STRUCTURAL ENGINEERING

BEHAVIOUR OF CABLE TRUSS WEB ELEMENTS OF PRESTRESSED SUSPENSION BRIDGE

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ABSTRACT

A suspension bridge is more appropriate type of structure for extremely long-span bridges due to the rational use of structural materials. Increased deformability, which is conditioned by the appearance of the elastic and kinematic displacements, is the major disadvantage of suspension bridges.

Prestressing can solve the problem of increased kinematic displacements under the action of non-symmetrical load. A prestressed suspension bridge with the spans of 50, 200 and 350 m was considered as the object of investigation. The cable truss with the cross web was considered as the main load carrying structure of the prestressed suspension bridge.

Optimization of the cable truss web by 9 variables was realized using genetic algorithm. It was obtained, that the displacements of the prestressed suspension bridge with the proposed cable truss are smaller by 26–30% than the displacements of the structure with the single main cable for the span interval from 50 to 350 m in the case of the worst situated load.

Key words: Suspension bridges, topology optimization, genetic algorithm

INTRODUCTION

Suspension bridges are structures where the deck is continuously supported by the stretched catenary cable (Chen and Lui, 2005). Suspension bridges are the most important and attractive structures possessing a number of technical, economical and aesthetic advantages (Grigorjeva et al., 2010a).

A suspension bridge is the most suitable type of structure for very long-span bridges at the present moment. Suspension bridges represent 20 or more of all the longest span bridges in the world. The bridge with the longest centre span of 1991m is the Akashi Kaikyo Bridge (Chen and Duan, 2000). So, long spans can be achieved because the main load carrying cables are subjected to tension and the distribution of normal stresses in the cable cross-section is close to uniform (Juozapaitis et al., 2010).

Increased deformability is one of the basic disadvantages of suspension bridges (Walther et al., 1999). Increased deformability is conditioned by appearance of elastic and kinematic displacements. The elastic displacements are caused by the large tensile internal forces. The elastic displacements are maximal at the centre of the span in the case of symmetrical load application. The kinematic displacements are caused by the initial parabolic shape change, resulting from non-symmetrical or local loads (Fig. 1) (Juozapaitis and Norkus, 2004; Grigorjeva et al., 2010b). These displacements are not connected with the cable elastic characteristics. Serviceability limit state is dominating for suspension cable structures.

The elastic displacements can be reduced by applying of low strength steel structural profiles, elastic modulus increase, reinforced concrete application and cable camber increase (Кирсанов, 1973).

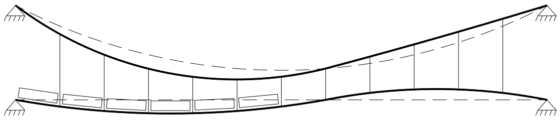

Figure 1. Initial shape change under the action of non-symmetrical load

The problem of increased kinematic displacements can be solved by increasing of the ratio of dead weight and imposed load values, which is achieved by adding of cantledge (Fig. 2). However, this method causes the increase of material consumption. Stiffness of suspended structures can be increased also by increasing of girder stiffness (Fig. 3), increasing of main cable camber, connecting of main cable and girder at the centre of the span (Fig. 4), application of diagonal suspenders (Fig. 5) or inclined additional cables (Fig. 6), application of two chain systems (Fig. 7), stiff chains (Fig. 8) and stress ribbons (Fig. 9) (Кирсанов, 1973; Strasky, 2005; Бахтин et al., 1999; Качурин et al., 1999). Nevertheless, these systems are characterized also with the increased material consumption, and system stiffness is not sufficient in many cases.

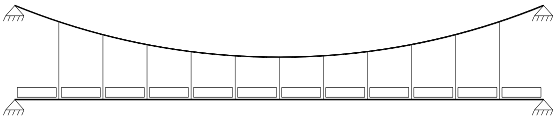

Figure 2. Suspension bridge stabilization by adding of cantledge

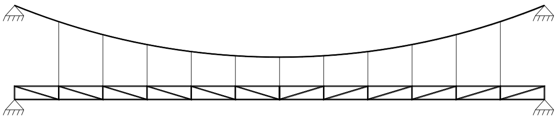

Figure 3. Suspension bridge stabilization by increasing of girder stiffness

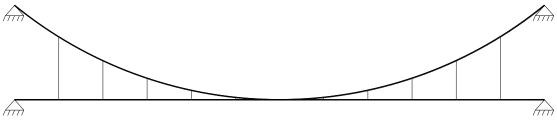

Figure 4. Suspension bridge stabilization by connecting of main cable and girder at the centre of the span

