STEEL STRUCTURES
Steel Structures 8 (2008) 109-118
www.ijoss.org

External Post-tensioning of Composite Bridges by a Rating Equation Considering the Increment of a Tendon Force Due to Live Loads

Dong-Ho Choi, Yong-Sik Kim and Hoon Yoo*

Department of Civil Engineering, Hanyang University, 17 Haengdang-dong, Seoungdong-gu, Seoul 133-791, South Korea

Abstract

Strengthening by external post-tensioning is an effective technique to restore the load-carrying capacity of many types of bridge superstructures. In this paper, external tendons are used for strengthening steel-concrete composite bridges. Analytic expressions for the increment of the initial tendon force are derived by the principle of virtual work for configurations of straight and draped tendons under design loads. A new rating equation for bridges is then introduced considering the initial tendon force and its increment. A systematic procedure is illustrated to determine the number of strands in external tendons and the initial tendon force using the proposed rating equation. It is demonstrated with an example bridge that the proposed method is suitable for the strengthening of existing bridges with an external post-tensioning technique.

Keywords: Strengthening, External post-tensioning, Rating Equation, Initial tendon force, Increment of tendon force

1. Introduction

Many bridges that were designed to previous loading specifications or that have suffered damage or aging, are now inadequate for current traffic loadings. In general, existing bridge strengthening as an alternative to complete replacement or construction of a new one can provide an effective and economic solution (Conner *et al*., 2005). Post-tensioning with external tendons has been considered an effective method of strengthening or rehabilitating existing bridges (Troisky, 1989). The advantages of this technique are to enlarge the elastic range of bridge behavior, to increase the ultimate load capacity of bridges, and to improve the fatigue and fracture strength of bridge components (Saadatmanesh *et al*. 1989a; 1989b; 1989c). In addition, this technique is easy to perform and convenient to maintain because the tendons are exposed outside of bridges. For this reason, post-tensioning with external tendons has been widely applied to various types of bridges as a means of strengthening existing bridges (Harajli 1993, Ng 2003).

There are many achievements for the post-tensioning technique concerning both experimental and analytical results. Interesting work was done in three consecutive papers by Saadatmanesh *et al*. (1989a, b and c). They derived analytical equations for positive and negative moment regions in composite girders strengthened with external tendons, and showed the validity of the analytical approach by comparing it with experimental results. Tong and Saadatmanesh (1992) proposed a general model for analytical approach in composite girders strengthened with external tendons and studied the behavior of continuous composite girders considering the effects of design variables such as the initial tendon force, eccentricity of tendons, tendon configurations and the length of tendons. Li *et al*. (1995) investigated the fatigue behavior of composite steel-concrete bridges by strengthening bridges with external tendons. They carried out parametric studies of the fatigue test for various components such as strands, shear studs, and cover plates and discussed the results by comparing them with the current bridge design specifications. Similarly, the external post-tensioning technique for strengthening existing bridges has been adopted to the wide rages of applications such as strengthening of two continuous span bridges (Kaliber *et al*., 1998), investigation of nonlinear behavior (Dall'Asta *et al*., 1998), analytical models for dynamic behavior (Miyamoto *et al*., 2000), and the behavior of lateral-torsional buckling (Gupta *et al*., 2003). Recently, Park *et al*. (2005) investigated the behavior of an in-service plate girder bridge strengthened with external pre-stressing tendons. A field-load test was performed using a design truck load to evaluate the behavior of the bridge

This manuscript for this paper was submitted for review and possible publication on June 3, 2008; approved on June 23, 2008.

*Corresponding author
Tel.: +82-2-2220-0328; Fax: +82-2-2220-4322
E-mail: csmile@hanyang.ac.kr

before and after strengthening. Based on these previous achievements, we realize that the variables such as the configuration of tendons, the number of strands and the initial tendon force should be considered carefully with respect to the behavior of the bridges in order to strengthen existing bridges with external tendons effectively.

The main objective of this paper is to propose a new rating equation considering the increment of the tendon force due to live loads of bridges in order to determine optimum numbers of strands in external tendons and the initial tendon force. Post-tensioning with external tendons is used for strengthening of steel-concrete composite bridges. Analytic expressions considering the increment of the initial tendon force are derived using the principle of virtual work for configurations of straight and draped tendons under external loads. Based on these analytical expressions, a new rating factor equation is proposed considering the initial tendon force and its increment under external loads. A systematic procedure is illustrated to determine the number of strands in external tendons and the initial tendon force using the proposed rating equation. An example bridge is also given to demonstrate the effect of the proposed equation on increasing the load-carrying capacity of existing steel-concrete composite bridges.

