial load which is estimated by applying load and resistance factor design (LRFD) approach which considers the probabilities associated with simultaneous occurrence of different types of loads. Equations (7) and (8) yield ultimate axial loads for stay cables of cable-stayed and extradosed bridges, respectively [10]:

$$N_{u,CSB} = 1.25(DC + PS) + 1.5DW + 1.75(LL + IM) \tag{7}$$

$$N_{u,EDB} = 1.25DC + 1.5DW + PS + Pi + 1.75(LL + IM) \tag{8}$$

where the subscripts CSB and EDB are cable-stayed and extradosed bridges, respectively, DC is dead load (components and attachment), DW is dead load (wearing surface and utility), PS is pretension force, Pi is prestress force, LL is live load and IM is dynamic load allowance. In case of extradosed bridge, PS and Pi are

not factored with the same coefficient of dead load. This approach is more reasonable for bridges with a rigid deck according to Mermigas [11].

In design viewpoint of long-span cable-supported bridges, PTI [12] suggests two methods. The first method consists of a simplified quasi-static analysis of cable-supported bridge with a missing cable under factored dead and live loads. These loads are combined with the static cable loss dynamic impact force (CLDF) resulting from the sudden breakage of a cable with the additional load factor of 1.1 on CLDF. In second method, PTI allows the usage of a dynamic analysis to compute the structural response more accurately due to an abrupt cable failure. However, little guidance is provided by PTI on how to conduct such a dynamic analysis. That is why, first method is selected in this paper for the sake of simplification.

