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Topology Optimization of Cable Truss Web for Prestressed Suspension Bridge

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Abstract**—**A suspension bridge is the most suitable type of structure for a long-span bridge due to rational use of structural materials. Increased deformability, which is conditioned by appearance of the elastic and kinematic displacements, is the major disadvantage of suspension bridges.

The problem of increased kinematic displacements under the action of non-symmetrical load can be solved by prestressing. The prestressed suspension bridge with the span of 200 m was considered as an object of investigations. The cable truss with the cross web was considered as the main load carrying structure of the prestressed suspension bridge.

The considered cable truss was optimized by 47 variable factors using Genetic algorithm and FEM program ANSYS.

It was stated, that the maximum total displacements are reduced up to 29.9% by using of the cable truss with the rational characteristics instead of the single cable in the case of the worst situated load.

Keywords**—**Decreasing displacements, Genetic algorithm.

I. INTRODUCTION

SUSPENSION bridges are structures where the deck is continuously supported by the stretched catenary cable [1]. Suspension bridges are the most important and attractive structures possessing a number of technical, economical and aesthetic advantages [2].

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 [3]. So long spans can be achieved because the main load carrying cables are subjected to tension and distribution of normal stresses in the cable cross-section are close to uniform [4].

Increased deformability is one of the basic disadvantages of suspension bridges [5]. Increased deformability is conditioned by appearance of elastic and kinematic displacements. The elastic displacements are caused by the large tensile inner forces. The elastic displacements are maximal at the centre of 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) [6], [7]. 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 [8].

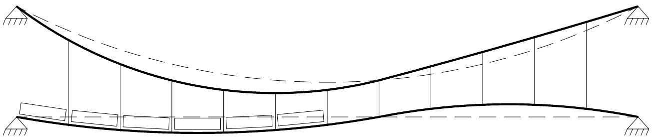

Fig. 1 Initial shape change under the action of non-symmetrical load

The problem of increased kinematic displacements can be solved by increasing of dead weight and imposed load relation, which is achieved by adding of cantledge (Fig. 2). However, this method causes the increase of material consumption. Stiffness of suspended structure 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 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) [8], [9], [10], [11]. Nevertheless, these systems are characterized also with the increased material consumption, and system stiffness is not sufficient in many cases.

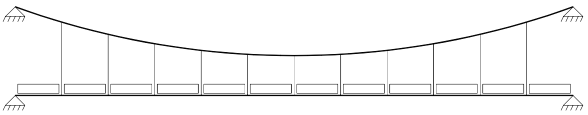

Fig. 2 Suspension bridge stabilization by adding of cantledge

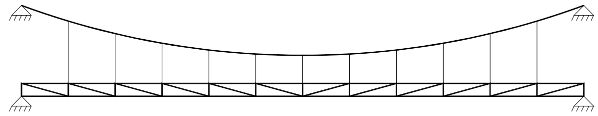

Fig. 3 Suspension bridge stabilization by increasing of girder stiffness

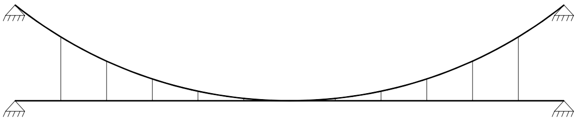

Fig. 4 Suspension bridge stabilization by connecting of main cable and girder at the centre of span

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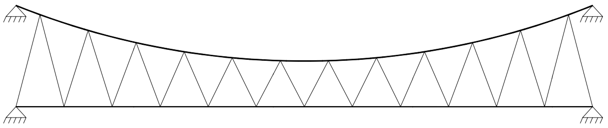

Fig. 5 Suspension bridge stabilization by application of diagonal suspenders

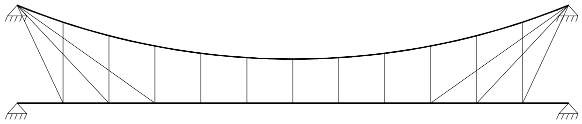

Fig. 6 Suspension bridge stabilization by application of inclined additional cables