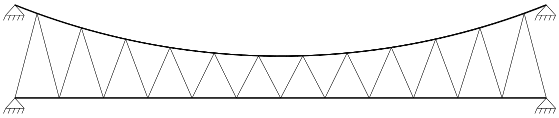

Figure 5. Suspension bridge stabilization by application of diagonal suspenders

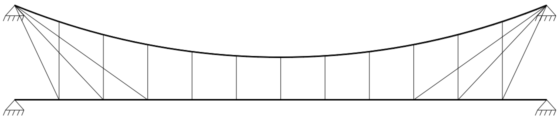

Figure 6. Suspension bridge stabilization by application of inclined additional cables

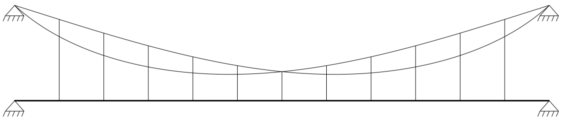

Figure 7. Suspension bridge stabilization by application of two-chain system

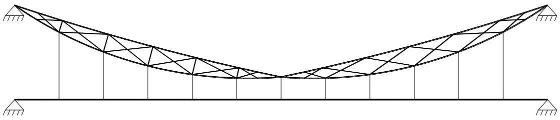

Figure 8. Suspension bridge stabilization by application of stiff chains

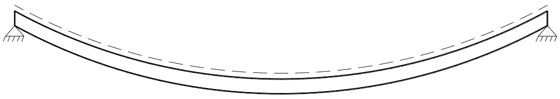

Figure 9. Suspension bridge stabilization by application of stress ribbons

Use of prestressed cable truss is another method to solve the problem of increased kinematic displacements under the action of unsymmetrical load (Serdjuks and Rocens, 2004; Goremikins et al., 2011a). Different types of cable trusses are known, such as convex cable trusses, convex-concave cable trusses, cable trusses with centre compression strut or parallel cable truss (Schierle, 2012). But one of the most efficient and convenient for application for bridges is the concave cable truss (Fig. 10) (Goremikins et al., 2011). Cable truss usage allows developing bridges with reduced requirements for girder stiffness, where overall bridge rigidity will be ensured by prestressing of the stabilization cable (Кирсанов, 1973). The deck can be made of light composite materials (Goremikins et al., 2010a; Goremikins et al., 2010b).

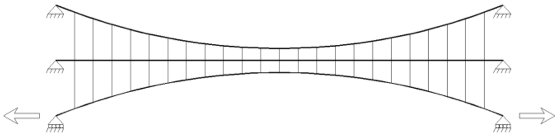

Figure 10. Suspension bridge stabilization by prestressing

The kinematic displacements of a prestressed suspension bridge can be decreased by replacing of the main single cable with the cable truss with a cross web (Fig. 11) (Goremikins et al., 2012a; Goremikins et al., 2012b; Goremikins et al., 2012c; Serdjuks et al., 2005).

Cables can be cambered in horizontal plane to increase the structure stiffness in the same plane (Fig. 12) (Кирсанов, 1973).

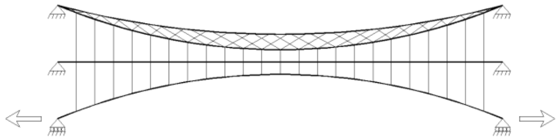

Figure 11. Suspension bridge stabilization by using of prestressed stabilization cable and cable truss

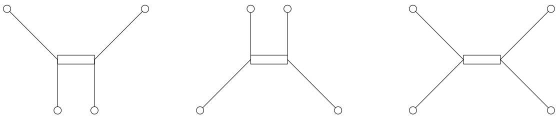

Figure 12. Suspension bridge stabilization in horizontal plane by cambering of main or stabilization cables. Cross-sectional view

Decrease of displacements can be achieved by rational positioning of the cable truss elements and rational material distribution between them. Topology optimization of the cable truss web is presented in this paper.

MATERIALS AND METHODS

Description of Investigation Object

A prestressed suspension bridge with a cable truss with cross web was chosen as the object of the investigation (Fig. 13) (Goremikins et al., 2012a).