The dynamic cable force is applied as an equivalent static force in the correct orientation on both anchorage points of cable by considering CLDF of 2.0 in the load combination. Following the aforementioned approach, the effects of cable loss on DCR of stay cables of cable-stayed and extradosed bridges are investigated thoroughly. **Figure 9** compares the DCR of stay cables of the cable-stayed bridge with and without sudden loss of single and multiple stay cables at different safety
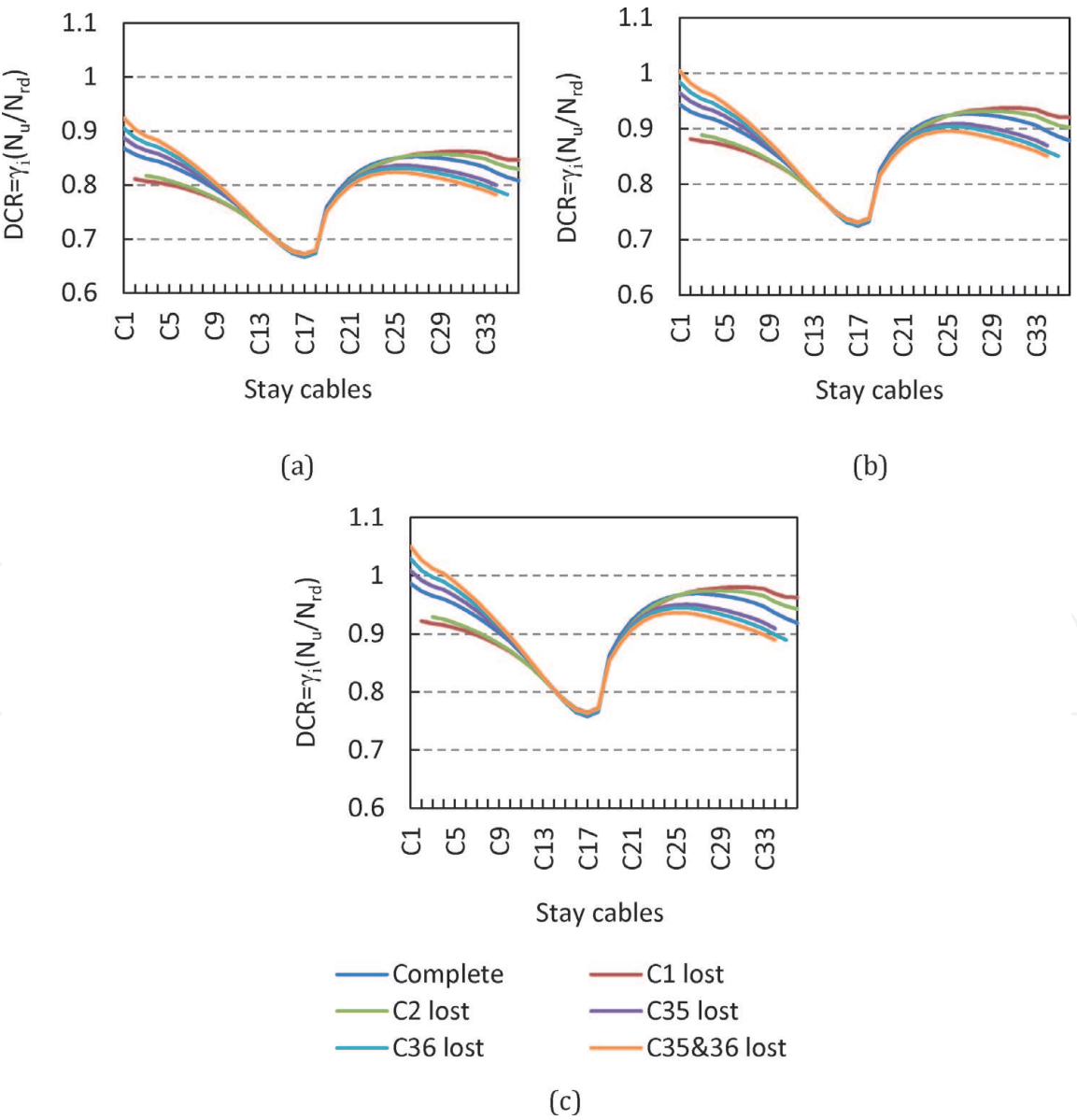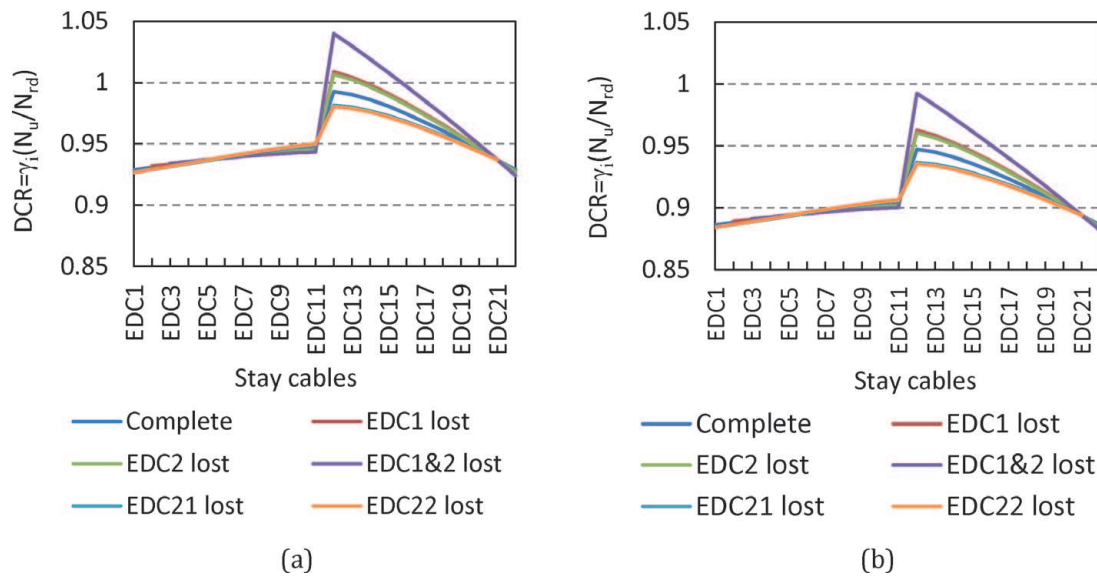

Figure 9.
Effect of cable loss on DCR of stay cables of cable-stayed bridge. (a) Safety factor of 2.5, (b) safety factor of 2.3, and (c) safety factor of 2.2.

factors. It can be observed from **Figure 9** that loss of two cables (C35&36) yields maximum DCR in the adjacent stay cables. This multiple cable loss event can also trigger the progressive collapse of the entire cable-stayed bridge.

