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].

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.

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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].

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

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].

The main span \( I \) 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 \( f_2 \) 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
dek. Prestressed horizontal cables are placed along the deck
to minimize effects of horizontal braking force (Fig. 16). The
dek 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](image)

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](image)

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

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

![Fig. 16](image)

Fig. 16 Cross section of prestressed suspension bridge
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](image)

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].

$$x_2 = x_1 - (\text{root}_1 \cdot x_1^2 + \text{root}_2 \cdot x_1 + \text{root}_3),$$

$$x_4 = x_1 + (\text{root}_4 \cdot x_1^2 + \text{root}_5 \cdot x_1 + \text{root}_6),$$

where $x_2$ and $x_4$ – distances from the pylon to the connection
of web element and top chord;

$x_1$ and $x_3$ – distances from the pylon to the connection of web
element and bottom chord;

$\text{root}_1$–$\text{root}_6$ – 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).

$$\begin{align*}
\text{root}_1 \cdot a_x^2 + \text{root}_2 \cdot a_x + \text{root}_3 = x_1 \\
\text{root}_1 \cdot a_x^2 + \text{root}_2 \cdot a_x + \text{root}_3 = x_3
\end{align*}$$
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 of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population of individual solutions. 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. 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].

![Flow chart](image)

**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>
<thead>
<tr>
<th>Nr.</th>
<th>Characteristic</th>
<th>Symbol</th>
<th>Value</th>
<th>Nr.</th>
<th>Characteristic</th>
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<tbody>
<tr>
<td>1</td>
<td>Relation of top and bottom chord cambers</td>
<td>( \delta/h )</td>
<td>0.4842</td>
<td>25</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00229</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>( s_1, m )</td>
<td>4.9546</td>
<td></td>
<td>26</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00151</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>( s_2, m )</td>
<td>19.9830</td>
<td></td>
<td>27</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00387</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>( s_3, m )</td>
<td>17.8008</td>
<td></td>
<td>28</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00192</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>( s_4, m )</td>
<td>0.7753</td>
<td></td>
<td>29</td>
<td>Relation of material consumption of t-th web</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00218</td>
</tr>
<tr>
<td>6</td>
<td>( s_5, m )</td>
<td>15.1424</td>
<td></td>
<td>30</td>
<td>element and whole truss</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00016</td>
</tr>
<tr>
<td>7</td>
<td>( s_6 )</td>
<td>18.2514</td>
<td></td>
<td>31</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00124</td>
<td></td>
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<tr>
<td>8</td>
<td>Relation of material consumption of bottom chord and whole truss</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.4035</td>
<td>32</td>
<td>( \delta_{w, v} / \delta )</td>
<td>0.00043</td>
<td></td>
</tr>
</tbody>
</table>
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 single cable was the same as the material consumption of the single cable. The analysis were carried out by using of 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.

ACKNOWLEDGMENTS

This work has been supported by the European Social Fund within the project “Support for the implementation of doctoral studies at Riga Technical University”.

REFERENCES


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