2. Behavior of a Composite Beam Strengthened with External Tendons

2.1. Stress distribution

Figure 1 shows the stress distribution in any cross section of a simply supported composite beam strengthened with external tendons under each stage of loading. Dead load and live load cause compressive stresses in the concrete slab and top flange, and tensile stresses in the bottom flange of a steel beam (f_{DL} and f_{LL} in Fig. 1). The external tendon force causes compressive stress throughout the cross section of a bridge. The negative moment due to the tendon force causes a tensile stress in the upper section, and a compressive stress in the lower section of the neutral axis (f_T in Fig. 1). Since the initial tendon force is introduced to a bridge under the dead load, this force may change when a bridge is subjected to live loading. Accordingly, the increment of a tendon force also causes stresses in the cross section of a composite beam as does the initial tendon force ($f_{\Delta T}$ in Fig. 1). The total stress of the cross section (f_{total} in Fig. 1) are calculated analytically by Eqs. (1)-(3).

$$f_c^{\,t} = \frac{1}{n}\left(-\frac{M_{DL}}{I_{cp}}y_{ct} - \frac{T}{A_{cp}} + \frac{Te_{cp}}{I_{cp}}y_{ct} - \frac{M_{LL}}{I_{cp}}y_{ct} - \frac{\Delta T}{A_{cp}} + \frac{\Delta Te_{cp}}{I_{cp}}y_{ct}\right) \quad (1)$$

$$f_s^{\,t} = -\frac{M_{DL}}{I_{cp}}y_{st} - \frac{T}{A_{cp}} + \frac{Te_{cp}}{I_{cp}}y_{st} - \frac{M_{LL}}{I_{cp}}y_{st} - \frac{\Delta T}{A_{cp}} + \frac{\Delta Te_{cp}}{I_{cp}}y_{st} \quad (2)$$

$$f_s^{\,b} = +\frac{M_{DL}}{I_{cp}}y_{sb} - \frac{T}{A_{cp}} - \frac{Te_{cp}}{I_{cp}}y_{sb} + \frac{M_{LL}}{I_{cp}}y_{sb} - \frac{\Delta T}{A_{cp}} - \frac{\Delta Te_{cp}}{I_{cp}}y_{sb} \quad (3)$$

where $f_c^{\,t}$ = stress at the top of a concrete slab; $f_s^{\,t}$ = stress at the top of a upper flange; $f_s^{\,b}$ = stress at the bottom of a lower flange; M_{DL} = moment due to the dead load; T = tendon tensile force; M_{LL} = moment due to the live load; ΔT = increment of a tendon tensile force due to the live load; I_{cp} = moment of inertia of a transformed composite section; A_{cp} = cross-sectional area of a transformed composite section; e_{cp} = eccentricity of a tendon with respect to the neutral axis of a composite section; y = distance from the considered point to the neutral axis of a composite section; n = the modulus ratio of a steel beam to a concrete slab. The plus sign indicate a tensile stress.

2.2. Loads and tendon configurations

Figure 2(a) shows the bending moment diagram of a simply supported bridge subjected to the truck load and the lane loads. Figure 2(b) and 2(c) show bending moment diagrams for the tendon configurations of straight and draped cases considered in this study. Under the truck load (DB) and the lane load (DL) prescribed in the Korean Highway Bridge design Specification (KHBS, 2005), the increment of a tendon force is calculated with respect to different tendon configurations in Fig. 2(b) and 2(c). For the DB-truck, the ratio of axle loads (A, B and C in Fig. 2(a)) is 1/4 : 1 : 1, and the distances among axles of the DB-truck are K and V. The DL-lane load is composed of an equally distributed load (q) and two concentrated loads (P_m and P_s).

2.3. Determination of the increment of a tendon force by virtual work principle

The increment of a tendon force for different tendon configurations can be determined by various approaches such as the principle of virtual work (Saadatmanesh *et al.*

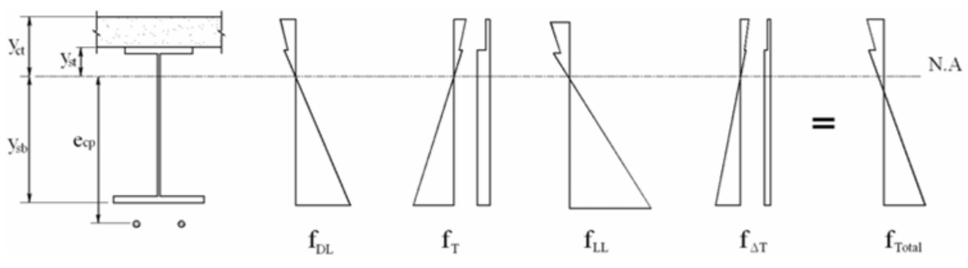


Figure 1. Stress distribution of a composite beam strengthened with external tendons under each stage of loading.

