RIGA TECHNICAL UNIVERSITY
Faculty of Civil Engineering
Institute of Structural Engineering and Reconstruction

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RATIONAL LARGE SPAN PRESTRESSED CABLE STRUCTURE

Summary of the Doctoral Thesis

Riga Technical University Promotion Council "RTU P-06" in Field of Building, Transport and Traffic Sciences

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GENERAL WORK DESCRIPTION

Motivation

Limited raw materials and energy resources are actual national economy problems. The decrease of weight, increase of span and durability of load carrying structures are the possible solutions of these problems. The increase of structural efficiency could be achieved by applying the high strength materials for prestressed tensioned structures, where stress distribution by cross-section is close to uniform. Application of high strength materials with increased specific strength (strength and mass ratio), comparing with traditional materials, for prestressed tensioned structures allow to essentially decrease the ratio between applied load and structural dead weight (for constant span), which save raw materials and energy resources.

The largest structural span (up to 1991 m) was achieved by application of suspension structures. However, increased deformability that is conditioned by appearance of kinematic displacements is one of the suspension structures disadvantages. A prestressed cable truss usage is an effective way of kinematic displacements decrease. Prestressed cable truss without compressed elements allows to provide large load carrying capacity, increase structural stiffness, as well as regulate natural frequencies of a structure. However, in many cases it is not possible to ensure required stiffness of structure by application of cable trusses with rational prestressing level. It is necessary to develop cable truss with increased stiffness and without compressed elements.

Prestressed cable trusses are widely used for large span ceiling structures. However, in bridge engineering cable trusses application technologies are used only for pedestrian and pipeline bridges, which are characterized by small imposed loads. There are no published detailed investigations about the advantages and disadvantages of prestressed cable truss application for road bridges.

Structural dynamic analyse is one of the regulated bridge design parts. Determination of natural frequencies is realized by labour-consuming discrete methods. There is a lack of simplified methods of determination of natural frequencies of prestressed cable structure, which would simplify computations in the stage of structure version development.

A span of suspension structures can be significantly increased by application of carbon fiber reinforced polymers (CFRP), due to significantly increased specific strength of CFRP comparing with steel. The safety of these structures can be increased by application of hybrid composite cables, where CFRP layer is strengthened by steel layers with variable cross-section area by its length. A variable cross-section area by cable length allows to minimize differences of stresses by cable length.

Consequently, it is actually to develop design method of prestressed cable truss, to obtain the possibility of increase of prestressed cable truss stiffness and the possibility of application of composite materials for creation of prestressed cable trusses. Simplified method of determination of natural frequencies of prestressed suspension structures should be developed also. This would make possible of broad application of prestressed suspension cable structures, especially for large span structures.

Aims and Tasks of the Work

The aim of the work is to develop a rational solution of prestressed cable structure, which provide smaller displacements in comparison with a single suspension cable using the same material consumption; to implement cable truss design algorithm; to analyse advantages of this cable truss in case of its application for the large span bridge structure instead of single main cable and experimentally verify obtained results.

In compliance with the aim the following tasks are suggested:

- The development of rational from the point of view of displacements placement of elements of the prestressed suspension structure; development of design algorithms of the prestressed cable truss for FEM program ANSYS and optimization algorithms of the prestressed cable truss by genetic algorithm for MatLAB and ANSYS programming environments; finding of rational characteristics of the cable truss; as well as developing of rational from the point of view of material consumption hybrid composite cable for prestressed suspension structure and checking safety of structure in the case of CFRP layer destruction.
- The research of the prestressed suspension structure behaviour under the action of different loading cases, evaluation of the advantages and disadvantages of the developed cable structure in comparison with the single cable and development of rational suspended structure.
- Experimental verifying of the models of prestressed suspension structure with cable truss and single cable and comparison of them; experimental verifying of the developed numerical models of prestressed suspension cable structures; experimental evaluation of temperature change and prestression level loose on the prestressed suspension cable structure behaviour.
- The development of the simplified determination method of natural frequencies of the prestressed suspension structure and experimental

verifying of this method on the physical model of the prestressed suspension cable structure, as well as determining of natural frequencies of the prestressed suspension bridge.

Scientific Novelty of the Work

The new placement of elements of large span prestressed cable truss without compressed elements was developed, which is characterized with smaller kinematic displacements and reduced material consumption in comparison with existing solutions.

