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Evaluation of Rating Factors for Steel Cable-Stayed Bridges Using Load and Resistant Factor Rating

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Abstract

Since the girders and towers in cable-stayed bridges are subjected to bending moments as well as axial forces, the conventional load rating equation, which considers single force effect only, cannot be used to evaluate the load carrying capacity of cable-stayed bridges. The load rating equations for components in cable-stayed bridges have not currently been established yet. This paper proposes load rating equations for girders and towers in cable-stayed bridges using the interaction equations for beam-column members. Moving load analyses are performed for the cases of maximum axial compressive force, maximum positive moment and maximum negative moment for each component in cable-stayed bridges, and detailed procedures to apply proposed equations are presented. The Dolsan Grand Bridge is used to verify the validity of the proposed equations. The conventional load rating equation overestimates the rating factors of girders and towers in the Dolsan Grand Bridge, whereas proposed equations properly reflect the axial-flexural interaction behavior of girders and towers in cable-stayed bridges.

Keywords: Rating factor, Beam-column interaction equations, Cable-stayed bridge, Dolsan grand bridge

1. Introduction

Since harsh environmental conditions, aging materials and impacts from heavy vehicles cause defects that affect load carrying capacities of existing bridges in a service life, periodic evaluation and adequate maintenance process are needed in order to ensure safety and serviceability of bridge. Evaluation of load carrying capacity and condition inspection of existing bridges are performed as the processes prescribed in the condition evaluation manual of bridges (Korean ministry of construction and transportation, 2003; AASHTO, 1994; AASHTO, 2003). These processes are classified into three steps: analytical load rating of components, diagnostic field testing and safety evaluation of a bridge. Each step of condition evaluation of a bridge has complementary relations with each other. Analytical load ratings of a bridge are simple and economical, but analytical methods underestimate load carrying capacities of a bridge (Chajes *et al*., 1999; Barker, 1999). In contrast, field testing of a bridge have the advantage of reflecting current conditions of a bridge, but required great costs and engineers with wide experiences (Fu *et al.*, 1997).

For these reason, researchers have concentrated on the proper solutions in order to apply information from field-testing to analytical load ratings of a bridge. Shultz *et al.* (1995) proposed integrated load testing procedures for short and medium bridges. They used modified numerical models of bridges, which could reflect bridge behaviors from load testing and concluded that numerical models of bridges must be modified in order to estimate the exact load carrying capacities of bridges. Barker (1999) classified major factors for load carrying capacity of bridges into self-weight, impact factors, longitudinal distribution factor, transverse distribution factor, additional stiffness and composite effect. Similarly, Schenck *et al*. (1999) compared the load rating by analytical rating method with one by load testing for pony-truss bridges. On the other side, it was pointed out that the analytical load rating method is valid only when the bridges is subjected to the single force, such as bending moment, and it may not be applied when the bridges is subjected to more than a single forces.

However, it is well known that the main components of cable-stayed bridges are subjected to both bending and axial load. Therefore, the conventional rating equation for typical highway bridges cannot be applied to cable-stayed bridges. In addition, it is specified that the evaluation of load rating of complex bridges such as cable suspension bridges, cable-stayed bridges and curved girder bridges needs a special analysis and process in the prescribed condition evaluation manuals of bridges (Korean ministry of construction and transportation, 2003; AASHTO, 1994; AASHTO, 2003).

Despite the need for research, there are no reported studies for load ratings of cable-stayed bridges. Analytical

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load rating method of cable-stayed bridges is currently not established, whereas the stabilities of main components in cable-stayed bridges have been evaluated qualitatively. These provisional methods may cause bridge maintenance problems. Therefore, a rational quantitative rating method must be needed in order to evaluate the exact load carrying capacity of existing cable-stayed bridges.

The main objective of this paper is to propose reasonable rating equations for main components in a steel cable-stayed bridge. Main issues, which arise when the conventional rating equation is applied to a cable-stayed bridge, were summarized, and correlations between the conventional rating equation and the axial-flexural interaction equations were considered. New rating equations are proposed for girders and towers in a cable-stayed bridge in load and resistance factor rating. In order to prove the validity of the proposed equations, the Dolsan Grand Bridge was rated. Moving load analyses were performed to determine the live load case, which causes the maximum forces and moments in components. Three extreme conditions for the live load case were used: the maximum axial compressive forces, the maximum positive moments and the maximum negative moments in girders and towers. Rating factors by the proposed rating equations were compared with those by the conventional rating equation, and obtained results were discussed.

2. Load Rating Method for Conventional Highway Bridges

2.1. Rating equation in load and resistance factor rating

Load rating for conventional highway bridges are derived assuming that a component in a bridge is subject to a single force effect (axial force, flexural moment or shear force). Rating equation for components in a conventional highway bridge in load and resistance factor rating is expressed as (AASHTO, 2003)

$$RF=\frac{C-(\gamma_{DC})(DC)-(\gamma_{DW})(DW)\pm(\gamma_P)(P)}{(\gamma_L)(LL+IM)} \tag{1}$$

where C is the capacity of each component in a bridge. DC, DW, P and LL indicate the forces from dead loads of structural and nonstructural elements in a bridge, the forces from dead loads of pavements and other attachments, the forces from permanent loads except for dead loads, and the forces from live loads, respectively. In addition, IM is an impact factor for live loads and γ_{DC}, γ_{DW}, γ_P and γ_L represent load factors prescribed in the design specifications (AASHTO, 2004). Numerator terms of Eq. (1) means a redundancy of sectional forces in a component for axial forces, flexural moments or shear forces, whereas denominator terms of Eq. (1) indicate sectional forces from currently applied live loads. Therefore, rating factor calculated from Eq. (1) is the ratio of a redundancy in a component to a sectional force from live loads.