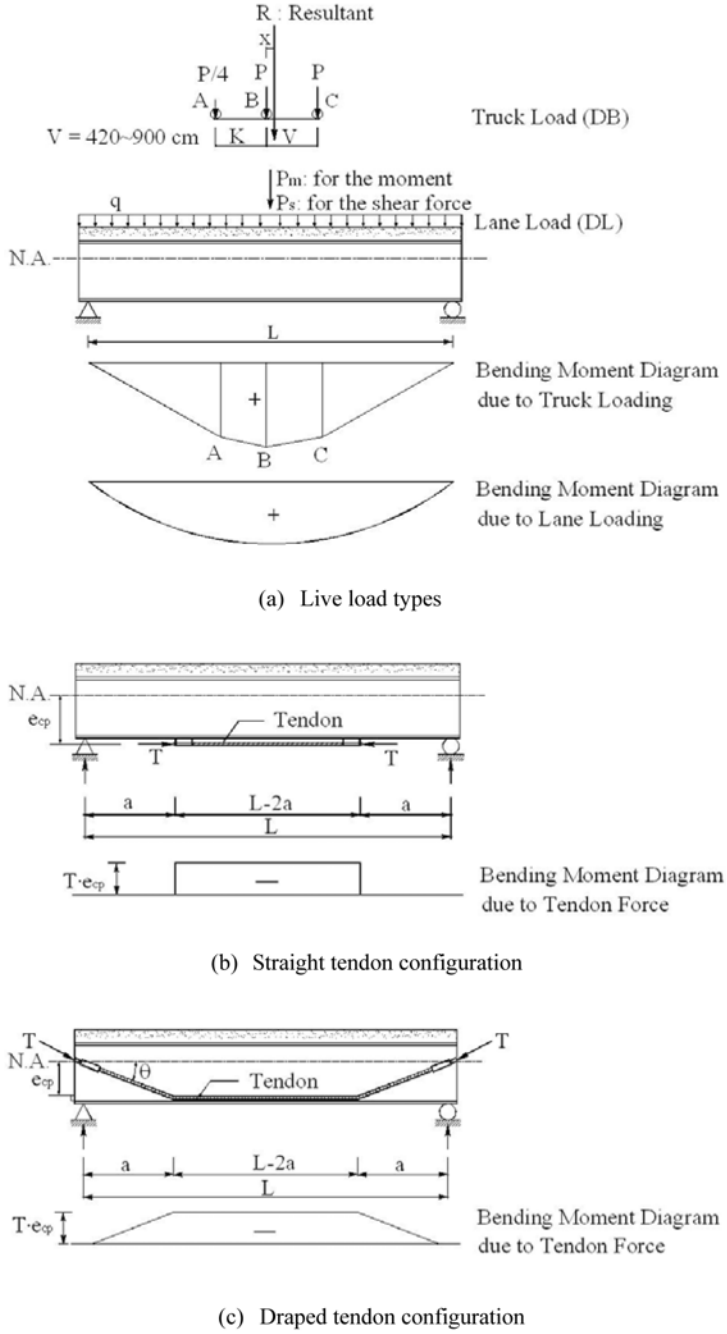


Figure 2. Bending moment diagrams of a simply supported bridge.

1989c, Troitsky 1990), incremental deformation method (Saadatmanesh *et al*. 1989a) and finite element analysis. In this study, we selected the principle of virtual work to determine the increment of a tendon.

Based on the geometric compatibility, the displacement at the center of a bridge caused by a unit tendon force should be equal to the displacement due to applied loads. The compatibility condition at the center of a bridge may be written as (Saadatmanesh *et al*., 1989; Troitsky, 1990)

$$\delta_{11}\Delta T + \delta_{1P} = 0 \tag{4}$$

where δ_{11} and δ_{1P} are the displacements due to a unit tendon force and applied loads, respectively.

For the straight tendon configuration in Fig. 2(b), each term of displacements is given by the principle of virtual work as

$$\delta_{11} = (L-2a)\left(\frac{e^2}{E_sI_{cp}} + \frac{1}{E_sA_{cp}} + \frac{1}{E_tA_t}\right) \tag{5}$$

$$\delta_{1P} = \frac{Pe}{E_sI_{cp}}(0.281L^2 + 0.532K^2 - 1.125a^2)$$

for the DB-truck load (6)

$$\delta_{1P}=\frac{qe}{12E_sI_{cp}}(4a^3-6a^2L+L^3)$$

for the DL-lane load (7)

where E_s is the elastic modulus of steel girder; E_t is the elastic modulus of tendon; A_t is the nominal area of tendon, respectively.

For the draped tendon configuration in Fig. 2(c), each term of displacements is similarly given by

$$\delta_{11}=\frac{e^2}{E_sI_{cp}}\left(L-2a-2b+\frac{2b\cos^2\theta}{3}\right)+\frac{L}{E_sA_{cp}}+\frac{\left(L-2a-2b+\frac{2b}{\cos\theta}\right)}{E_tA_t} \tag{8}$$

$$\delta_{1P}=\frac{Pe}{E_sI_{cp}}(0.281L^2-0.532K^2-0.375a^2)$$

for DB-truck load (9)

$$\delta_{1P}=\frac{qe}{12E_sI_{cp}}(L^3-a^2(2L-a))$$

for the DL-lane load (10)

The increment of a tendon force can be obtained by substituting Eqs. (5)-(10) into Eq. (4). Table 1 shows derived equations of the increment of a tendon force with respect to tendon configurations of straight and draped cases illustrated in Fig. 2.

3. Verification

3.1. Experiments

A simply supported composite beam was tested to verify the analytical expressions of the increment of a tendon force. Fig. 3 shows test specimens for different tendon configurations of the straight and draped cases, and Fig. 4 indicates the composite section of the test specimen. The span length of the test specimen was 4.0 m and the distance between supports was 3.8 m. A thick concrete slab compositely connected to an H-shaped steel beam by shear studs. The width and thickness of the concrete slab were 700 mm and 100 mm, respectively. An H-shaped steel beam had a web height of 294 mm and flange width of 200 mm. The thicknesses of the web and a flange were 8 mm and 12 mm, respectively.