Moreover, **Figure 9** also depicts that with the decrease of safety factor of stay cables, DCR increases accordingly and a minimum safety factor of 2.3 is essential to meet the requirements of ultimate limit state. Similarly, the effects of cable loss on DCR of EDCs are also investigated as shown in **Figure 10**. It is observed that the loss of two cables (EDC1&2) yields maximum DCR of EDCs and a safety factor of 1.67 is compulsory under normal loading condition which should be increased to achieve higher safety under extreme damaging condition.

In addition to that, the effect of corrosion as well as the combined effect of corrosion and cable loss on DCR of C1 and EDC1 are also examined at different safety factors in this study. For that, a simple corrosion model is adopted by introducing the uniform corrosion of 10% throughout the cable length as a change in cable area. The effective modulus of elasticity of corroded cable is determined and static analyses are performed. **Figure 11** shows that DCR of C1 is greater than 1.0 at a safety factor of 2.4 which indicates that the safety factor of 2.5 is the minimum factor required to avoid the rupture of C1. On the other hand, DCR of EDC1 is

Figure 10.
Effect of cable loss on DCR of stay cables of extradosed bridge. (a) Safety factor of 1.67 and (b) safety factor of 1.75.
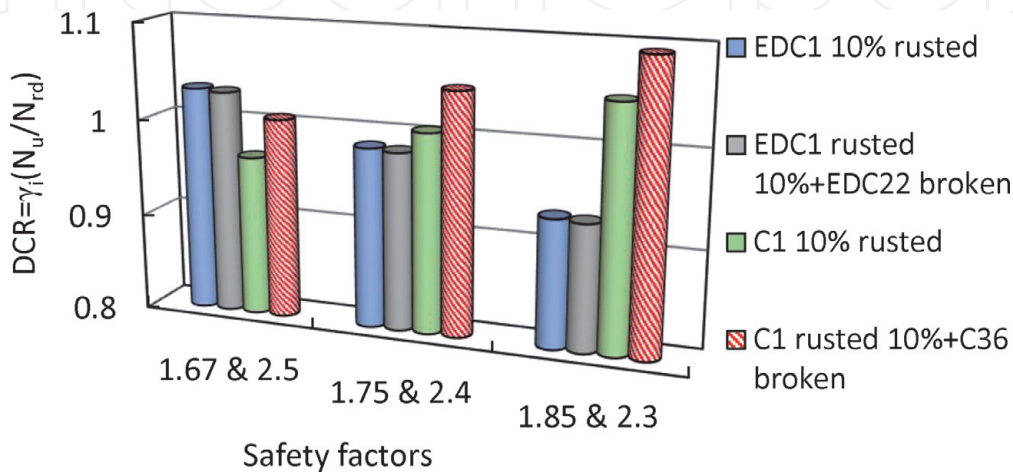
Figure 11.
Effect of corrosion and, combined effect of cable loss and corrosion on DCR of C1 and EDC1.

greater than 1.0 even at a safety factor of 1.67 which elucidates that a minimum safety factor of 1.75 is essential under extreme loading condition for the safe design of extradosed bridges.

4. Safety evaluation of stay cables by nondeterministic method

With the development of reliability-based methods, it has become evident that the traditional deterministic finite element method is not sufficient to properly design advanced structures or structural components subjected to a variety of complex loading conditions. Therefore, uncertainties in loads, material behavior and geometric configuration must be considered to provide rational reliability analysis and to describe the structural behavior with higher level of confidence.

In this paper, the safety factors of stay cables are also assessed by the nondeterministic method. For that, a probabilistic based reliability analysis code is prepared based on the mean value first order second moment (MVFOSM) reliability method. Basic random variables used for this program are material strength, dead loads and live loads. One million samples of normally distributed random variables are generated by using Monte Carlo simulation technique. The coefficient of variations (COV) of random variables are taken from the Ref. [13]. The program calculates the cable force (S) and resistance (R), and verifies the limit state function, i.e., $Z = R - S$ where R and S are linear and uncorrelated random variables. Subsequently, reliability index (β) and probability of failure (P_f) are determined from the relationships $\beta = \frac{\mu_z}{\sigma_z}$ and $P_f = \Phi(-\beta)$, respectively where μ_z is mean value, σ_z is standard deviation and Φ is cumulative distribution function for normal distribution.