2.2. Considerations of applying the conventional rating equation to a cable-stayed bridge

As can be seen in Eq. (1), the conventional rating equation is derived on the assumption that a component of a bridge is subjected to a single force effect. Since components in a typical highway bridge is mainly subjected to flexural moments, it is reasonable that Eq. (1) is applied to a typical highway bridge in order to rate a bridge. However, it is questionable whether the conventional rating equation can be applied to girders and towers in a cable-stayed bridge or not, because girders and towers are beam-column components, which are subjected to axial forces as well as bending moments. The conventional rating equation as Eq. (1) cannot consider combined effect of axial forces and bending moments of a beam-column component.

Furthermore, prescribed manuals for condition evaluation of bridges specified that the conventional rating equation is only for typical highway bridges, and special analysis and procedures may be needed in order to evaluate complex bridges such as cable suspension bridges, cable-stayed bridges and curved girder bridges (Korean ministry of construction and transportation, 2003; AASHTO, 1994; AASHTO, 2003). In this paper, issues on load rating for cable-stayed bridges are summarized as follows:

(1) Since the term of capacity C in the conventional rating equation can reflect only a single force effect of a component, it cannot consider combined effects of axial-flexural interaction of girders and towers in a cable-stayed bridge.

(2) The conventional rating equation cannot handle the effect of secondary moments in beam-column components such as girders and towers in a cable-stayed bridge.

(3) It is specified that special analysis and procedures are needed in order to rate complex bridges in prescribed manuals of condition evaluation of bridges and the load rating equation for components in a cable-stayed bridge are not established yet.

3. A Proposal for Rating Equations for Girders and Towers in a Steel Cable-stayed Bridge

3.1. Interaction equations for beam-column components

It is well known that the secondary moments occur in beam-column components because of the combined effect between axial forces and flexural moments. Secondary moments are usually small and can be neglected in typical columns and beams. However, these effects must be considered if axial forces are large in beam-column components such as girders and towers in a cable-stayed bridge. The axial-flexural interaction equations as Table 1 are usually used to evaluate stabilities for beam-column components (AASHTO, 2004).

Table 1. Beam-column interaction equations

Axial force	Condition of axial force	Interaction equations
Tension	$\frac{P_u}{P_r}<0.2$	$\frac{P_u}{2P_r}+\left(\frac{M_{uy}}{M_{ry}}+\frac{M_{uz}}{M_{rz}}\right)\le 1.0$
	$\frac{P_u}{P_r}\ge 0.2$	$\frac{P_u}{P_r}+\frac{8}{9}\left(\frac{M_{uy}}{M_{ry}}+\frac{M_{uz}}{M_{rz}}\right)\le 1.0$
Compression	$\frac{P_u}{P_r}<0.2$	$\frac{P_u}{2P_r}+\left(\delta_y\frac{M_{uy}}{M_{ry}}+\delta_z\frac{M_{uz}}{M_{rz}}\right)\le 1.0$
	$\frac{P_u}{P_r}\ge 0.2$	$\frac{P_u}{2P_r}+\frac{8}{9}\left(\delta_y\frac{M_{uy}}{M_{ry}}+\delta_z\frac{M_{uz}}{M_{rz}}\right)\le 1.0$

where P_u, M_{uy}, M_{uz} are sectional forces and moments for each axis in components. P_r indicates tensile or compressive strength of components. M_{ry} and M_{rz} indicate flexural strengths of components. In addition, δ is introduced in order to consider secondary moments in beam-column components if compressive axial forces occur in components. Tensile strengths of components are determined as the minimum value between $\phi_y F_y A_y$ and $\phi_u F_u A_n U$, where ϕ_y and ϕ_u represent resistance factors for tensile yield and tensile fracture, respectively. A_g, A_n and U are the gross sectional area, the nominal sectional area and the reduction factor for shear lags, respectively. Compressive strength of components are determined as $0.66^{\lambda}F_yA_s$ or $0.88F_yA_s/\lambda$ according to their slenderness ratio (λ), where the slenderness ratio is defined as $\left(\frac{Kl}{r_s\pi}\right)\frac{F_y}{E}$ and F_y, E, A_s and r_s represent the yield strength, the modulus of elasticity, the gross sectional area and the radius of gyration, respectively. Kl indicates the effective buckling length for each components. Moreover, flexural strengths of components are calculated as $\phi_y F_y S$, where ϕ_f and S represent the flexural resistance factor and section modulus.