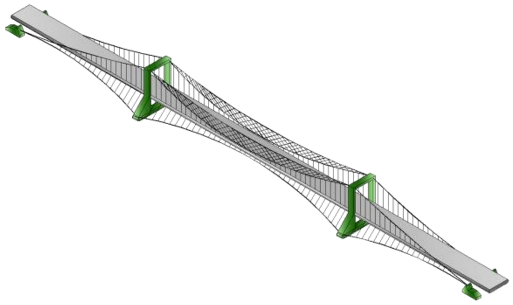

Figure 13. Prestressed suspension bridge with cable truss load carrying structure

Three different spans were considered for the bridge. The main span *l* of the considered bridge is equal to 50, 200 and 350 m. The bridge has two lines in each direction, two pedestrian lines and their total width is equal to 18.2 m (Fig. 14). The chamber of the bottom chord of the cable truss f_b is equal to 1/10 from the span. The bridge is prestressed in horizontal and vertical planes by the stabilization cables. The camber of the stabilization cable is equal to 1/200 from the span. The deck is connected with the main load-carrying cables by the suspensions with a step *a* equal to 5 m (Fig. 15). The cable string is placed between suspensions to minimize the horizontal prestressing force effects acting in the deck. Prestressed horizontal cables are placed along the deck to minimize the effects of horizontal transport braking force (Fig. 16). The deck of the bridge is made of pultrusion composite trussed beams, pultrusion composite beams with the step 1 m and pultrusion composite plank with the height 40 mm that is covered with asphalt layer (Fig. 14) (Goremikins et al., 2010a; Goremikins et al., 2010b; Fiberline Composites A/S, 2002). It is assumed that cables are covered with high-density polyethylene and are heated with electricity to reduce the influence of temperature effects (Xiang et al., 2009). Possible prestressing loosing is reduced by active tendons (Achkire and Preumont, 1996). It is possible to reduce the requirements for girder stiffness by bridge prestressing. This allows using the composite pultrusion materials in the deck structure and makes it possible to develop constructions of bridges with a large span and reduced dead weight in comparison with steel or concrete bridges (Бахтин et al., 1999).

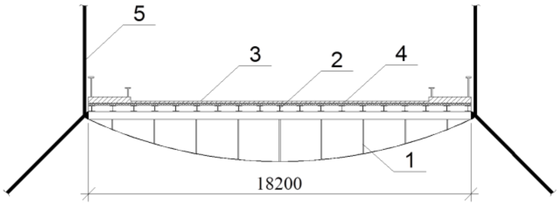

Figure 14. The bridge deck structure.
1 – composite trussed beam, 2 – composite I type beams, 3 – composite plank, 4 – cover of the bridge, 5 – suspensions

The design scheme of the investigation object is shown in Fig. 15 and Fig. 16. The structural material is a prestressed steel rope (Eurocode 3, 2003; Feyrer, 2007). The dead load *g* that is applied to the structure is equal to 51.1 kN/m. The bridge is loaded by the imposed load *q*, which is equal to 82.2 kN/m (Eurocode 1, 2009). Imposed load can be applied to any place of the span. Distributed load is transformed to the point load and is applied to the connections of the deck and suspensions. There are 39 possible points of load application (Fig. 15).

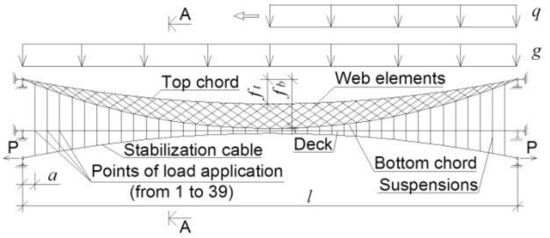

Figure 15. Design scheme of suspension bridge.
q – imposed load, *g* – dead load, *P* – prestressing, f_b – bottom chord camber, f_t – top chord camber, *l* – main span, *b* – width, *a* – suspension step

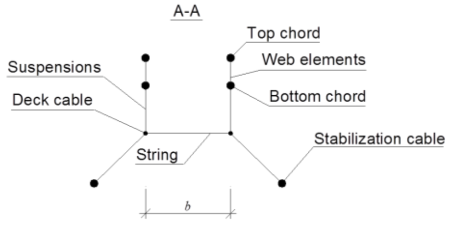

Figure 16. Cross section of prestressed suspension bridge

Position of each web element of the cable truss is defined by the distance from the pylon to the connection of the web element with the top chord, depending on the distance from the pylon to the connection of the same element with the bottom chord (Fig. 17). The web elements are divided into two groups – the elements inclined to the centre of the cable truss and the elements inclined to the edges of the cable truss. Each element of the web may have its own angle on inclination. The second order polynomial equation is assumed to express the position of each web element and to minimize the amount of variable factors.