The new design and optimization algorithms of prestressed suspension structure by FEM program ANSYS and programming environment MatLAB were developed, which can be used for broad range of tasks.

It was proved that the developed cable truss with rational parameters allows to decrease displacements in the case of the worst situated load in comparison with the single cable in the interval of spans from 50 to 350 m by 26–30%. The results were experimentally verified.

The rational from the point of view of material consumption structure of hybrid composite cable, which is characterized by increased safety comparing with composite cables and increased specific strength comparing with steel cables, was developed.

The simplified method of determination of natural frequencies of prestressed suspension structure with precision in 20% was developed and experimentally verified.

Practical Use of the Work

The developed large span prestressed cable truss structure, its design and optimizations algorithms make it possible for engineers to design ceilings and bridge structures with reduced displacements and material consumption comparing with ordinary solutions of cable trusses. The simplified method of determination of natural frequencies allows to evaluate behaviour of prestressed cable trusses.

The Following Topics are Presented for Defence

- The developed large span prestressed cable truss with concave chords and cross web with rational characteristics from the point of view of displacements, where all elements are tensioned, and its application possibility for prestressed suspension structure, which was experimentally verified;
- The developed algorithms of design and optimization of the cable truss;
- The hybrid composite cable with rational from the point of view of material consumption and the safety structure for large span prestressed suspension structure;
- The developed simplified determination method of natural frequency of prestressed suspension structure, which was experimentally verified.

Methodology and Applied Materials

Approximate computations of cable truss shape evaluation were done by finite element method (FEM) in program LIRA 9.6 using of geometrically nonlinear approach. Cable truss elements were modelled by geometrically nonlinear cable type finite elements FE310. Prestressing was modelled by jack type finite element FE308 with defined prestressing force.

Computations of cable truss were done by FEM program ANSYS, which allows to take geometrical nonlinearity of a structure into account. Cable truss elements were modelled by two joints finite elements LINK10, which work in tension only. Prestression is modelled by assignment of the initial strain to finite elements.

The special program was written in MatLAB programming environment for cable truss optimization, which uses a genetic algorithm function.

Numerically obtained results were experimentally validated by static and dynamic testing of small-scale physical models of prestressed suspension structures. Elements of the models were made from steel cables. The influence of temperature change on cable elements behaviour and the possibility of cable elastic modulus increase were verified on steel cable samples. Cables were certified by “Certex Latvia” Ltd. The elastic modulus of cables is equal to 60 GPa, the tensile strength of wires is equal to 1770 MPa.

The interaction of layers of the hybrid composite cable was checked by three layered steel samples, which were glued together by epoxy glue.

Research Theory and Methodology

Theoretical methodologies of the following engineering sciences were used in the work:

- mechanics of composite materials;
- building statics;
- natural frequency theory of structures;
- ceiling and bridge structures;
- tensioned structure theory;
- theory of optimization of structures.

Research Restrictions

The developed prestressed suspension structures are rational for distributed loading cases, which are typical for bridges, and for relatively stiff support types in the span interval from 50 to 350 m.

Size of the Work

The work consists of an introduction part, five chapters, conclusions and references. The volume of work is 155 p., 157 figures, 29 tables and 152 references.

Work Approbation and Publications

The research results were presented and discussed at the following scientific conferences:

- Goremikins V., Rocens K., Serdjuks D. Topology Optimization of Cable Truss Web for Prestressed Suspension Bridge. ICCSEE 2012: International Conference on Civil, Structural and Environmental Engineering. January 14-15, 2013, Zurich, Switzerland;
- Goremikins V., Rocens K. and Serdjuks D. Behavior of Prestressed Suspension Bridge. Riga Technical University 53rd International Scientific Conference, October 11-12, 2012, Riga, Latvia;
- Goremikins V., Rocens K. and Serdjuks D. Analysis of Hybrid Composite Cable for Prestressed Suspension Bridge. 17th International Conference „Mechanics of Composite Materials". May 28-June 1, 2012, Riga, Latvia;
- Goremikins V., Rocens K. and Serdjuks D. Cable Truss Analyses for Suspension Bridge. 10th International Scientific Conference "Engineering for Rural Development". May 24-25, 2012, Jelgava, Latvia;
- Goremikins V., Rocens K., Serdjuks D. Cable Truss Analyses for Prestressed Suspension Bridge. 8th International DAAAM Baltic Conference Industrial Engineering. April 19-21, Tallinn, Estonia;
- Goremikins V., Rocens K., Serdjuks D. Decreasing of Displacements of Prestressed Cable Truss. ICCEE 2012: International Conference on Civil and Environmental Engineering. March 28-29, 2012, Madrid, Spain;
- Goremikins V., Rocens K., Serdjuks D. Daži racionāli konstrukciju risinājumi inženierbūvēm. Apvienotais pasaules latviešu zinātnieku 3.