3.2. Correlation between the conventional rating equation and the axial-flexural interaction equations

The conventional rating equation can be transformed into the form of Eq. (2) by transposing left and right terms of Eq. (1)

$$\frac{RF(\gamma_L)(LL+IM)C+(\gamma_{DC})(DC)+(\gamma_{DW})(DW)\mp\gamma_P(P)}{C}=1.0 \tag{2}$$

As can be seen in Eq. (2), numerator terms in transposed conventional rating equation represent the sum of force and moment effects in components induced from dead loads, while nominator terms indicate the capacity of components. If force and moment terms on numerator in the axial-flexural interaction equations, Table 1, are divided into terms of dead loads and live loads including RF, these equations are the conceptually same as the conventional rating equation, Eq. (2). Therefore, in this study, the numerator terms of force and moments in the axial-flexural interaction equations, Table 1, are split into the terms of dead loads and live loads including RF, as shown Eqs. (3)-(5)

$$P_u=P_u^d+RF\cdot P_u^l \tag{3}$$

$$M_{uy}=M_{uy}^d+RF\cdot M_{uy}^l \tag{4}$$

$$M_{uz}=M_{uz}^d+RF\cdot M_{uz}^l \tag{5}$$

where superscript d and l represent sectional forces from dead loads and live loads, respectively. Rating equations for beam-column components can be derived by substituting Eqs. (3)-(5) into the axial-flexural interaction equations.

3.3. Proposed rating equations for girders and towers in a steel cable-stayed bridge

Rating equations for girders and towers in a steel cable-stayed bridge are proposed in this study by using previously stated procedures in chapter 3.2. The proposed rating equations for girders and towers in a cable-stayed bridge can be classified according to the sign of axial forces in components.

1) If tensile axial forces occur in components ($P_u^d+RF\cdot P_u^l\ge 0$)

If $\frac{P_u^d+RF\cdot P_u^l}{P_r}<0.2$:

$$\frac{P_u^d+RF\cdot P_u^l}{2P_r}+\left(\frac{M_{uy}^d+RF\cdot M_{uy}^l}{M_{ry}}+\frac{M_{uz}^d+RF\cdot M_{uz}^l}{M_{rz}}\right)\le 1.0 \tag{6}$$

If $\frac{P_u^d+RF\cdot P_u^l}{P_r}\ge 0.2$:

$$\frac{P_u^d+RF\cdot P_u^l}{P_r}+\frac{8}{9}\left(\frac{M_{uy}^d+RF\cdot M_{uy}^l}{M_{ry}}+\frac{M_{uz}^d+RF\cdot M_{uz}^l}{M_{rz}}\right)\le 1.0 \tag{7}$$

where P_r, M_{ry} and M_{rz} are the tensile strengths and the flexural strengths for each axis, respectively. P_u, M_{uy} and M_{uz} indicate sectional forces and moments in components induced from currently applied dead loads and live loads.

2) If compressive axial forces occur in components ($P_u^d+RF\cdot P_u^l<0$)

If $\dfrac{P_u^d+RF\cdot P_u^l}{P_r}<0.2$:

$$\frac{P_u^d+RF\cdot P_u^l}{2P_r}+\left(\delta_y\frac{M_{uy}^d+RF\cdot M_{uy}^l}{M_{ry}}+\delta_z\frac{M_{uz}^d+RF\cdot M_{uz}^l}{M_{rz}}\right)\le 1.0 \tag{8}$$

If $\dfrac{P_u^d+RF\cdot P_u^l}{P_r}\ge 0.2$:

$$\frac{P_u^d+RF\cdot P_u^l}{P_r}+\frac{8}{9}\left(\delta_y\frac{M_{uy}^d+RF\cdot M_{uy}^l}{M_{ry}}+\delta_z\frac{M_{uz}^d+RF\cdot M_{uz}^l}{M_{rz}}\right)\le 1.0 \tag{9}$$

where P_r is the compressive strength of components. Moment amplification factors (δ) must be introduced in order to consider secondary moments in components. Moment amplification factors for each axis are defined as

$$\delta_y=\frac{1}{1-\dfrac{P_u^d+RF\cdot P_u^l}{0.9P_{ey}}},\quad \delta_z=\frac{1}{1-\dfrac{P_u^d+RF\cdot P_u^l}{0.9P_{ez}}} \tag{10}$$

where P_{ey} and P_{ez} are the Euler buckling loads. The compressive strength P_r and Euler buckling load is closely associated with its effective buckling length. According to the literature, the effective buckling length for components in a cable-stayed bridge can be determined by elastic buckling analysis and inelastic buckling analysis (Choi *et al*., 2005, and Zu-Yan *et al*., 2004). In this study, elastic buckling analysis is used to calculate the effective buckling length of components in a cable-stayed bridge.

3.4. Procedure for determination of rating factors

The proposed rating equations are derived based on the axial-flexural interaction equations for beam-columns. Fig. 1 (a) shows the relations between rating factors and the axial-flexural interaction equations in a plane surface. In Fig. 1(a), RF_n indicates the rating factors, which are calculated when live loads increase by *n* times of initial values; thus RF_0 is the rating factor considering only dead loads excluding live load. The conclusive rating factor of a component is determined at the point where the increasing rating factor meets the axial-flexural interaction curve. Fig. 1 (b) shows the relations between rating factors and the axial-flexural interaction equations in 3-dimensional space. A component is stable when the sum of sectional forces and moments in a component is in the boundary of surface of the axial-flexural interaction curve. Therefore, the conclusive rating factor of a component is also determined when the increasing rating factor meets the axial-flexural interaction curve.