Anchorages of tendons were connected by high strength bolts at the bottom flange of a steel beam. Vertical stiffeners were installed near anchorages, load points and supports to avoid local deformations of the beam. The sectional area of tendon was 98.7 mm^2. The

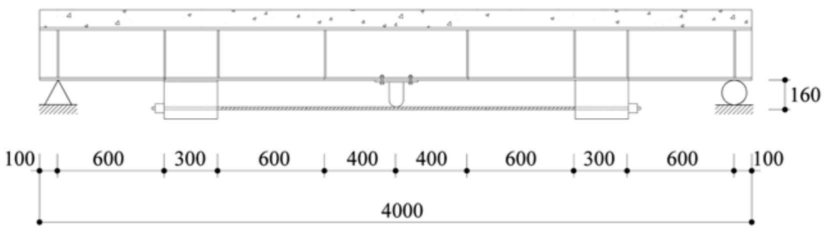
Table 1. Increment of a tendon force due to live loads

Tendon configuration	Load	Increment in the initial tendon force (ΔT)
Straight case	Truck (DB)	$\Delta T=\dfrac{Pe(0.281L^2-1.125a^2-0.115K^2-0.083KV-0.333V^2)}{(L-2a)\left(e^2+\frac{I_{cp}}{A_{cp}}+\frac{E_sI_{cp}}{A_tE_t}\right)}$
	Lane (DL)	$\Delta T=\dfrac{2qe(L^3-6La^2+4a^3)+3Pe(L^2-4a^2)}{24(L-2a)\left(e^2+\frac{I_{cp}}{A_{cp}}+\frac{E_sI_{cp}}{A_tE_t}\right)}$
Draped case	Truck (DB)	$\Delta T=\dfrac{Pe(0.281L^2-0.375a^2-0.532K^2-0.083KV-0.333V^2)}{\left[\frac{e^2(3L-4a)}{3}+\frac{LI_{cp}}{A_{cp}}+\frac{E_sI_{cp}}{A_tE_t}\left\{L+\frac{2a}{\cos\alpha}(1-\cos\alpha)\right\}\right]}$
	Lane (DL)	$\Delta T=\dfrac{2qe\{L^3-a^2(2L-a)\}+Pe(3L^2-4a^2)}{24\left[\frac{e^2(3L-4a)}{3}+\frac{LI_{cp}}{A_{cp}}+\frac{E_sI_{cp}}{A_tE_t}\left\{L+\frac{2a}{\cos\alpha}(1-\cos\alpha)\right\}\right]}$

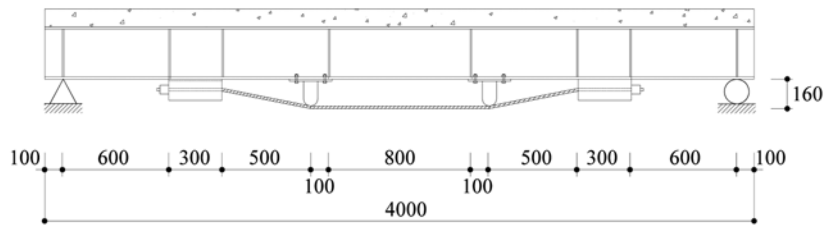
Note: $e = e_{cp}$

Table 2. Sectional and material properties of a composite beam

Components	Area (m^2)	Moment of inertia (m^4)	Modulus of elasticity (MPa)	Unit weight (N/m^3)
Steel beam	7.238×10^{-3}	1.13×10^{-4}	2.06×10^{5}	78,500
Concrete slab	7.000×10^{-2}	5.83×10^{-5}	2.40×10^{4}	25,000
Composite section	1.362×10^{-2}	2.46×10^{-4}	-	



(a) Straight tendon configuration



(b) Draped tendon configuration

Figure 3. Test specimens.

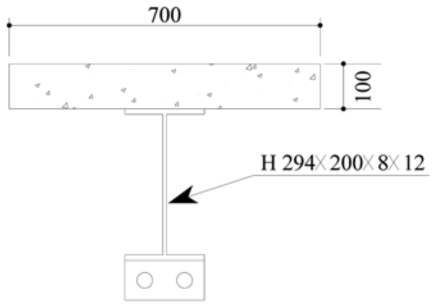


Figure 4. Composite section of the test specimen.

tensile strength and yield strength of tendon were 187 kN and 159 kN, respectively. Tendons were stressed to 50 percent of their tensile strength (93.2 kN per each tendon). The compressive strength of concrete was 27MPa and the yield strength of steel was 320MPa. Table 2 summarizes sectional and material properties of a composite beam used in this study.

External loads were applied to test specimens at two load points as shown in Fig. 5. Strain gauges were attached on each tendon, upper and lower flanges and the mid point of a web. Displacements of composite beams were measured at locations spaced L/4 apart by the linear variable differential transformer (LVDT). Figure 6 shows the test specimen with the test machine.

3.2. Analytical expressions

Analytical expressions for obtaining the increment of a tendon force of test specimens can be obtained by a similar manner as in Section 2.3. Since experimental loads of test specimens are different from design loads of Section 2.3, the terms of Eq. (4) were modified as given in Table 3.