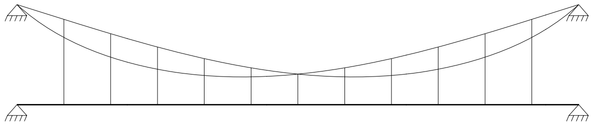

Fig. 7 Suspension bridge stabilization by application of two-chain system

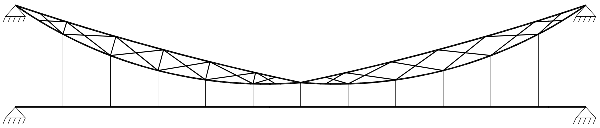

Fig. 8 Suspension bridge stabilization by application of stiff chains

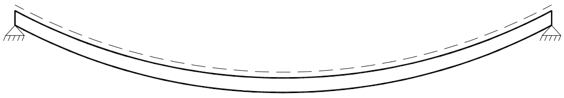

Fig. 9 Suspension bridge stabilization by application of stress ribbons

Usage of prestressed cable truss is another method of increased kinematic displacements under the action of unsymmetrical load problem fixing [12], [13]. 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 [14]. But one of the most efficient and convenient for application for bridges is the concave cable truss (Fig. 10) [13]. Cable truss usage allows to develop bridges with reduced requirements for girder stiffness, where overall bridge rigidity will be ensured by prestressing of the stabilization cable [8]. The deck can be made of light composite materials [15], [16].

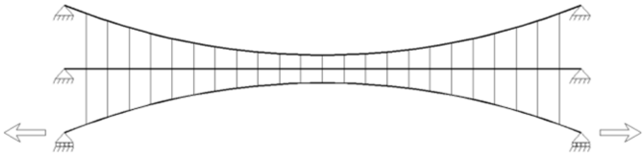

Fig. 10 Suspension bridge stabilization by the prestressing

The kinematic displacements of prestressed suspension bridge can be decreased by replacing of the main single cable with the cable truss with a cross web (Fig. 11) [17], [18], [19].

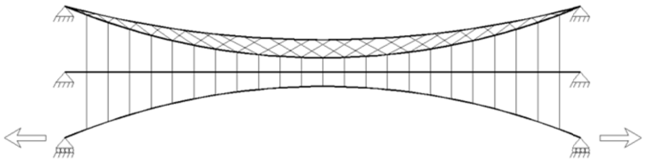

Fig. 11 Suspension bridge stabilization by the using of prestressed stabilization cable and cable truss

Cables can be cambered in horizontal plane to increase structure stiffness in the same plane (Fig. 12) [8].

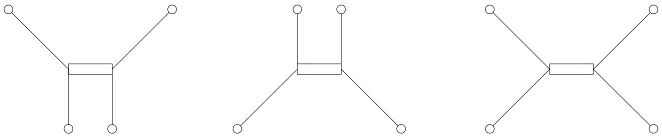

Fig. 12 Suspension bridge stabilization in horizontal plane by cambering of main or stabilization cables. Cross-sectional view

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

II. DESCRIPTION OF INVESTIGATION OBJECT

Prestressed suspension bridge with cable truss with cross web was chosen as objects of investigation (Fig. 13) [17].

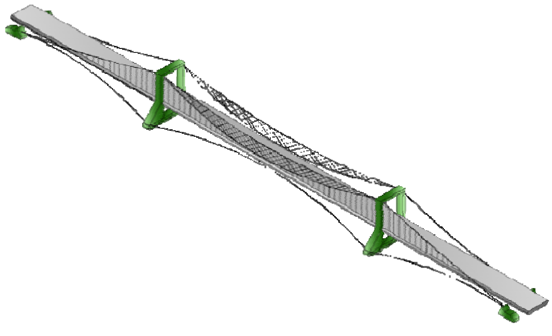

Fig. 13 Prestressed suspension bridge with cable truss load carrying structure

The main span l of considered bridge is equal to 200 m. The distances from the top of the pylon and from the connection of stabilization cable up to the deck are equal to 21 m and 11 m, respectively. 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 cable truss bottom chord f_b is equal to 20 m. The bridge is prestressed in horizontal and vertical planes by the stabilization cables. The stabilization cable camber is equal to 10 m. The deck is connected with the main load-carrying cables by the suspensions with step a equal to 5 m (Fig. 15). The cable string is placed between suspensions to minimize horizontal prestressing force effects acting in the deck. Prestressed horizontal cables are placed along the deck to minimize effects of horizontal braking force (Fig. 16). The deck of the bridge is made of pultrusion composite trussed beams, pultrusion composite beams with step 1 m and pultrusion composite plank with height 40 mm that is covered with asphalt layer (Fig. 14) [15], [16], [20]. It is assumed that cables are covered with high-density polyethylene and are heated with electricity to reduce the influence of temperature effects [21]. Possible prestressing loosing is reduced by active tendons [22].