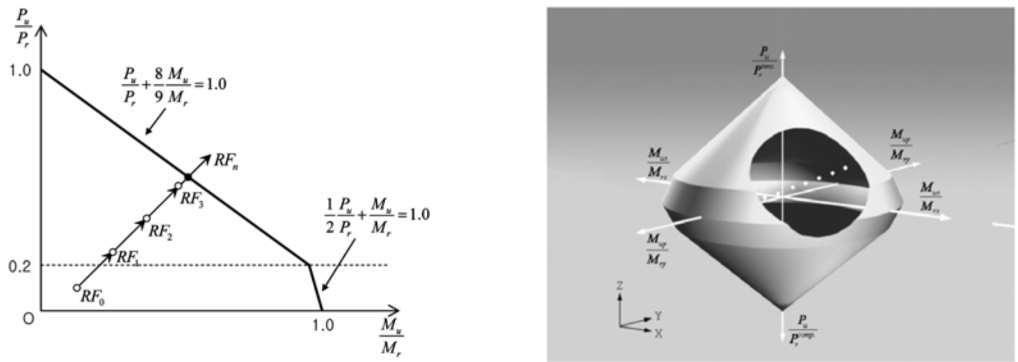
In order to calculate rating factors of girders and towers in a cable-stayed bridge, the first step is to determine dead load-induced sectional forces and moments (P_u^d, M_{uy}^d, M_{uz}^d) of components by linear static stress analysis. The second step is that live load-induced sectional forces and moments (P_u^l, M_{uy}^l, M_{uz}^l) of components are determined as follow.

① Moving load analyses are performed in order to obtain each type of live loads so the maximum forces and moments occur in each component. Table 2 shows the conditions of extreme cases for live loads. Three extreme cases are considered in this study: live load case where the maximum axial compressive force occurs in a component, live load case where the maximum positive moment occurs in a component, and live load case where the maximum negative moment occurs in a component.

② Calculate rating factors for all of component by using the proposed rating equations. However, it is impossible to choose which equation is appropriate to calculate the reasonable rating factor of a component because the condition of equations in Eqs. (6)-(9) include undetermined value, RF.

③ All rating factors from Eqs. (6)-(9) should be calculated for each component, and the proper rating factor can be found out by substituting all of calculated rating factors to the each condition of equations in Eqs. (6)-(9).

Since three live load cases are obtained per component



(a) In a plane surface (b) In a 3-dimensional space

Figure 1. Rating factors and the axial-flexural interaction equations.

Table 2. Extreme cases for live loads in moving load analysis

	Sectional forces for each member	P_u^l	M_{uy}^l	M_{uz}^l
Case 1	Maximum Axial Compressive forces	$P_{u,\min}^l$	M_{uy}^l	M_{uz}^l
Case 2	Maximum Positive flexural forces	P_u^l	$M_{uy,\max}^l$	M_{uz}^l
Case 3	Maximum Negative flexural forces	P_u^l	$M_{uy,\min}^l$	M_{uz}^l

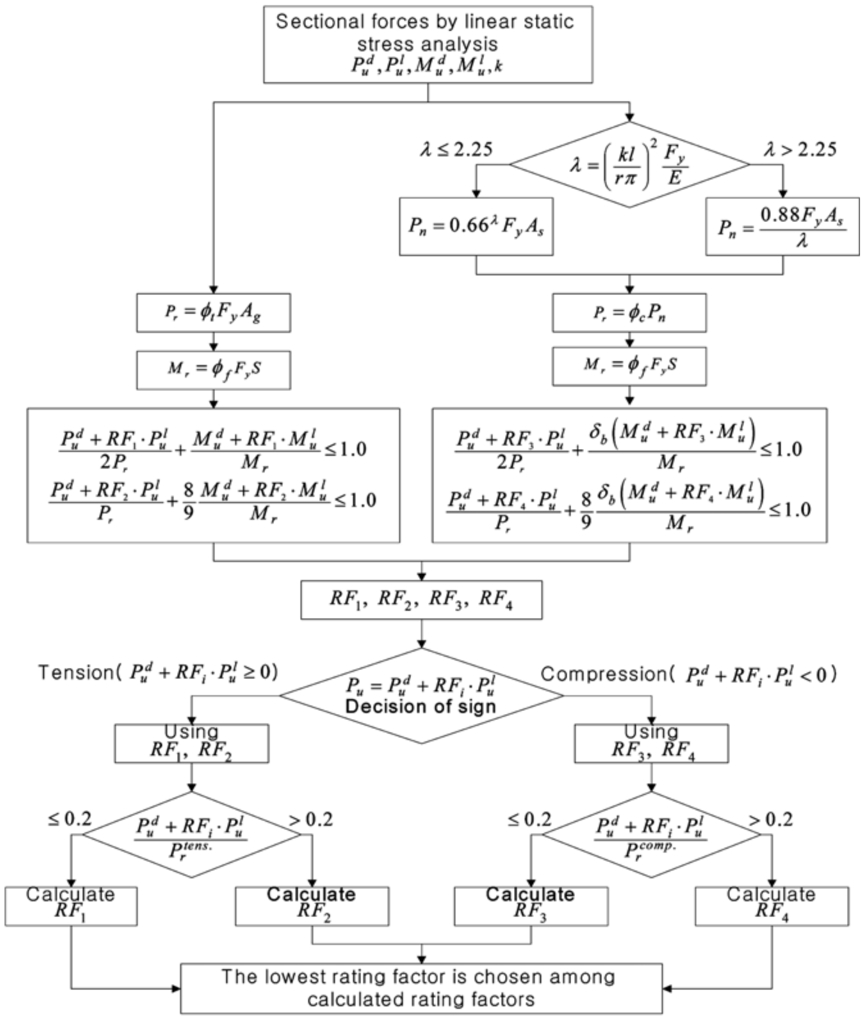


Figure 2. Calculation procedures of rating factors using the proposed rating equations.

by moving load analyses for three extreme cases, the rating factor of a component is determined as the minimum values among rating factors calculated for each extreme cases. Fig. 2 presents calculating procedures of rating factors using the proposed rating equations.