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- V. Goremikins, K. Rocēns, D. Serdjuks. Experimental Testing of Cable Truss. RTU 52st International Scientific Conference. Section “Construction Science”, October 13, 2011, Riga, Latvia;
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- Goremikins V., Rocens K. and Serdjuks D. Cable Truss Analyses for Suspension Bridge. International Scientific Conference Civil Engineering ‘11. May 12-13, 2011, Latvia, Jelgava;
- Goremikins V., Rocens K., Serdjuks D. Rational Structure of Cable Truss. ICBSE 2011 : "International Conference on Building Science and Engineering", April 27-29, 2011, Venice, Italy;
- Goremikins V., Rocēns K., Serdjuks D. Režģojuma veida ietekme uz vanšu kopņu darbu. RTU 51. starptautiskā zinātniskā konference. Rīga, 2010.gada 11.-15. oktobris;
- Goremikins V., Rocēns K., Serdjuks D. Šprengeļsijas no pultrūzijas kompozītiem racionāla liellaiduma konstrukcija. RTU 51. starptautiskā zinātniskā konference. Rīga, 2010.gada 11.-15. oktobris;
- Goremikins V., Rocens K. and Serdjuks D. Rational Structure of Composite trussed beam. 16th international conference „Mechanics of Composite Materials”. May 24-28, 2010, Latvia;
- Goremikins V. and Serdjuks D. Rational Structure of Trussed Beam. 10th international conference “Modern building materials, structures and techniques”. May 19-21, 2010, Lithuania;

- Goremikins V., Grabis J. un Serdjuks D. Telpisko tērauda kopņu izmantošana pārsegumā. Rīgas Tehniskās universitātes 50. starptautiskā zinātniskā konference. 12.-16. oktobris, 2009, Latvija;
- Goremikins V. un Serdjuks D. Šprengeļsijas racionāla konstrukcija. Rīgas Tehniskās universitātes 50. starptautiskā zinātniskā konference. 12.-16. oktobris, 2009, Latvija.

The work main results are published at the following publications:

Scientific journals:

- Goremikins V., Rocens K. and Serdjuks D. Topology Optimization of Cable Truss Web for Prestressed Suspension Bridge // Journal "World Academy of Science, Engineering and Technology". Special Journal Issues (accepted for publication);
- Goremikins V., Rocens K. and Serdjuks D. Decreasing Displacements of Prestressed Suspension Bridge // Journal of Civil Engineering and Management. – 2012. – Volume 18, Issue 06. – pp. 858-866 (journal indexed by SCOPUS and EBSCO databases);
- Goremikins V., Rocens K. and Serdjuks D. Decreasing of Displacements of Prestressed Cable Truss // International Journal of Civil and Environmental Engineering. – 2012. – Issue 6. – pp. 291-299;
- Goremikins V., Rocens K. and Serdjuks D. Decreasing of Displacements of Prestressed Cable Truss // Journal "World Academy of Science, Engineering and Technology". Special Journal Issues. – 2012. – Issue 63. – pp. 554-562;
- Goremikins V., Rocens K., Serdjuks D. Rational Structure of Cable Truss // Journal "World Academy of Science, Engineering and Technology". Special Journal Issues. – 2011. – Issue 76. – pp. 571-578 (indexed by SCOPUS and EBSCO databases).