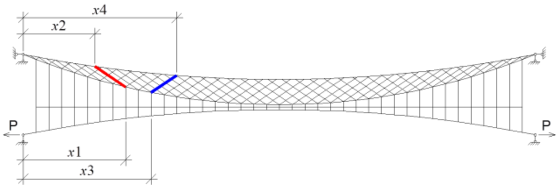

Figure 17. Position of web elements

The position of the web elements, which are inclined to the edges of the cable truss, is expressed by Eq. (1), the position of the web elements, inclined to the edges of the cable truss, is expressed by Eq. (2) (Goremikins et al., 2012a; Goremikins et al., 2012b).

$$x_2 = x_1 - (root1 \cdot x_1^2 + root2 \cdot x_1 + root3)\,, \qquad (1)$$

$$x_4 = x_3 + (root4 \cdot x_3^2 + root5 \cdot x_3 + root6)\,, \qquad (2)$$

where x_2 and x_4 – distances from the pylon to the connection of the web element and top cord;
x_1 and x_3 – distances from the pylon to the connection of the web element and bottom cord;
$root1 \ldots root6$ – roots of the system of Eqs. (3) and Eqs. (4).

The roots of the polynomial equation for the web elements were found by solving the system of Eqs. (3) and Eqs. (4).

$$\begin{cases} s_1 = root1 \cdot a_1^2 + root2 \cdot a_1 + root3 \\ s_2 = root1 \cdot a_2^2 + root2 \cdot a_2 + root3\,, \\ s_3 = root1 \cdot a_3^2 + root2 \cdot a_3 + root3 \end{cases} \qquad (3)$$

$$\begin{cases} s_4 = root4 \cdot a_1^2 + root5 \cdot a_1 + root6 \\ s_5 = root4 \cdot a_2^2 + root5 \cdot a_2 + root6\,, \\ s_6 = root4 \cdot a_3^2 + root5 \cdot a_3 + root6 \end{cases} \qquad (4)$$

where s_1– distance x_2 for $x_1 = a_1$;
s_2 – distance x_2 for $x_1 = a_2$;
s_3 – distance x_2 for $x_1 = a_3$;
s_4– distance x_4 for $x_3 = a_1$;
s_5 – distance x_4 for $x_3 = a_2$;
s_6 – distance x_4 for $x_3 = a_3$;
a_1 – distance from the pylon to the connection of the first web element with bottom chord;
a_2 – distance from the pylon to the connection of the middle web element with bottom chord;
a_3 – distance from the pylon to the connection of the last web element with bottom chord, counting for the middle of the span.

Distribution of the material among the cable truss elements can be expressed by Eq. (5):

$$\begin{aligned} g &= g_b + g_t + g_w \\ g_t &= g - g_b - g_w \end{aligned}\,, \qquad (5)$$

where g – material consumption of cable truss;
g_b – material consumption of bottom chord;
g_t – material consumption of top chord;
g_w – material consumption of all web elements;

Definition of Optimization Problem

The aim of optimization is to evaluate rational, from the point of view of total vertical displacements minimization, characteristics of the cable truss for the prestressed suspension bridge.
The bottom chord camber f_b, material consumption of the cable truss g, material consumption of the stabilization cable, level of prestressing, bridge geometrical parameters: pylon height, main span and suspension step are considered as constants in objective function.
Relation of the top and bottom chord cambers f_t/f_b, the distances s_1, s_2, s_3, s_4, s_5, s_6, the rations g_b/g and g_w/g are variables of the optimization, 9 factors in all.
The optimization problem is to minimize the objective function:

$$w_{tot}\left(s_1, s_2, s_3, s_4, s_5, s_6, \frac{g_b}{g}, \frac{g_w}{g}, \frac{f_t}{f_b}\right), \qquad (6)$$

subject to:

$$\left[K(U)\right] \cdot \{U\} = \left[F(U)\right], \qquad (7)$$

and Eqs. (1) – (5),

where [K (U)] is the stiffness matrix, {U} is the displacement vector and [F (U)] is the force vector.

Total displacements w_{tot} are found by summing the displacements upwards w^+ and downwards w^- (Fig. 18). Maximum vertical displacements for suspended cable structures appear under the action of load applied to different parts of the span, therefore 39 different loading cases were analysed. The problem has been solved for elastic material behaviour stage taking into account geometrical non-linearity.

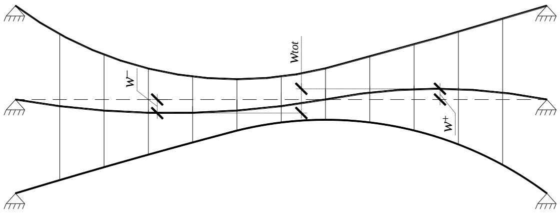

Figure 18. Deformed shape of prestressed suspension bridge in non-symmetrical loading case

Optimization Method for Calculation of Rational Characteristics of Cable Truss

The optimization of the cable truss by 9 variable factors for three different spans was done by the genetic algorithm (Goremikins et al., 2012a; Lute et al., 2009; Šešok and Belevičius, 2008).