For the acceptable values of probability of safety of structures, United States Army Corps of Engineers (USACE) suggests that the estimated reliability indices should be at least 3.0 (for above average performance) and 4.0 (for good performance) [14]. Based on it, the calculations of reliability index and failure probability for both bridge types are carried out and shown in **Tables 4** and **5**. These tables clarify that reliability index decreases when safety factor decreases from 2.5 to 2.2 in case of cable-stayed bridge. For instance, the safety factors of 2.5, 2.3 and 2.2 yield

Safety factor	β	P_f
2.5	8.17	1.48×10^{-16}
2.4	6.79	5.31×10^{-12}
2.3	5.04	2.36×10^{-7}
2.2	2.91	1.8×10^{-3}

Table 4.
Reliability analysis results of C1 of cable-stayed bridge.

Safety factor	β	P_f
1.60	1.9	2.84×10^{-2}
1.67	4.37	6.03×10^{-6}
1.75	6.81	4.66×10^{-12}
1.85	9.32	5.76×10^{-21}

Table 5.
Reliability analysis results of EDC1 of extradosed bridge.
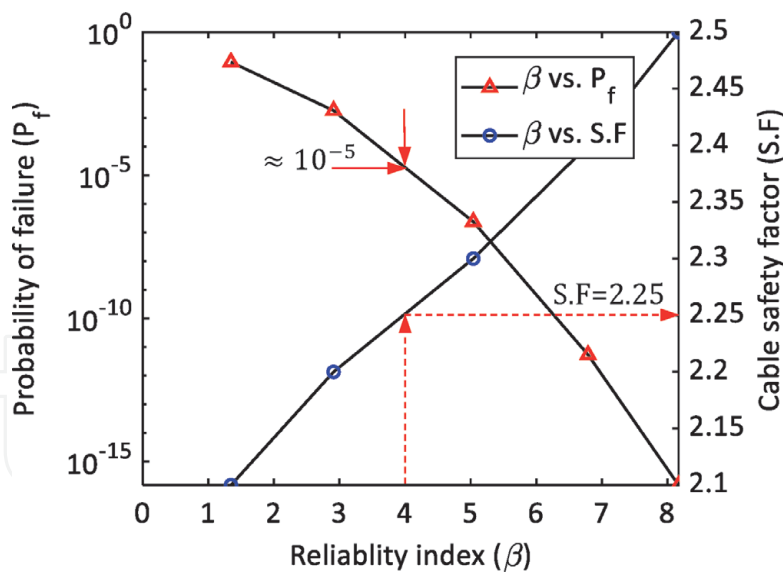
Figure 12.
Graphical evaluation of safety factor of C1 of cable-stayed bridge.
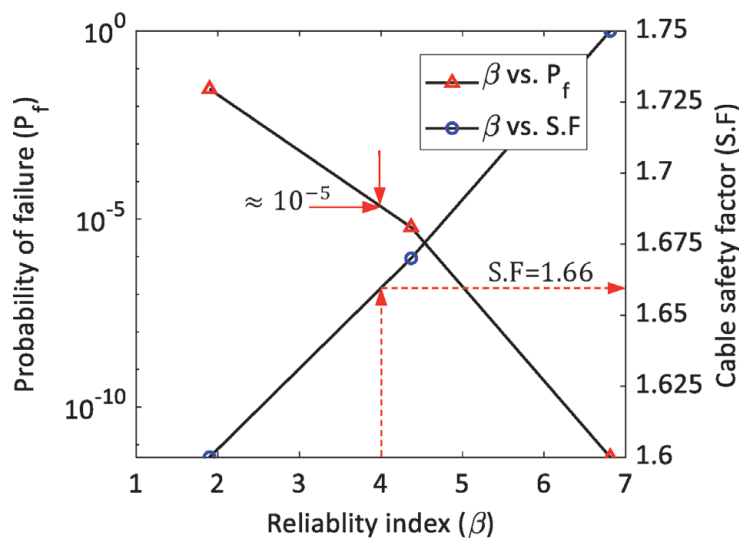
Figure 13.
Graphical evaluation of safety factor of EDC1 of extradosed bridge.

the reliability indices of 8.17, 5.04 and 2.91 for C1, respectively. Similarly, in case of extradosed bridge, the reliability index increases as safety factor increases from 1.60 to 1.85 for EDC1. The reliability analysis results also show that the safety factors of 2.3 and 1.67 yield the target reliability index greater than 4.0 for good performance of both bridge types. Based on these results, the optimum safety factors of C1 and EDC1 are calculated graphically as shown in **Figures 12** and **13**, respectively. It is observed that the safety factors of 2.25 and 1.66 yield the target reliability index of 4.0 and failure probability of 10^{-5} for stay cables C1 and EDC1, respectively. This also elucidates that the safety factor of 1.66 for extradosed bridges yields same reliability index as the safety factor of 2.25 for cable-stayed bridges.