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- Goremikins V., Rocens K., Serdjuks D. and Gaile L. Experimental Determination of Natural Frequencies of Prestressed Suspension Bridge Model // Scientific Journal of RTU. Construction Science (accepted for publication);
- Goremikins V., Rocens K. and Serdjuks D. Evaluation of Rational Parameters of Trussed Beam // Scientific Journal of RTU. Construction Science. – 2010. – Vol. 11. – pp. 21-25 (indexed by EBSCO database);

- Goremikins V., Rocens K. and Serdjuks D. Rational Large Span Structure of Composite Pultrusion Trussed Beam // Scientific Journal of RTU. Construction Science. – 2010. – Vol. 11. – pp. 26-31 (indexed by EBSCO database);
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- Goremikins V., Rocens K. and Serdjuks D. Cable Truss Analyses for Suspension Bridge // Proceedings of the International Scientific Conference "Civil Engineering '11", Jelgava, Latvia, May 12-13, 2011 (accepted for publication);
- Goremikins V., Rocens K., Serdjuks D. Rational Structure of Cable Truss // Proceedings of the ICBSE 2011 : "International Conference on Building Science and Engineering", Venice, Italy, April 27-29, 2011, pp. 513-520;
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- Goremikins V., Rocens K. and Serdjuks D. Behavior of Prestressed Suspension Bridge // Proceedings of Riga Technical University 53rd International Scientific Conference, Latvia, Riga, October 11-12, 2012, p. 384;
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- Goremikins V., Rocens K. and Serdjuks D. Rational Structure of Composite trussed beam // Proceedings of the 16th international conference „Mechanics of Composite Materials", Latvia, Riga, May 24-28, 2010, p. 75.

Methodical instructions:

- Goremikins V., Rocēns K., Serdjuks D. Konstruktīvo elementu no plastmasām (pultrūzijas kompozītmateriāliem) aprēķins (aprēķinu pamatprincipi un piemēri). Metodiskie norādījumi. – Rīga: RTU, 2010, – 34. lpp. (ISBN 978-9934-8151, www.goremikins.com).

CONTENT OF THE WORK

Motivation, aims, scientific novelty and practical application of the work are formulated at the beginning of the work.

In **First Chapter** large span structures are considered. It was stated that the longest spans were achieved by suspension structures (up to 1991 m). The increased deformability is one of the main disadvantages of suspension structures. The increased deformability is conditioned by appearance of elastic and kinematic displacements. The elastic displacements are caused by large tensile inner 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. 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 the low strength steel structural profiles, by elastic modulus increase, reinforced concrete application and cable camber increase. The problem of increased kinematic displacements can be solved by increasing the dead weight and imposed load relation, which is achieved by adding a cantledge. However, this method increases of material consumption. Stiffness of suspended structures can be also improved by increasing of girder stiffness; increasing of main cable camber; connecting of the main cable and girder at the centre of span; application of diagonal suspenders or inclined additional cables; application of two chain systems; stiff chains and stress ribbons. However, these systems are also characterized with the increased material consumption, and system stiffness is not sufficient in many cases. The usage of prestressed cable truss is an efficient method of decreasing of kinematic displacements caused by action of unsymmetrical load. This method allows to regulate stiffness and natural frequencies of the structure by prestressing.

In the first chapter different types of cable trusses are considered. Cable trusses can be divided to concave cable trusses, convex cable trusses, convex-concave cable trusses, cable trusses with centre compression strut and cable trusses with parallel chords. The most efficient cable trusses are with tension elements only.

In the first chapter suspension bridge structures, as structures with longest spans in the world, are considered. The history, different types, main components and application of prestressed cable trusses of suspension bridges are described in this chapter.

The static analysis of suspension structures can be done by the approximate, analytical and numerical analysis. The approximate analysis can be used in specific situations. Analytical analyses take into account support location at different levels, displacements of supports, temperature effects and prestressing, however calculations by this methods are very time-consuming. Precise and low time-consuming results can be achieved by application of automate numerical analyses, which use the finite element method (FEM). FEM program ANSYS is one of the most powerful programs. Two joint spatial elements are used for cable modelling in ANSYS program. The elements work in tension only. The elements are characterized with bilinear stiffness matrix, which is dependent on deformation direction. The analysis of cable structures is geometrically nonlinear and is realized by Newton-Raphson method. Cable structures are characterized by geometrical nonlinearity, which is taken into account by the special deformation-displacement dependence matrix.

The natural frequency determination method of suspension structures is described in the first chapter. It was concluded that there is a lack of simple determination methods of natural frequencies of prestressed suspension structure.