3.3. Finite element analysis

The increment of a tendon force was also calculated by finite element analysis. A proprietary software LUSAS (2005) was used to analyze three-dimensional numerical models of test specimens. Numerical models of test specimens for two tendon configurations are given in Fig. 7. A concrete slab, a steel beam and tendons were modeled by 2240 solid elements, 800 shell elements and 132 bar elements, respectively. Rigid links were used to model shear connectors between a concrete slab and a steel beam. External loadings were applied to numerical models at the same load points of tests. Bar elements, which represent external tendons, were subjected to initial strains to describe the initial tendon force.

3.4. Results

Figure 8 compares the increment of a tendon force obtained from analytical expressions with those of experiments and finite element analysis. Horizontal and vertical axes indicate the increment of a tendon force and applied loads, respectively. As can be seen in Fig. 8, the increments of a tendon force by analytical expressions are in good agreement with those of experiments and finite element analysis for both tendon configurations of straight and draped cases.

4. Strengthening Strategy for Existing Bridges

4.1. Rating equation

The initial tendon stress due to external post-tensioning decreases the stress caused by dead loads of a bridge. Consequently, external post-tensioning improves the load carrying capacity of a bridge. Based on the allowable stress rating (ASR), the required rating factor (RF) of a

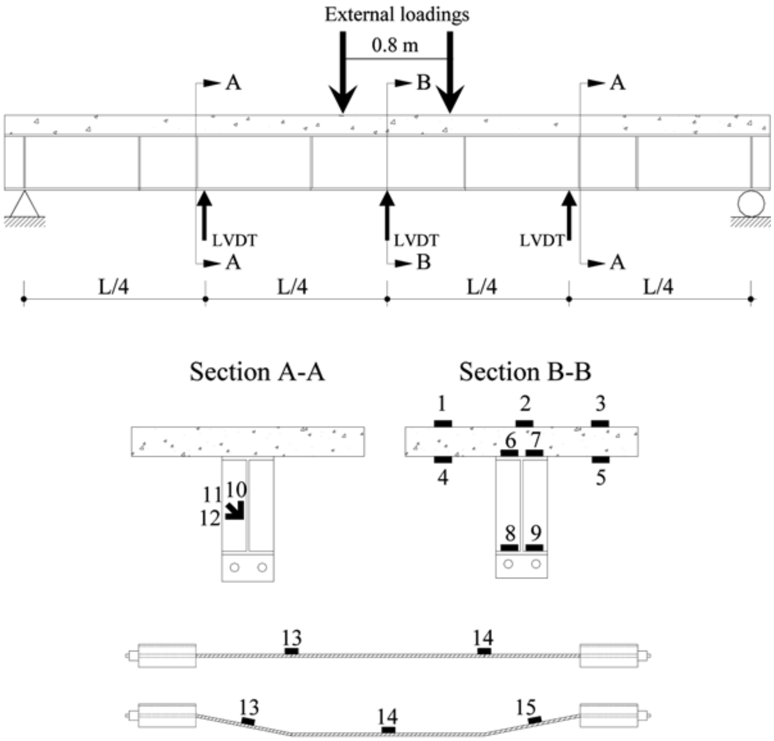


Figure 5. External loadings and configurations of gauges.

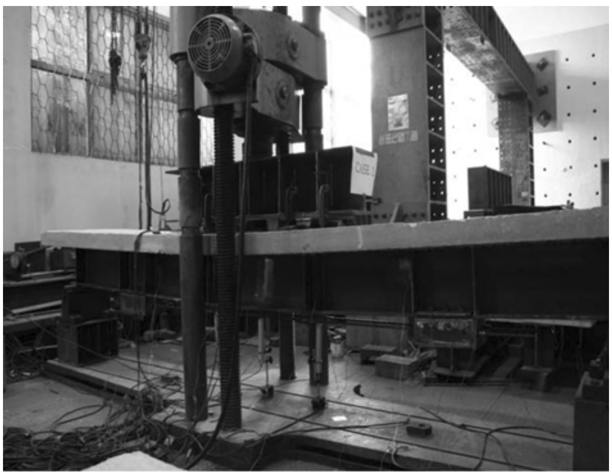


Figure 6. A photo of test specimen.

member in a composite bridge strengthened by external tendon stresses is given by

$$RF=\frac{f_a-(f_{DL}+f_T)}{f_{LL}(1+i)} \tag{11}$$

where f_a is the allowable stress of a member; f_{DL} and f_{LL} indicate the stresses due to dead load and live loads, respectively; f_T represents the stress due to the external tendon force and is defined as $-T/A_{cp} \pm (Te_{cp}y_{sb})/I_{cp}$ in the upper and lower sections; i is the impact factor calculated by 15/(40 + span length).

As previously mentioned, the initial tendon force may change when a bridge is subjected to live loads after external post-tensioning is carried out. This change of a tendon force decreases the stress caused by live loads of a bridge. Eq. (11) does not account for this aspect of a bridge behavior. To consider the increment of a tendon force, we propose a new rating equation as given by

$$'F=\frac{f_a-(f_{DL}+f_T)}{(f_{LL}+f_{\Delta T})(1+i} \tag{12}$$

where $f_{\Delta T}$ is the stress due to the increment of a initial tendon force and defined as $-\Delta T/A_{cp} \pm (\Delta Te_{cp}y_{sb})/I_{cp}$ in the upper and lower sections. It is noted that the terms of f_T and $f_{\Delta T}$ always have the opposite sign with respect to those of f_{DL} and f_{LL}. Since the increment of a tendon force has a favorable effect on improving the load carrying capacity of a bridge as well as the initial tendon force, we can establish a more economical strategy for strengthening existing bridges using Eq. (12) instead of Eq. (11).