5. Conclusions

In this paper, a parametric study on safety factor of stay cables of cable-stayed and extradosed bridges is carried out by using deterministic and nondeterministic methods. Following conclusions can be drawn from this study:

- Finite element analysis results show that cable-stayed and extradosed bridges are sufficiently redundant at safety factors ranging from 2.3 to 2.5 and 1.67, respectively under normal loading conditions. For cable-stayed bridges, ultimate strengths of stay cables are more critical than their fatigue strengths and a minimum safety factor of 2.3 is essential to satisfy the fatigue and ultimate limit states. However, in case of extradosed bridges, the ultimate strengths of stay cables are even more critical than their fatigue strengths and a minimum safety factor of 1.67 is indispensable to meet the limit state design requirements under normal loading conditions and it should be increased under extreme damaging conditions.

- The reliability analysis results elucidate that a minimum safety factor of 2.25 is necessary for stay cables of cable-stayed bridge to achieve the target reliability index of 4.0. Whereas, in case of extradosed bridge, a safety factor of 1.67 yields the reliability index greater than 4.0 and a minimum safety factor of 1.66 is essential for the safe design of extradosed bridges. Moreover, the safety factor of 1.66 for extradosed bridges yields same reliability index as the safety factor of 2.25 for cable-stayed bridges.

- The optimum safety factors evaluated by nondeterministic method are close to those obtained by deterministic finite element method. These outcomes imply that the structural reliability solutions for stay cables are rational and correct.

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References

[1] Collings D, Gonzalez AS. Extradosed and cable-stayed bridges, exploring the boundaries. Proceedings of the Institution of Civil Engineers—Bridge Engineering. 2013;**166**(4):231-239

[2] Prestressed Concrete Technical Institute. Extradosed Bridge Design and Construction Standard. Japan: Gihodo Shuppan; 2009

[3] Ali K, Katsuchi H, Yamada H. Parametric study on cable safety of cable-stayed bridge considering ultimate and fatigue limit states. Journal of Structural Engineering, JSCE. 2018; **64**(A):99-108

[4] Japan Road Association. Japanese Specifications for Highway Bridges. Japan; 2002

[5] Elishakoff I. Safety factors and reliability: Deterministic actual stress & random yield stress. Safety Factors and Reliability, Friends or Foes. 2004:75-96. Available from: https://doi.org/10.1007/978-1-4020-2131-2_4

[6] Xiangyang W, Guanghui Z. Bridge reliability analysis based on the FEM and Monte-Carlo method. In: 2010 International Conference on Intelligent Computation Technology and Automation. 2010

[7] Zhang W, Cai CS. Fatigue reliability assessment for existing bridges considering vehicle speed and road surface conditions. Journal of Bridge Engineering. 2012;**17**(3):443-453

[8] Japanese Society of Steel Construction. Fatigue Design Recommendations for Steel Structures. Japan; 1995

[9] Japan Society of Civil Engineers. Standard Specifications for Steel and Composite Structures. Japan; 2007

[10] American Association of State Highway and Transportation Officials. LRFD Bridge Design Specifications. America; 2012

[11] Mermigas K. Behavior and design of extradosed bridges [thesis]. Toronto: University of Toronto; 2008

[12] Post-tensioning institute. Recommendations for Stay cable design, testing and installation. America; 2007

[13] Nowak AS. Calibration of LRFD Bridge Design Code. NCHRP Report 368. Washington, DC: Transportation Research Board, National Research Council; 1999

[14] Phoon KK, editor. Reliability-Based Design in Geotechnical Engineering: Computations and Applications. London and New York: Taylor & Francis; 2008