4. Application to the Existing Bridge

4.1. The numerical model of the Dolsan Grand Bridge

The Dolsan Grand Bridge is analyzed in order to verify the proposed rating equations. Rating factors of each component in the Dolsan Grand Bridge using the proposed rating equations are compared with those using the conventional rating equations.

The Dolsan Grand Bridge is a steel cable-stayed bridge with a center span of 280 m. It has three continuous girders and two towers. Girders and towers in the Dolsan Grand Bridge are modeled as 48 frame elements and 50 frame elements, respectively. All sections of girders and towers are idealized as one cell box. Cables in the Dolsan Grand Bridge are modeled by 56 bar elements. In addition, the equivalent modulus of elasticity is applied to bar elements in order to consider the sag nonlinearity of cables. Rigid elements are used between the centroid of

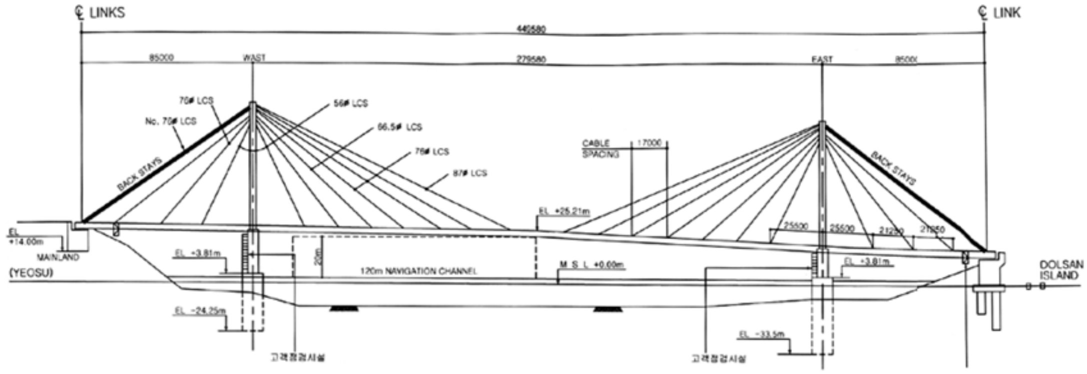
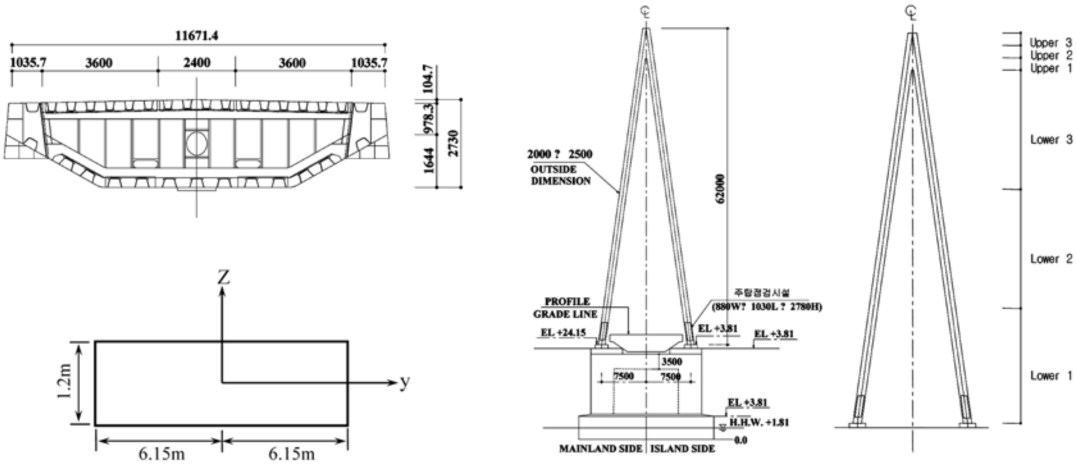


Figure 3. Elevation view of the Dolsan Grand Bridge.



(a) A cross section of girder (b) A cross section of tower

Figure 4. Girders and towers in the Dolsan Grand Bridge.

girders and the anchored location. Four types of cables are used in the Dolsan Grand Bridge according to a sectional area, and the allowable stress of cables is 520 MPa (Korea infrastructure safety & technology corporation, 2001). Fig. 3 shows the elevation view and 3-dimensional model of the Dolsan Grand Bridge. Fig. 4 shows the sections of girders and towers. In addition, Table 3 summarizes sectional and material information of components in the Dolsan Grand Bridge.