4.2. Number of strands and initial tendon force

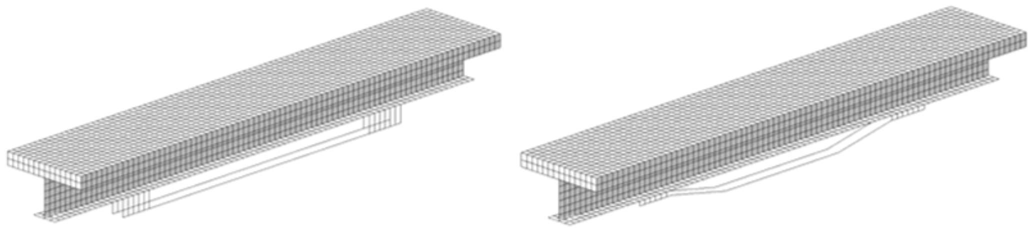
Once the required rating factor for existing bridges has been determined based on the current traffic loadings, the number of strands and the initial tendon force can be obtained by Eq. (12). By transposing both terms, Eq. (13) can be rewritten as

$$f_T + RF \cdot f_{\Delta T}(1+i) = f_a - f_{DL} - RF \cdot f_{LL}(1+i) \tag{13}$$

By substituting the initial tendon force and its increment into Eq. (13), the equation can be arranged as

Table 3. Increment in the initial tendon force due to experimental load

Tendon configuration		δ_{11}, δ_{1P}, ΔT
Straight	δ_{11}	$\delta_{11}=(L-2a)\left(\frac{e^2}{E_sI_{cp}}+\frac{1}{E_sA_{cp}}+\frac{1}{E_tA_t}\right)$
	δ_{1P}	$\delta_{1P}=\frac{Pe}{E_sI_{cp}}(a^2+0.25K^2-0.25L^2)$
	ΔT	$\Delta T=\frac{Pe(0.25L^2-0.25K^2-a^2)}{(L-2a)\left(e^2+\frac{I_{cp}}{A_{cp}}+\frac{I_{cp}}{A_t}\right)}$
Draped	δ_{11}	$\delta_{11}=\frac{e^2}{E_sI_{cp}}\left(L-2a-2b+\frac{2b\cos^2\theta}{3}\right)+\frac{L}{E_sA_{cp}}+\frac{\left(L-2a-2b+\frac{2b}{\cos\theta}\right)}{E_tA_t}$
	δ_{1P}	$\delta_{1P}=\frac{Pe}{E_sI_{cp}}\left\{\cos\theta\left(ab+\frac{2b^2}{3}\right)-(a+b)^2-\frac{K^2-L^2}{4}\right\}$
	ΔT	$\Delta T=\frac{Pe\left\{\cos\theta\left(ab+\frac{2b^2}{3}\right)-(a+b)^2-\frac{K^2-L^2}{4}\right\}}{e^2\left(L-2a-2b+\frac{2b\cos^2\theta}{3}\right)+\frac{E_sI_{cp}\left(L-2a-2b+\frac{2b}{\cos\theta}\right)}{E_tA_t}+\frac{LI_{cp}}{A_{cp}}}$



(a) Straight case (b) Draped case

Figure 7. FEM models of test specimens.

$$T+RF\cdot\Delta T(1+i)=\frac{f_a-f_{DL}-RF\cdot f_{LL}(1+i)}{\left(-\frac{1}{A_{cp}}\pm\frac{e_{cp}}{I_{cp}}y_{sb}\right)} \tag{14}$$

Therefore, the initial tendon force for satisfying the required rating factor of an existing bridge is determined as

$$T=\frac{f_a-f_{DL}-RF\cdot f_{LL}(1+i)}{\left(-\frac{1}{A_{cp}}\pm\frac{e_{cp}}{I_{cp}}y_{sb}\right)}-RF\cdot\Delta T(1+i) \tag{15}$$

The number of required strands (N_t) is subsequently determined as

$$N_t=\frac{T}{\phi_tF_u} \tag{16}$$

where ϕ_t is the reduction factor of the tendon force, normally taken as 0.4 - 0.6, and F_u is the tensile strength of a strand.

In general, the number of strands is determined as an even number greater than indicated by Eq. (16). Gross sectional area of tendons is calculated as the sectional area of each strand multiplied by the number of strands. The initial tendon force of each tendon is also obtained as the value of the tendon force T divided by the number of strands.

