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Optimization of post-tensioning forces in stay-cables of cable-stayed bridges

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Abstract: Stay-cables are one of the most crucial structural elements of cable-stayed bridges. This structural element is used in the support of the bridge deck, transferring dead and live load exposed to the deck through the pylon and controls the vertical deck and horizontal pylon displacement with the help of post-tensioning forces of the stay-cables. Under the dead load of the structural and non-structural elements of the bridge, the vertical deck and horizontal pylon displacement must be almost zero. To determine the post-tensioning forces of the stay-cables, to ensure the desired displacement of deck and pylon with a trial-and-error procedure, is sometimes impossible. In this paper, we will determine the post-tensioning forces of a cable-stayed bridge's stay-cable by developing a program that integrates a finite element analysis, and a Jaya algorithm with MATLAB codes. To achieve this aim an existing bridge was selected as an example. A three dimensional (3D) finite element model (FEM) of the selected bridge was created by SAP2000. 3D FEM of the selected bridge was repeatedly analyzed by using the Open Applicable Programming Interface (OAPI) properties of SAP2000. The results of numerical examples are presented and discussed to show efficiency of the optimization process. By minimizing the weight of the steel structure, CO_2 emissions are also kept low.

Keywords: Jaya algorithm, post-tensioning forces, cable-stay, bridges, SAP2000-OAPI, CO_2 emissions

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Introduction

Cable-supported bridges are divided mainly into two groups: suspension and cable-stayed bridges. In recent decades, these bridges have been frequently constructed to cross both medium and long spans. The main structural elements of these bridges are the foundation, deck, pylon, and cables. Differing from suspension bridges, cables directly join the deck and pylons in cable-stayed bridges (CSB). The cables are used to perform multiple tasks such as; support the bridge deck, transfer dead and live loads exposed to the deck through the pylons, distribution of the bending moment in the deck and control of the vertical deck and horizontal pylon displacement with the help of post-tensioning forces (PTF) of the stay-cables. The stay-cables cannot act as a structural element until PTFs are applied. Therefore, the determination of applied PTFs in the stay-cables is very important for overall design (Li et al., 2018). Under the dead load of structural and non-structural elements of the bridge, the vertical deck and horizontal pylon displacement must be zero (Hassan et al., 2012). To determine the PTF of the stay--cables to ensure the desired displacement of deck and pylon using a trial-and-error procedure is time-consuming, expensive and generally fails to find an optimum solution. PTFs of the stay-cables influences the overall design of the bridge, consequently, most of the time, calculating the PTFs of the stay-cables at the design stage is considered one of the most common difficulties (Freire et al., 2006; Xiao et al., 2001). The zero displacement and force equilibrium method are generally used to obtain appropriate initial cable forces in CSB. Chen et al. (2000) used the force equilibrium method to determine the initial cable forces of two real cable--stayed bridges. They mentioned that the force equilibrium method is very simple and rational compared to the zero displacement method. Fabbrocino et al. (2017) selected as an example a CSB formed using composite material such as Fiber Reinforced Polymer (FRP). They proposed an optimization procedure to determine the prestress force of the stay-cable for any kind of CSB. Song et al. (2018) used an optimization and finite element method together to find pre-tension forces of asymmetric span stay-cables in a long-span CSB in order to take into consideration a counterweight.

In this study, an optimization algorithm called Jaya is proposed to determine the PTF of the stay-cable. The design variables for the optimization were the PTF of the stay-cables as a strain. The lower and upper bounds of the strains for stay--cables were adjusted by taking into account the mechanical properties of Grade 270 strands (AASHTO LRFD, 2012). The stress of stay-cables, displacement of deck and pylon obtained under the effect of the self-weight of the bridge elements and PTF were taken into account as design constraints. The Jaya algorithm and FEM analysis were combined with the help of MATLAB (2003) for the optimization process. To overcome the difficulties of the subsequent 3D FEM analysis of the CSB, Open Applicable Programming Interface (OAPI) properties of SAP2000 (2008) was preferred in this study.