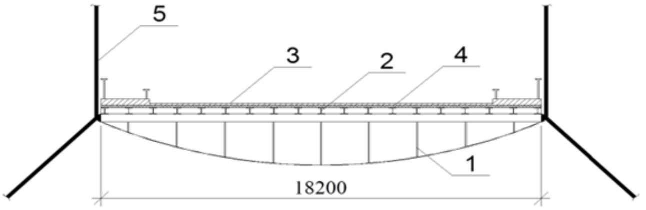

Fig. 14 The bridge deck structure.
1 – Composite trussed beam, 2 – Composite I type beams, 3 – Composite plank, 4 – Cover of the bridge, 5 – Suspensions

It is possible to reduce requirements for girder stiffness by bridge prestressing. This aspect allows to use the composite pultrusion materials in the deck structure and makes possible to develop construction of bridges with large span and reduced dead weight in comparison with steel or concrete bridges [10].

Design scheme of the investigation object is shown in the Fig. 15 and Fig. 16. The structural material is prestressed steel rope [23], [24]. 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 [25]. Imposed load can be applied to any place of the span. Distributed load is reduced 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).

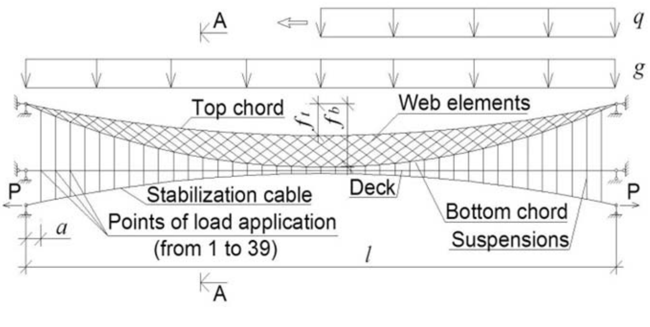

Fig. 15 Design scheme of suspension bridge.
q – imposed load, *g* – dead load, *P* – prestressing, f_b – bottom chord camber, f_t – top chord camber, *l* – main span, *b* – width, *a* – suspension step.

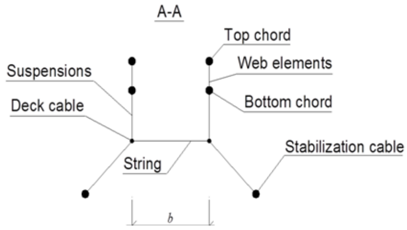

Fig. 16 Cross section of prestressed suspension bridge

Position of each web element of the cable truss is defined by the distance from the pylon to the connection of 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 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 position of each web element and to minimize amount of variable factors.

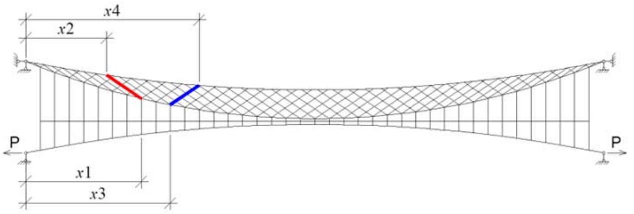

Fig. 17 Position of web elements

The position of the web elements, which are inclined to the edges of the cable truss is expressed by Eq. (1), the position of web elements, inclined to the edges of cable truss, is expressed by Eq. (2) [17], [18].

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

$$x_4 = x_3 + (root4 \cdot x_3^2 + root5 \cdot x_3 + root6)\,, \tag{2}$$

where x_2 and x_4 – distances from the pylon to the connection of web element and top cord;
x_1 and x_3 – distances from the pylon to the connection of web element and bottom cord;
*root*1…*root*6 – 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).

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

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

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 first web element with bottom chord;
a_2 – distance from the pylon to the connection of middle web element with bottom chord;
a_3 – distance from the pylon to the connection of last web element with bottom chord, counting for the middle of span.

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

$$\begin{aligned} & g = g_b + g_t + g_w \\ & g_w = \sum_{i=01}^{39} g_{w,i} \qquad , \\ & g_t = g - g_b - g_w \end{aligned} \tag{5}$$

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;
$g_{w,i}$ – material consumption of i-th web element.

The web elements of the cable truss, which are inclined to the supports of the cable truss, are numbered from 1 to 20, starting from the support. The web elements, which are inclined to the centre of the cable truss, are numbered from 21 to 39, starting from the support.

III. TOPOLOGY OPTIMIZATION OF CABLE TRUSS WEB

A. 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 cable truss g, material consumption of stabilization cable, level of prestressing, bridge geometrical parameters: pylon height, main span and suspension step are considered as constants of the optimization.

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 $g_{w,1}/g$ – $g_{w,39}/g$ are variable factors for the optimization, 47 factors in all.