The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that are based on natural selection, the process that reproduces a biological evolution. The genetic algorithm repeatedly modifies population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" towards an optimal solution. Genetic algorithms are used to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, non-differentiable, stochastic, or highly nonlinear (MathWorks, 2011).

The genetic algorithm uses three main types of rules at each step to create the next generation from the current population:

-Selection rules select the individuals, called parents, which contribute to the population at the next generation.

-Crossover rules combine two parents to form children for the next generation.

-Mutation rules apply random changes to individual parents to form children (MathWorks, 2011).

GA Toolbox of mathematical software MatLAB was used in the optimization. A special program was written in MatLAB programming environment to calculate the fitness using FEM. FEM program ANSYS was used to calculate displacements of the suspension bridge. A specially written MatLAB function calls ANSYS and ANSYS returns vertical displacements. The cable truss is modelled by two-node link type compression less finite elements (LINK10 in ANSYS). The analysis type is geometrically nonlinear static including large-deflection effects, because suspension cable structures are characterized with large deflections before stabilization (Sliseris and Rocens, 2011; Озолиньш et al., 1979).

RESULTS AND DISCUSSION

Topology optimization by the genetic algorithm was realized, using 10 generations, population size was equal to 50, elite child number was equal to 5. The rational characteristics of the cable truss were evaluated and are generalized in the Table 1.

Table 1

Characteristics of Rational Cable Truss

Characteristic	Symbol	Value		
		Span 50 m	Span 200 m	Span 350 m
Ratio of top and bottom chord cambers	f_t/f_b	0.4293	0.5089	0.5358
Ratio of material consumption of bottom chord and whole truss	g_b/g	0.5870	0.4512	0.4684
Ratio of material consumption of web elements and whole truss	g_w/g	0.0842	0.0673	0.0673
Distances, which define position of web elements	s_1, m	0.7785	4.8147	1.5595
	s_2, m	7.1937	16.3004	24.6802
	s_3, m	9.6487	16.3190	28.5679
	s_4, m	0.7150	0.9800	0.5029
	s_5, m	7.9753	12.6897	24.2618
	s_6, m	2.4367	16.2324	22.7034

The displacements of the prestressed suspension bridge with the rational cable truss were compared with the displacements of the prestressed suspension bridge with a single main cable for three selected spans. The material consumption of the cable truss was the same as the material consumption of the single cable. The analysis were carried out by the FEM software ANSYS.

The maximum total displacements are reduced from 26 to 30% depending on the span by using of the cable truss instead of the single cable in the case of the worst situated load. The dependence between the differences of displacements of structures with a single cable and cable truss and span of structures in the case of the worst situated load is shown in Fig. 19.

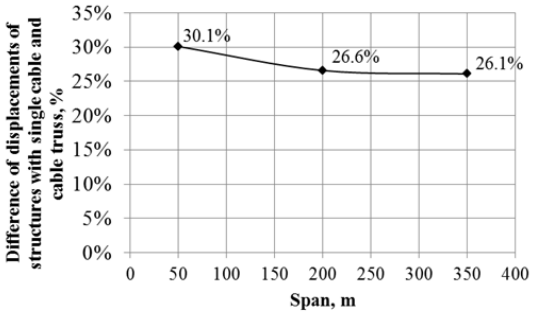

Figure 19. Dependence between differences of displacements of structures with single cable and cable truss and span of structures in the case of worst situated load

CONCLUSIONS

The application of the cable truss with concave chords, optimized chord shape and cross web topology considerably decreases displacements of the prestressed suspension structure.

The displacements of the prestressed suspension bridge with the proposed cable truss are smaller by 26–30% than the displacements of the structure with the single main cable for the span interval from 50 to 350 m.

Rational characteristics of the cable truss with spans 50, 200 and 350 m and bottom chord camber 1/10 of the span from the point of view of structural stiffness are the following: the ratio between the top and bottom chord chambers is 0.429, 0.510 and 0.536, the ratio between the bottom chord material consumption and material consumption of the whole truss is 0.587, 0.451 and 0.468, the relation between material consumption of the web elements and the whole truss is 0.084, 0.067 and 0.067, respectively. The position of the web elements was evaluated in the form of the second order polynomial.

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