4.2. Moving load analysis

The design loads of the Dolsan Grand Bridge consist of dead loads and design live loads. Dead loads include self-weight, additional attachments, initial cable forces, pedestrian loads, temperature loads and wind loads. Design live loads are applied to the bridge as DL-18 prescribed in Korean Highway Bridge Design Specifications. Since the objective of this paper is to propose new rating equations and to verify the validity of the proposed equations, only dead loads, which included only self-weight and initial cable forces, and design live loads are considered in this paper. The impact factor for girders is 0.18 and it is determined by field testing (Korea Infrastructure Safety & Technology Corporation, 2001). Table 4 presents dead

Table 3. Sectional and material information of girders and towers in the Dolsan Grand Bridge

		A (m^2)	J (m^4)	I_y (m^4)	I_z (m^4)	Material
Girder		0.455	1.49	0.64	6.17	SM490
Tower	Lower part1	0.30	0.36	0.20	0.30	
	Lower part 2	0.24	0.29	0.16	0.24	
	Lower part 3	0.22	0.26	0.15	0.21	
	Upper part 1	0.88	2.10	2.25	1.10	
	Upper part 2	0.86	2.66	1.96	1.69	
	Upper part 3	0.80	2.06	1.33	1.33	

Table 4. Dead loads and design live loads of the Dolsan Grand Bridge

Load case		Load	Note
Dead Load	Self-weight	Self-weight of girder and tower	Girder: 144.4 kN/m^3 Tower: 78.1 kN/m^3 (upper) 103.1 kN/m^3 (lower)
	Initial cable forces	Field testing	Equivalent modulus elasticity
Live Load	Design live load	DL-18 (Korean highway bridge design specifications)	Traffic lane load: 9.3 kN Concentrated load: 158.9 kN
	Impact factor	0.18	

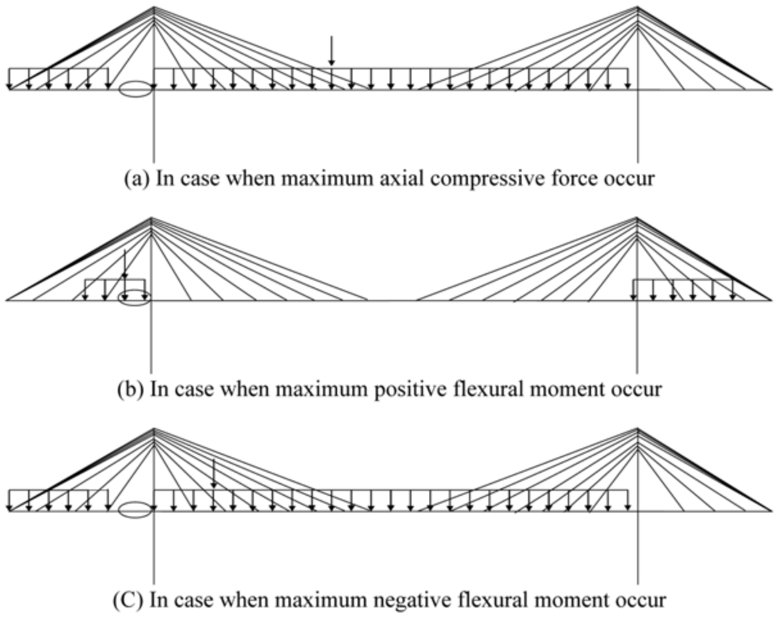


Figure 5. Three live load cases determined from moving load analyses.

loads and design live loads of the Dolsan Grand Bridge.

Moving load analyses are performed for the live load cases where the maximum axial compressive forces, the maximum positive moment and the maximum negative moment occur at girders and towers. Therefore, there are three types of live load cases per component, and three numbers of rating factors are calculated for each component. The minimum rating factor is chosen among these three rating factors. In contrast, moving load analysis are performed only for the live load case where the maximum axial tensile forces occur at cables because cables are subjected to only axial tensile forces. Fig. 4 shows three live load cases determined from moving load analyses when the maximum axial compressible forces, the maximum positive moment and the maximum negative moment occurs at the component, which are located at intersection between girders and left towers.

4.3. Rating factors of girders and towers in the Dolsan Grand Bridge

Figs 6-8 show comparisons of rating factors of girders by the proposed rating equations and the conventional rating equation for three extreme cases in moving load analyses of the Dolsan Grand Bridge. In addition, Fig. 9 shows the comparison of the minimum rating factors. The horizontal axis and the vertical axis represent the location of girders measured from the left end of girders and rating factors of girders, respectively.

In Fig. 6, there are two kinds of conventional rating equation according to application force: axial compressive forces and flexural forces. For conventional rating equation with axial force, since the largest axial compressive forces in each girder by moving load analyses does not change, the rating factors of girders near of the intersection between girders and towers are almost the same, irrespective of the location, whereas rating factors increase to very large values in girders near the center of span. This phenomenon is because that very small axial force from moving load analyses occurs in these girders. Although Fig. 6 presents rating factors of girders for the extreme cases of live loads where the maximum compressive force occurs in girders, rating factors by the

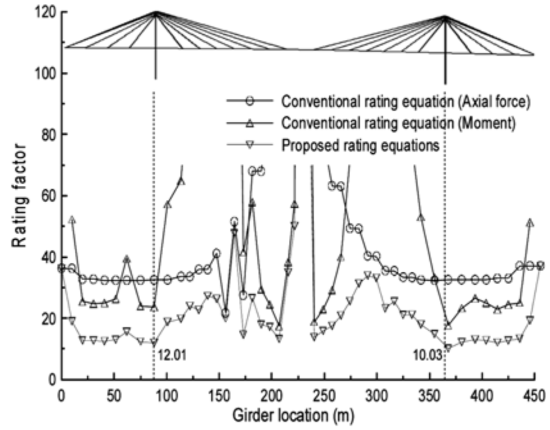


Figure 6. Rating factors for the extreme case of live load (Case 1: maximum axial compressive forces in girders).