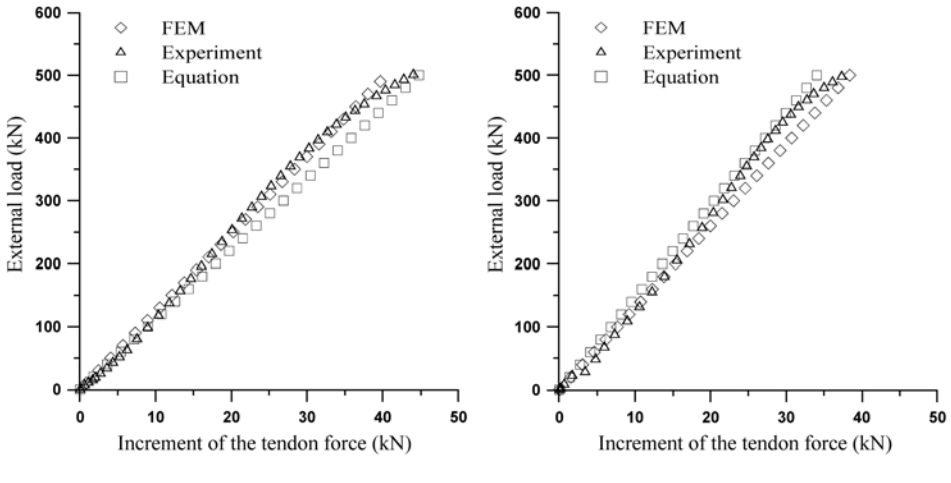


Figure 8. Comparison of the increments of a tendon force.

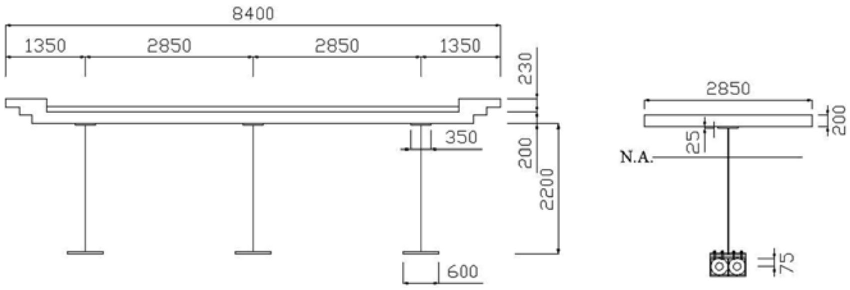


Figure 9. A plate girder bridge strengthened with external tendons (unit: mm).

5. Strengthening of an Example Bridge

A plate girder bridge in Korea, which was constructed in 1973, was selected to illustrate the procedure proposed in this paper. The length of span is 40 m and the width of the bridge is 8.4 m as shown in Fig. 9. The thickness of a slab is 0.2 m. A full shear connection between the concrete slab and steel beam is assumed. The bridge is simply supported. The girder of the bridge is composed of three H-shaped steel beams. The height of steel beam is 2.2 m. The area of the composite section (A_{cp}) is 1161.75 cm^2. The moment of inertia (I_{cp}) is 9732070 cm^4. The distance between the bottom of the girder and the neutral axis of the composite section (y_{sb}) is 168.76 cm.

The bridge was originally designed to the live load of DB-18 truck prescribed in KHBS (2005). To enhance the performance of this bridge enough to keep it in-service for the live load of DB-24, external tendons with straight configuration were installed at the bottom of the lower flange. Two tendons were anchored at 75 mm below the bottom of the lower flange of each steel beam. The eccentricity of tendons (e_{cp}) is 176.26 cm. Table 4 shows the mechanical properties of the strand.

The number of strands and the initial tendon force were calculated based on the strengthening procedure with the proposed rating equation. The required rating factor of the bridge was assumed as 1.2 for the live load of DB-24.

For the lower flange of a steel section, the maximum bending stresses due to dead and live loads are f_{DL} = 77.50 MPa and f_{LL} = 76.67 MPa, respectively. Eq. (14) was used to calculate $T + RF \cdot \Delta T(1 + i)$ as

$$T+RF\cdot\Delta T(1+i)=\frac{+1372-7750-1.2\times7667}{-\frac{1}{1161.75}-\frac{176.26}{9732070}\times168.76}=824.47\text{kN} \tag{17}$$

Assuming that ϕ_t is 0.6, the number of strands was calculated by Eq. (15). The result was 824.47 kN/(0.6× 260.68 kN) = 5.27; thus six numbers of strands in tendons may be appropriate to strengthen this bridge. Cross sectional area of a tendon (A_t) was calculated as 1.387 cm^2×6 = 8.322 cm^2. The increment of an initial tendon

Table 4. Mechanical properties of the strand

Properties	Diameter (mm)	Area (mm^2)	Tensile strength (kN)	Yield strength (kN)
Strand	15.20	138.70	260.68	221.48

Table 5. Stresses due to load types (MPa)

Type of loading	Concrete slab stress	Upper flange stress	Lower flange stress	Tendon stress
Dead load, DL	-3.82	-23.53	77.50	-
Tendon force, T	0.39	0.52	-30.44	933.81
Live load, DB-24	-3.78	-23.28	76.67	-
Increment of tendon force, ΔT	0.02	0.03	-1.55	47.43
Total stress	-7.18	-46.26	122.18	981.23
Allowable stress	+2.2/-9.0	-137.20	137.20	1303.40
RF in Eq. (12)	1.48	2.47	1.20	7.79

force (ΔT) was calculated by substituting the cross sectional area of a tendon ($At = 8.322$ cm^2) into the equation of the Table 1. The corresponding equation gave ΔT as the value of 39.47 kN. Thus, the initial tensile tendon force T is calculated as 768.23kN from Eq. (17).