The better solution of the structure can be found using optimization algorithms. Optimization algorithms can be divided in two base classes: deterministic and probabilistic algorithms. Deterministic algorithms are used if a clear relation between the variable factors and optimization parameters exists. If the relation is not clear, too complicated, or the dimensions of search space are very high, than the problem can be solved by probabilistic algorithms. An adaptive search is used for increasing of efficiency of the probabilistic algorithm. The adaptive search uses heuristic functions, which use the information that the algorithm got in previous iterations to generate points for the next iteration. One of the probabilistic algorithms is a genetic algorithm. The method is based on the natural selection, the process that drives biological evolution. Tasks with large variable factor amount can be solved by this method.

The comparative analysis of cable trusses is performed in **Second Chapter**. It was stated that the cable truss with two concave chords can better keep the initial shape under the action of unsymmetrical load (Fig.1). This cable truss can work without prestressing. Rational cambers of the top and bottom chords, rational load application point number and rational web system were found for the considered cable truss. It was stated that the cross web is the most appropriate web for the cable truss with two concave chords from the point of view of displacements.

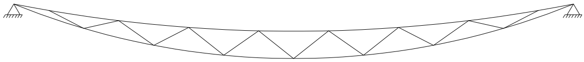


Fig. 1. Cable truss with two concave chords

The advantages and disadvantages of the cable truss with cross web and concave chords were discovered on the prestressed suspension structure with the span, equal to 200 m (Fig. 2). The structure is loaded by the load, which is typical for bridges. The load can be applied to any possible place of the deck.

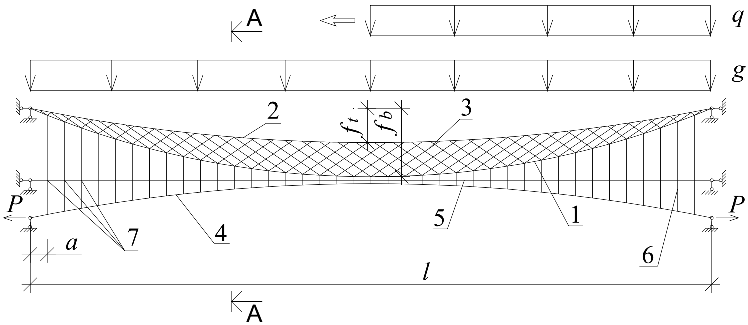


Fig. 2. Design scheme of prestressed suspension structure:
1 – bottom chord; 2 – top chord; 3 – web elements; 4 – stabilization cable; 5 – deck; 6 – suspensions; 7 – point of load application; *q* – imposed load; *g* – dead load; *P* – prestressing; f_b – bottom chord camber; f_t – top chord camber; *l* – main span; *b* – width; *a* – suspension step

A special design algorithm for ANSYS program was developed for the prestressed suspension structure with the cable truss. The algorithm builds geometry by input parameters, defines materials and cross-sections of elements, divides structure to finite elements and calculates deformations and stresses. The developed algorithm can be transformed to different analyses (e. g. optimization), as well as can be used for greater structures analyses, where the cable truss is the only part.

The special algorithm was developed in MatLAB programming environment for cable truss optimization, which is realized by genetic algorithm. Minimization of total displacements from the worst situated load is the aim of the optimization. Distances s_1, s_2, s_3, s_4, s_5 and s_6, which define placement of web elements of cable truss, rations g_1 and g_2, which define distribution of material consumption among the top chord, bottom chord and web elements of the cable truss, and dependence of top and bottom chord cambers f_t / f_b are variable factors of optimization. The position of web elements is described by equations (1) and (2).

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

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

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

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

root1…root6 – roots of the system of equations (3) and (4).

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

$$\begin{cases} s_4 = root4 \cdot a_4^2 + root5 \cdot a_4 + root6 \\ s_5 = root4 \cdot a_5^2 + root5 \cdot a_5 + root6 \\ s_6 = root4 \cdot a_6^2 + root5 \cdot a_6 + root6, \end{cases} \tag{4}$$

where s_1, s_2, s_3, s_4, s_5, s_6, – distance from the support to the connection of the corresponding web element with top chord;

a_1, a_2, a_3, a_4, a_5, a_6 – distance from the support to the connection of the corresponding web element with bottom chord.