Optimization problem is to minimize objective function:

$$w_{tot}\left(s_1, s_2, s_3, s_4, s_5, s_6, g_1, g_2, \frac{f_t}{f_b}\right), \tag{6}$$

subject to:

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

and Eqs. (1)-(6),

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

Total displacements w_{tot} are found by summing displacements upwards w^+ and displacements downwards w^- (Fig. 18). Maximum vertical displacements for suspended cable structures appears under the action of load applied to different parts of span, therefore 39 different loading cases were analysed. The problem has to be solved in static and in non-linear stage.

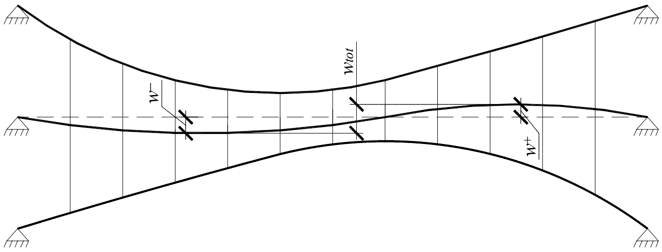

Fig. 18 Deformed shape of prestressed suspension bridge in non-symmetrical loading case

B. Optimization Method for Calculation of Rational Characteristics of Cable Truss

The optimization of the cable truss by 47 variable factors is done by genetic algorithm [17], [26], [27].

The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that are based on natural selection, the process that drives biological evolution. The genetic algorithm repeatedly modifies a 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 [28].

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 [28].

GA Toolbox of mathematical software MatLAB was used in the optimization. Special program was written in MatLAB programming environment to calculate fitness using FEM (Fig. 19). FEM program ANSYS was used to calculate displacements of suspension bridge. Specially written MatLAB function calls ANSYS and ANSYS returns vertical displacements. 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 [29], [23].