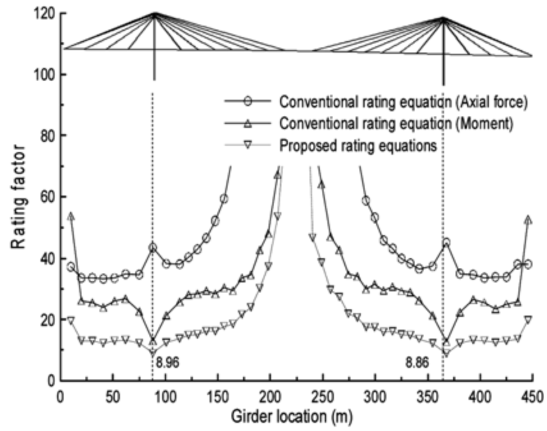


Figure 8. Rating factors for the extreme case of live load (Case 3: maximum negative moments in girders).

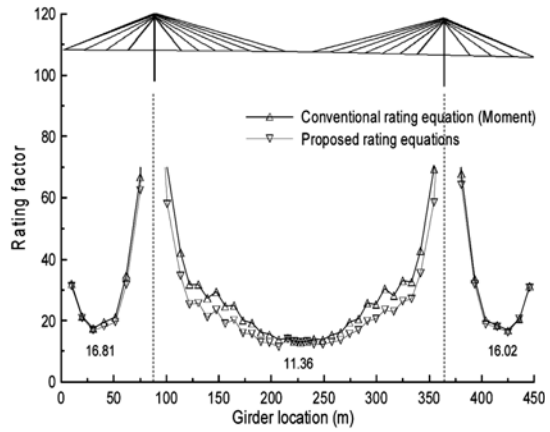


Figure 7. Rating factors for the extreme case of live load (Case 2: maximum positive moments in girders).

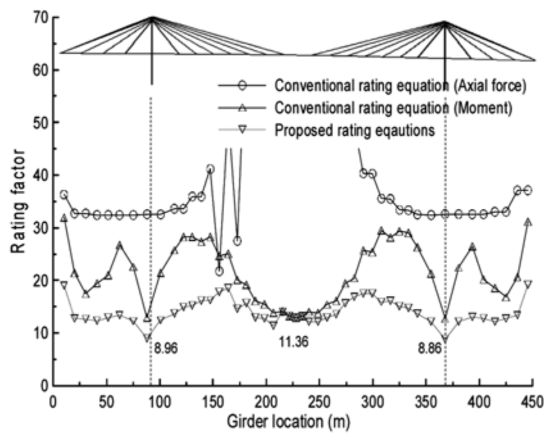


Figure 9. The minimum rating factors of girders for three extreme load cases.

conventional rating equation for moment are smaller than those for axial force in some portions of girders. Rating factors of girders by the proposed rating equations are smaller than those by the conventional rating equations with axial force and moment in all location of girders. In girder, the lowest rating factor is calculated on the intersection between girders and towers; thus, it can be concluded that the proposed rating equations can consider axial-flexural combined effect of girders.

Fig. 7 presents rating factors of girders for the extreme case of live loads where the maximum positive moment occurs in girders. Since the axial force of each girder for this case by moving load analyses is very small, rating factors by the conventional rating equation with axial force are calculated as the values larger than 120; thus they are excluded in Fig. 7. For the case of the conventional rating equation with moment, the lowest rating factor is calculated at the girders near of the center of span, where the maximum positive moment occurs. Similar trends are shown in Fig. 7 for rating factors by the proposed rating equations.

Fig. 8 shows rating factors of girders for the extreme case of live loads where the maximum negative moment occurs in girders. In contrast with the extreme case of the positive moment in Fig. 7, the effect of axial forces on rating factors of girders cannot be negligible in this extreme case of the negative moment. The lowest rating factor of girders is calculated at the girders near the intersection between girders and towers, where the maximum negative moment occurs.

For three extreme cases of live loads, the minimum rating factors of girders by the conventional rating equation and the proposed rating equations are summarized in Fig. 9. It can be seen that rating factors by the conventional rating equation with axial force terms are smaller than those with moment terms in all locations of girders. Moreover, the effect of axial forces on rating factors is considerable at the girders near of the intersection between girders and towers, whereas it can be negligible at the girders near the center of span. Therefore, for the girders near the center of span, the rating factors by the proposed rating equations are nearly the same with those of the conventional rating equation with moment terms. On the contrary, rating factors by the proposed rating

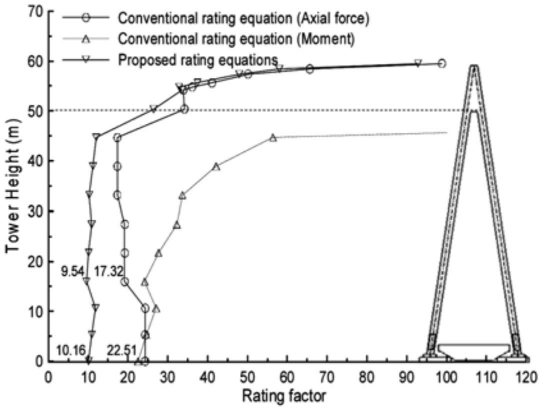


Figure 10. Rating factors for the extreme case of live load (Case 1: maximum axial compressive forces in towers).