1. Description and finite element model of the bridge

The Manavgat Cable-stayed Bridge was selected as an example in this study (Figs. 1 and 2). The total length is 202 m and serves 2-lanes of vehicle and pedestrian traffic. The bridge has a λ-shaped steel tower and composite deck. The composite deck was formed by placing 25 cm thick concrete and 10 cm thick asphalt on I steel profiles used in longitudinal and transverse directions. The bridge has a total of 28 steel stay-cables arranged in modified fan type.

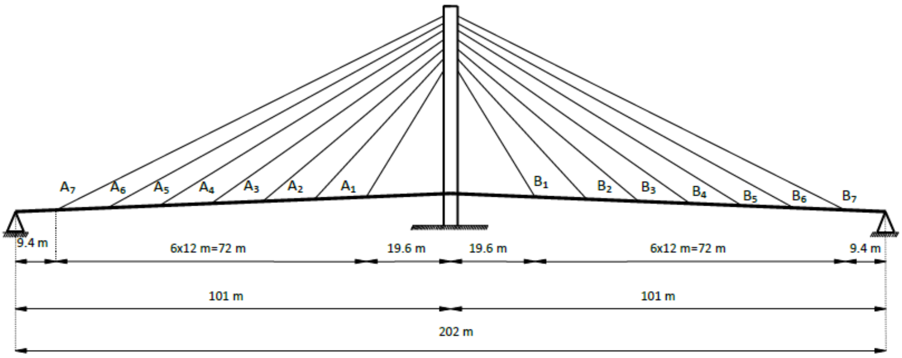

Fig. 1. Selected bridge elevation (*own study*)

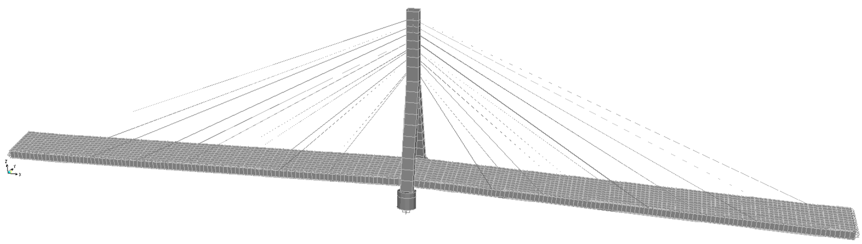

Fig. 2. FEM of selected bridge (*own study*)

The section properties of the cables and material properties of the bridge are shown in Table 1 and Table 2, respectively. 3D FEM of the bridge was created with SAP2000 (2008) in order to obtain the structural behavior of selected bridge. The bridge model consists of 28 truss elements (cables), 1102 beam elements (The steel I profile of deck and tower) and 1980 shell elements (concrete part of deck). In this study, the static analysis performed under the dead loads of the bridge was calculated by the program automatically.

Table 1. Properties of stay-cable (*own study*)

Stay cable number	Number of strand	Diameter of strand	Cross-sectional area of stay-cable [mm^2]
A_1-B_1	15	15.2	2100
A_2-B_2	16	15.2	2240
A_3-B_3	19	15.2	2660
A_4-B_4	19	15.2	2660
A_5-B_5	22	15.2	3080
A_6-B_6	19	15.2	2660
A_7-B_7	24	15.2	3360

Table 2. Material properties of the bridge (*own study*)

Material properties			Unit	Standard
Strand	Type	270K	–	ASTM A416
	Ultimate strength	1862	[MPa]	
	Weight per unit volume	78.5	[kN/m^3]	
	Modulus of elasticity	197000	[MPa]	
	Poisson's ratio	0.3	–	
Structural steel	Type	S355	–	EN 1993-1-1 per EN 10025-2
	Weight per unit volume	78.5	[kN/m^3]	
	Modulus of elasticity	200000	[MPa]	
	Poisson's ratio	0.3	–	
Deck concrete	Type	C40/50	–	EN 1992-1-1 per EN 206-1
	Modulus of elasticity	34000	[MPa]	
	Weight per unit volume	25	[kN/m^3]	
	Poisson's ratio	0.2	–	