Table 5 shows the stresses at the concrete slab, the upper flange, and the lower flange of the composite girder. To avoid the tensile cracks of a concrete slab, the tensile stress due to bending caused by the initial tendon force should be smaller than the allowable tensile stress of concrete, i.e. 2.2 MPa. As can be seen in Table 5, the tensile stress of a concrete slab of the girder due to the initial tendon force is smaller than the allowable tensile stress of concrete. The stress due to the increment of the initial tendon force was approximately 5% of that due to initial tendon force. For the live load of DB-24, the required rating factor 1.2 of this bridge was achieved by introducing external post-tensioning with the proposed rating equation.

6. Conclusions

The paper illustrates a systematic procedure of external post-tensioning technique for strengthening or rehabilitation of existing bridges. Based on the principle of virtual work, the initial tendon force and its increment caused by live loads are determined for external tendon configurations of straight and draped cases. Analytical expressions for the increment of a tendon force are verified by comparing with experiments and finite element analysis results. A new rating equation is proposed to account for the effect of the increment of a tendon force. The number of strands and the initial tendon force are determined to achieve the required rating factor of existing bridges. The following conclusions are drawn:

1. For the test specimens, the increment of a tendon force by the analytical expression is in good agreement with the results of the experiment and finite element analysis.
2. The application of an example bridge demonstrates that the proposed method is suitable for strengthening of existing bridges with external post-tensioning technique. Considering the increment of a tendon force, accurate load rating of a bridge may be possible based on the proposed rating equation.
3. The increment of a tendon force, which is due to the live load, is approximately 5% compared to the total amount of a tendon force. Since the total amount of strands can be reduced by considering this increment of a tendon force, a more economical design for strengthening of a bridge may be feasible.

Acknowledgment

This paper is a part of the result from the "Standardization of Construction Specifications and Design Criteria based on Performance ('06~'11)", the "Construction & Transportation R&D Policy and Infrastructure Project."

References

Conner, R. J. and Fisher, J. W. (2005). "Fielding testing of orthotropic bridge decks." *International Journal of Steel Structures*, KSSC, 5 (3), pp. 225-231.

Dall'Asta, A. and Dezi, L. (1998). "Nonlinear behavior of externally prestressed composite beams: analytical model." *Journal of Structural Engineering*, ASCE, 124 (5), pp. 588-597.

Gupta, L. M., Ronghe, G. N. and Naghate, M. K. (2003). "Behaviour and stability of prestressed steel plate girder for torsional buckling." *Steel and Composite Structures*, 3 (1), pp. 65-73.

Harajli, M. H. (1993). "Strengthening of concrete beams by external prestressing." *PCI Journal*, 38 (6), pp. 76-88.

Klaiber, F. W., Wipf, T. J. and Fanous, F. S. (1998). "Strengthening of two continuous-span steel stringer bridges." *Construction and Building Materials*, 12 (2), pp. 151-159.

Ministry of Construction and Transportation of Korea (2005). Korean Highway Bridge Design Specifications. (In Korean)

Li, W., Albrecht, P. and Saadatmanesh, H. (1995). "Strengthening of composite steel-concrete bridges." *Journal of Structural Engineering*, ASCE, 121 (12), pp. 1842-1849.

FEA ltd. (2005), LUSAS (2005). User Manual Version 13.7, Surrey, UK.

Miyamoto, A. Tei, K., Nakamura H. and Bull, J. W. (2000). "Behavior of prestressed beam strengthened with external tendons." *Journal of Structural Engineering*, ASCE, 126 (9), pp. 1033-1044.

Ng, C. K. (2003). “Tendon stress and flexural strength of externally prestressed beams.” *ACI Structural Journal*, 100 (5), pp. 644-653.

Park, Y. H., Park, C. and Park, Y. G. (2005). “The behavior of an in-service plate girder bridge strengthened with external prestressing tendons.” *Engineering Structures*, 27 (3), pp. 379-386.

Saadatmanesh, H., Albrecht, P. and Ayyub, B. M. (1989a). “Analytical study of prestressed composite beams.” *Journal of Sturctural Engineering*, ASCE, 115 (9), pp. 2364-2381.

Saadatmanesh, H., Albrecht, P. and Ayyub, B. M. (1989b). “Experimental study of prestressed composite beams.” *Journal of Sturctural Engineering*, ASCE, 115 (9), pp. 2348-2363.

Saadatmanesh, H., Albrecht, P. and Ayyub, B. M. (1989c). “Guidelines for flexural design of prestressed composite beams.” *Journal of Structural Engineering*, ASCE, 115 (11), pp. 2944- 2961.

Tong, W. and Saadatmanesh, H. (1992). “Parametric study of continuous prestressed composite girders.” *Journal of Sturctural Engineering*, ASCE, 118 (1), pp. 186-206.

Troitsky, M. S. (1990). *Prestressed Steel Bridges: Theory and Design*. Van Nostrand Reinhold Company, USA.

Troitsky, M. S., Zielinski, Z. A. and Nouraeyan, A. (1989). “Pre-tensioned and post-tensioned composite girders.” *Journal of Structural Engineering*, ASCE, 115 (12), pp. 3142-3153.