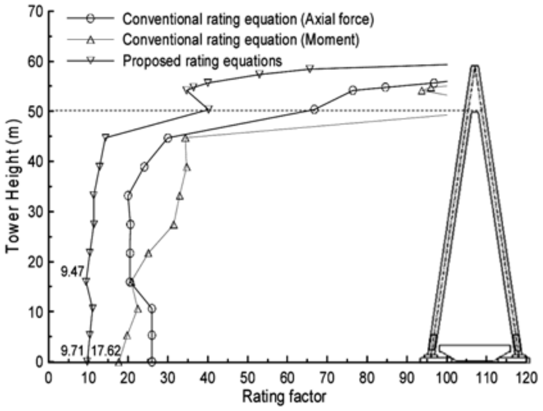


Figure 11. Rating factors for the extreme case of live load (Case 2: maximum moments in towers).

equations are smaller than those by the conventional rating equation with moment terms for the girders near the intersection between girders and towers.

Consequently, the conventional rating equation overestimates rating factors of girders in a bridge, whereas the proposed rating equations result in reasonable rating factors of girders since the proposed rating equations can reflect the axial-flexural combined effect of girders in a cable-stayed bridge.

4.4. Rating factors of towers in the Dolsan Grand Bridge

Figs 10-12 show rating factors of towers in the Dolsan Grand Bridge. The horizontal axis and the vertical axis in Figs. 10-12 indicate rating factors of towers and the height of towers, respectively. For the conventional rating equation, rating factors of towers are calculated according to two situations: with axial force terms and with moment terms.

Fig. 10 shows rating factors of towers for the extreme case of live loads where the maximum axial compressive force occurs at towers. In the case of the conventional rating equation, it can be seen that rating factors of towers

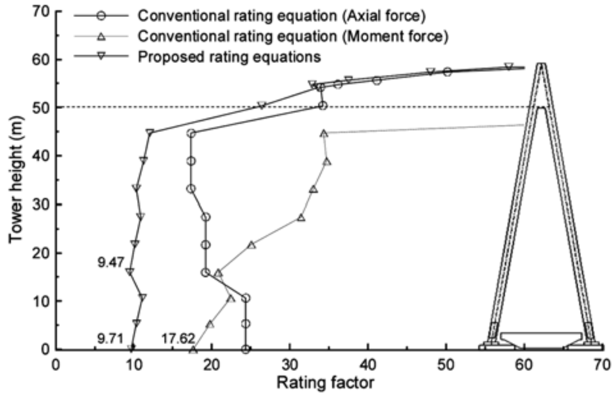


Figure 12. The minimum rating factors of towers for three extreme load cases.

are more susceptible to axial forces than moments because rating factors with axial terms are smaller than those with moment terms in all locations of towers. Rating factors of towers increase abruptly at the upper parts of towers in Fig. 10. It is probably because sectional properties of upper parts of towers are different with those of lower parts as shown in Table 3. The rating factors of towers by the proposed rating equations are smaller than those of the conventional rating equation with axial force terms and moment terms.

Fig. 11 shows rating factors of towers for the extreme case of live loads, which the maximum moment occurs at towers. In the case of the conventional rating equation, rating factors with axial force are smaller than those with moment in all locations of towers except the lowest parts, though Fig. 11 is for the extreme case of moments. Therefore, it can be concluded that the effect of axial forces on rating factors of towers is larger than the effect of moments.

The minimum rating factors of towers for three extreme cases are presented in Fig. 12. In the similar manner for girders, it can be seen that rating factors by the proposed rating equations are smaller than those of the conventional equations with axial force terms and moment terms; thus the proposed rating equations are proven reasonable for evaluation of rating factors of towers in a cable-stayed bridge.

5. Conclusions

The paper proposes new rating equations for girders and towers in steel cable-stayed bridge in load and resistance factor rating. In order to prove the validity of the proposed equations, the Dolsan Grand Bridge is evaluated. Rating factors by the proposed rating equations are compared with those by the conventional rating equation and following conclusions are made.

(1) The conventional rating equation for typical highway bridges is inadequate for cable-stayed bridges because it can consider only a single force effect, not a

combined force effect of girders and towers in cable-stayed bridges.

(2) The proposed rating equations are derived from the axial-flexural interaction equations in load and resistance factor rating. Quantitative rating factors of girders and towers in a cable-stayed bridge can be obtained by the proposed rating equations.

(3) The conventional rating equation overestimates rating factors of girders and towers. In constrast, the proposed rating equations are proven reasonable since the axial-flexural combined effect of components in a cable-stayed bridge can be considered properly in the proposed rating equations.

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