2. Determination of PTF with Jaya Algorithm

In this study, an optimization algorithm called Jaya originally presented by Rao (2016) was used to determine the PTF of the stay-cable. The Jaya algorithm and FEM analysis were combined with the help of MATLAB for the optimization process. To overcome the difficulties of the subsequent 3D FEM analysis of the CSB, Open Applicable Programming Interface (OAPI) properties of SAP2000 were preferred in this study. The design variables for the optimization were the PTF of stay-cables as a strain. The lower and upper bounds of the strains for stay-cables were adjusted by taking into account the mechanical properties of Grade 270 strands (AASHTO LRFD, 2012). The stress of stay-cables, displacement of deck and pylon obtained under the effect of self-weight of bridge elements and PTF were taken into account as design constraints.

$$g_i\left(x\right)=\frac{\delta_i}{\delta_u}-1\leq 0 \quad i=1,\ldots,n \tag{1}$$

$$g_j\left(x\right)=\frac{\sigma_i}{\sigma_u}-1\leq 0 \quad j=1,\ldots,m \tag{2}$$

$$\begin{aligned}&\text{if} \quad g\left(x\right)>0 \quad c=g\left(x\right)\\&\text{if} \quad g\left(x\right)<0 \quad c=0\end{aligned} \tag{3}$$

where n is the number of displacement constraints on the deck, δ_i is calculated displacement, and δ_u is allowable displacement. m is the number of stress constraints for the cable, σ_i is calculated stress, and σ_u is allowable stress. To calculate the sum of the constraints ("C") in the optimization problem, the following equations was written

$$C = \sum_{k=1}^{nc} c_k \tag{4}$$

where nc is the total number of constraints. The objective function is written in terms of the constraint to take into the constraints. Thus, the penalized objective function φ is given in equations

$$\varphi = W(x) \cdot [1 + P \cdot C] \tag{5}$$

where P is a constant value which is determined according to the problem.

3. Results

The purpose of this study is to find out the proper PTF of a stay-cable to meet strength and serviceability criteria simultaneously. 3D FEM was created using SAP2000 and the linear static analysis performed under a dead load and PTF of the stay-cables in order to obtain displacements and initial forces. To optimize the PTF of the stay-cable with the Jaya algorithm, the population size and max. generation number were taken as 30 and 200, respectively. There were 7 different cables so the strain of these stay-cables were determined as design variables. The lower and upper bounds of the strains were taken into account –0.0001 and –0.007 according to the material properties of a Grade 270 tendon, respectively. Three types of design constraints were taken into account: vertical displacement of the deck (5 mm), horizontal displacement of the pylon (5 mm) and stress of the stay-cables (1395 MPa).

The distribution of PTF in the stay-cables during the optimization process is given in Figure 3. As seen from this figure after 114 iterations the PTF of the stay-cables were determined. Vertical displacements of the bridge deck, the horizontal displacement of the pylon and stress of stay-cables before and after PTF are applied to the stay-cables are given in Figure 4a-b and Figure 5a-b and Figure 6a-b, respectively. As seen from these figures when the PTF was applied to the stay-cables, they start to act as structural elements and decreased the vertical deck displacements significantly. The horizontal pylon displacements decreased as well. Applying the PTF to the stay-cables caused the increase of the stress in the stay-cables.