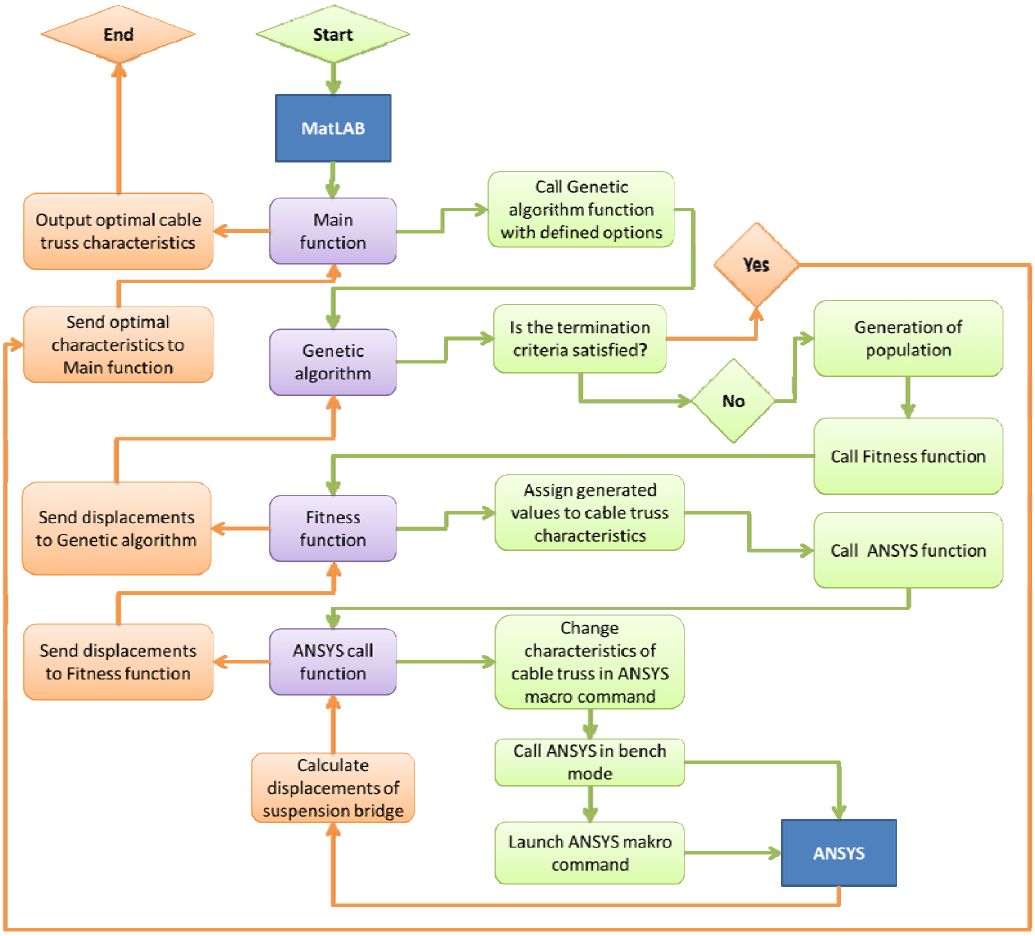

Fig. 19 Flow chart of calculation of rational characteristics

C. Rational Characteristics of Cable Truss

Topology optimization with the genetic algorithm was realized, using 40 generations, population size was equal to 100, elite child number was equal to 10. The rational characteristics of the cable truss were evaluated and are generalized in Table I. Optimized structure by 47 variable factors was compared with optimized structure by 9 variable factors [17]. It was determined, that displacements of the cable truss optimized by 47 variable factors are smaller by 4.5%, than displacements of the cable truss, optimized by 9 variable factors.

TABLE I
RATIONAL CHARACTERISTICS OF CABLE TRUSS

Nr.	Characteristic	Symbol	Value	Nr.	Characteristic	Symbol	Value
1	Relation of top and bottom chord cambers	f_t/f_b	0.4842	25	Relation of material consumption of *i*-th web element and whole truss	$g_{w,17}/g$	0.00229
2	Distances, which define position of web elements	s_1, m	4.9546	26		$g_{w,18}/g$	0.00151
3		s_2, m	19.9830	27		$g_{w,19}/g$	0.00387
4		s_3, m	17.8008	28		$g_{w,20}/g$	0.00192
5		s_4, m	0.7753	29		$g_{w,21}/g$	0.00218
6		s_5, m	15.1424	30		$g_{w,22}/g$	0.00016
7		s_6	18.2514	31		$g_{w,23}/g$	0.00124
8	Relation of material consumption of bottom chord and whole truss	g_b/g	0.4035	32		$g_{w,24}/g$	0.00043

9	Relation of material consumption of *i*-th web element and whole truss	$g_{w,1}/g$	0.00206	33		$g_{w,25}/g$	0.00039
10		$g_{w,2}/g$	0.00102	34		$g_{w,26}/g$	0.00132
11		$g_{w,3}/g$	0.00109	35		$g_{w,27}/g$	0.00056
12		$g_{w,4}/g$	0.00107	36		$g_{w,28}/g$	0.00086
13		$g_{w,5}/g$	0.00112	37		$g_{w,29}/g$	0.00064
14		$g_{w,6}/g$	0.00134	38		$g_{w,30}/g$	0.00144
15		$g_{w,7}/g$	0.00461	39		$g_{w,31}/g$	0.00279
16		$g_{w,8}/g$	0.00270	40		$g_{w,32}/g$	0.00278
17		$g_{w,9}/g$	0.00351	41		$g_{w,33}/g$	0.00440
18		$g_{w,10}/g$	0.00457	42		$g_{w,34}/g$	0.00332
19		$g_{w,11}/g$	0.00249	43		$g_{w,35}/g$	0.00251
20		$g_{w,12}/g$	0.00389	44		$g_{w,36}/g$	0.00489
21		$g_{w,13}/g$	0.00440	45		$g_{w,37}/g$	0.00262
22		$g_{w,14}/g$	0.00184	46		$g_{w,38}/g$	0.00205
23		$g_{w,15}/g$	0.00209	47		$g_{w,39}/g$	0.00436
24		$g_{w,16}/g$	0.00401				

IV. COMPARATIVE ANALYSIS OF PRESTRESSED SUSPENSION BRIDGES WITH SINGLE CABLE AND CABLE TRUSS

The displacements of the prestressed suspension bridges with the rational cable truss and single cable were compared. 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 up to 29.9% by using of the cable truss instead of the single cable in the case of the worst situated load.

V. CONCLUSION

New possibility to improve the main disadvantage of the cable structures (increased deformability) is proposed. Rational from the point of view of displacements decrease structure of the cable truss was developed. Rational relation of the top chord camber/the bottom chord camber and material consumption of the bottom chord/material consumption of the whole truss are equal to 0.48 and 0.40, correspondingly. The topology optimization of the cable truss web was realized.

It was stated, that displacements of the cable truss optimized by 47 variable factors are smaller by 4.5%, than displacements of the cable truss, optimized by 9 variable factors.

The maximum total displacements are reduced up to 29.9% by using of the cable truss instead of the single cable in the case of the worst situated load.

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