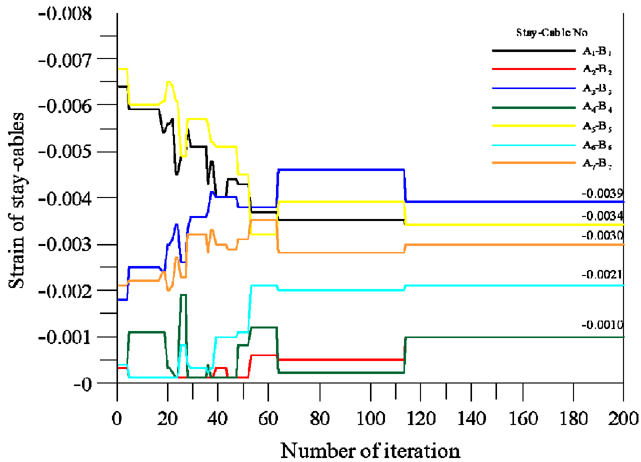

Fig. 3. Distribution of PTF of stay-cables during the optimization process (*own study*)

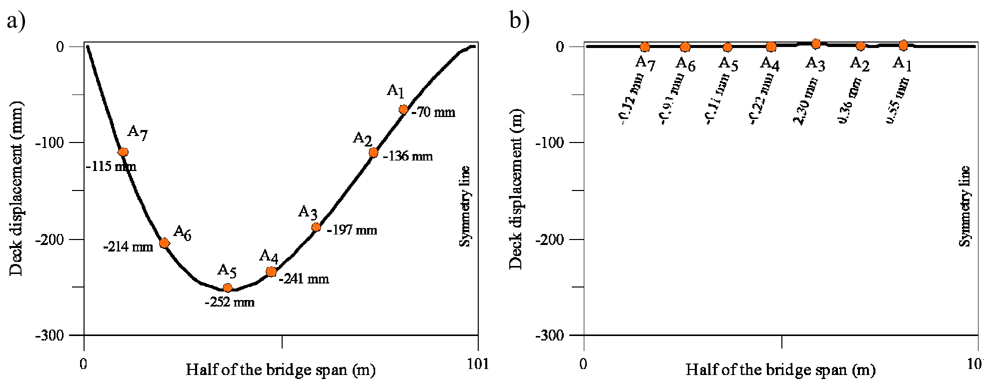

Fig. 4. Vertical displacement of the deck before (a) and after (b) PTF are applied to stay-cables (*own study*)

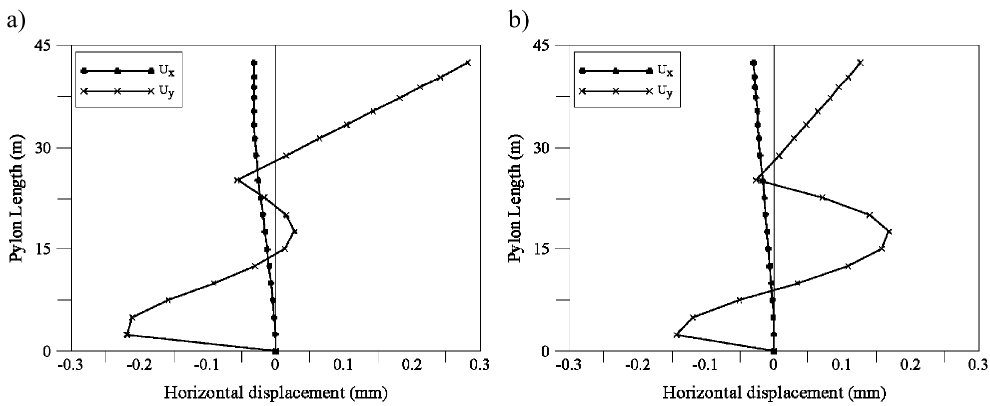

Fig. 5. Horizontal displacement of pylon before (a) and after (b) PTF are applied to stay-cables (*own study*)

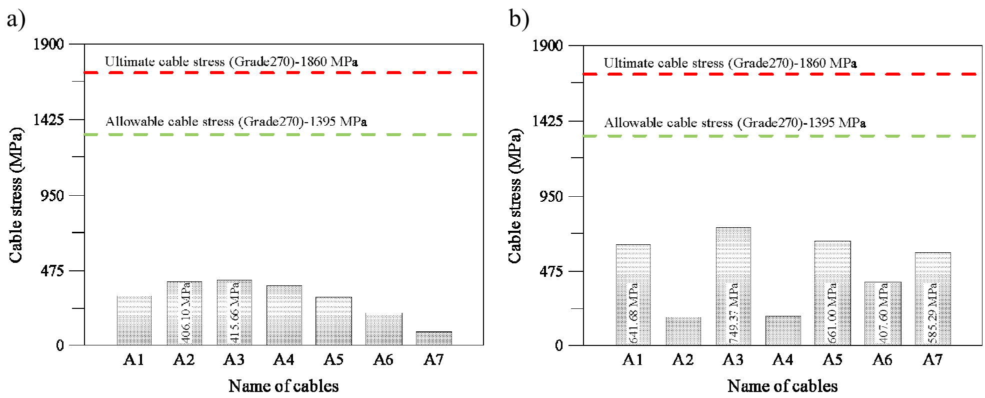

Fig. 6. Stress of stay-cables before (a) and after (b) PTF are applied to stay-cables (*own study*)

Conclusions

In this study, it was aimed to determine post-tensioning forces of stay-cables with an optimization process. To realize the optimization, the Jaya algorithm and FEM analysis were combined with the help of MATLAB programing. To overcome the difficulties of the subsequent three dimensional FEM analysis of the cable-stayed bridge the OAPI SAP2000 was preferred in this study. From the point of view of the study carried out, the following conclusions have been reached:

- Determining the post-tensioning forces of stay-cables in order to ensure the desired displacement of the deck and pylon and also the stress of the stay-cables, an optimization process is far more effective than a trial-and-error procedure.
- Stay-cables are used to support the bridge deck, transferring dead and live load exposed to the deck through pylon and control the vertical deck and horizontal pylon displacement. However, stay-cables cannot act as a structural element until post-tensioning forces are applied.
- It is also concluded that the Jaya algorithm can be effectively used in the determination of post-tensioning forces in the stay-cables. Minimalizing the weight of the steel structure also lowers CO_2 emissions.

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Optymalizacja sił sprężających w kablach w mostach podwieszanych

Streszczenie: Kable stężające są jednym z najważniejszych elementów konstrukcyjnych mostów podwieszanych. Ten element konstrukcyjny jest wykorzystywany do podparcia płyty pomostu, przenosząc obciążenie stałe i zmienne z płyty na pylon i wpływa na przemieszczenie pionowe płyty i poziome pylonu za pomocą sił naciągających w kablach. Pod obciążeniem stałym i zmiennym elementów konstrukcyjnych mostu przemieszczenie pionowe pomostu i poziome pylonu musi wynosić prawie zero. W celu określenia sił sprężających w kablach, aby zapewnić pożądane przemieszczenie pomostu i pylonu, zastosowano metodę prób i błędów. W artykule określono siły sprężające cięgna mostu wantowego, opracowując program, który integruje analizę metody elementów skończonych (MES) oraz algorytm Jaya zakodowany w MATLAB-ie. Aby osiągnąć ten cel, jako przykład wybrano istniejący most. Trójwymiarowy model (3D) metody elementów skończonych (MES) wybranego mostu został stworzony w programie SAP2000. 3D MES wybranego mostu był wielokrotnie analizowany z użyciem właściwości Open Applicable Programming Interface (OAPI) SAP2000. Wyniki przykładów numerycznych zaprezentowano i omówiono w celu wykazania wydajności procesu optymalizacji. Minimalizując ciężar konstrukcji stalowej, emisje CO_2 są również utrzymywane na niskim poziomie.

Słowa kluczowe: algorytm Jaya, siła sprężająca, kabel stężający, mosty, SAP2000-OAPI, niska emisja CO_2