Optimization of the cable truss by the genetic algorithm was realized using 10 generations, where population size was equal to 50 and selected elite child number was equal to five. Each experiment consists of 39 ANSYS calculations for different loading placements. The rational relation of the top chord camber and bottom chord camber: $f_t / f_b = 0.5089$. The rational relation of material consumption of the bottom chord and material consumption of the whole truss: $g_b / g = 0.4512$. The rational relation of web elements material consumption and material consumption of the whole truss: $g_w / g = 0.0673$. Rational values of distances s_1, s_2, s_3, s_4, s_5 and s_6 are 4.8147, 16.3004, 16.3190, 0.9800, 12.6897 and 16.2324 m respectively.

The topology optimization of the cable truss web by 47 variable factors was realized by the developed optimization algorithm. Variable factors of the topology optimization are 20 mass parts of web elements (g_{w01}–g_{w20}), which are inclined to the edges of the cable truss, 19 mass parts of web elements (g_{w21}–g_{w39}), which are inclined to centre of the cable truss, so as the distances s_1, s_2, s_3, s_4, s_5 and s_6, dependence of the top and bottom chord cambers f_t / f_b and relation of material consumption of the bottom chord and the whole truss g_1. The rations g_{w01}–g_{w39} define distribution of material consumption among the web elements of the cable truss, but the distances s_1, s_2, s_3, s_4, s_5 and s_6 define placement of the web elements of the cable truss. The topology optimization with the genetic algorithm was realized using 40 generations, population size was equal to 100 and selected elite child number was equal to 10. 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.

The hybrid composite cable, which consists of CFRP (Carbon fibre reinforced polymer) middle layer and steel external layers, can be used instead of the main steel cable of suspension structure for decreasing of dead weight and increasing of the span (Fig. 3). The hybrid composite cable reduces disadvantages of CFRP, such as small elongation at break, which decreases safety of structure, probability of surface damages, poor characteristics perpendicular to grains and difficulties in connections of CFRP elements. The hybrid composite cable allows using CFRP wider.

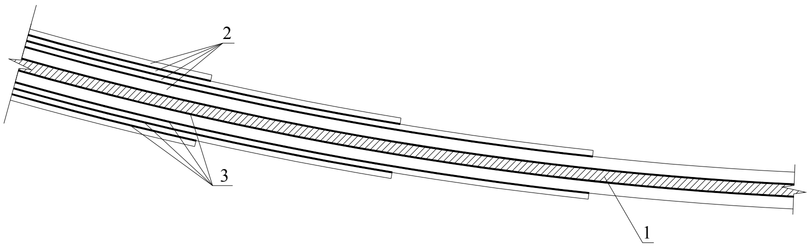


Fig. 3. Hybrid composite cable:
1 – CFRP layer; 2 – steel layers; 3 – glue

Distribution of internal loads is not uniform along the cable, so rational distribution of steel material by cable length (5) and minimal steel cross-section area (6) was determined by the genetic algorithm optimization. Determined steel volume allows the structure with the hybrid composite main cable not totally collapse in the case of the CFRP layer destruction. It was analytically and experimentally determined that in case of middle layer destruction at one cable place, CFRP layer will totally exclude from the cable work. It was stated that in case of taking into account of dynamic effects, steel layer cross-section area should be increased by 58% and CFRP layer cross-section should be decreased twice.

$$A_{steel,i} = 0.002798 + 0.0000824 \cdot i + 0.0000194 \cdot i^2, \tag{5}$$

$$A_{CFRP} = 1.0978 \cdot A_{steel,i=0}, \tag{6}$$

where i – section number of the cable counting from the middle part ($i = 0 \div 19$).

In **Third Chapter** the considered cable truss was compared with the single main cable in different loading cases (Table 1). The material consumption of the cable truss is the same as the material consumption of the single main cable. It was shown that displacements of the prestressed suspension structure in case of the worst situated load can be reduced by 27% by application of the cable truss instead of the single main cable. It was stated that displacements of the structure with the single cable under the action of symmetrical load are by 87% larger than displacements under the action of unsymmetrical load, but this difference of displacements of the structure with the cable truss is only 9%, which means that displacements of the structure with the cable truss are not depended on load application place.

Advantages of the cable truss from the point of view of displacements were discovered for different spans. It was shown that displacements of the prestressed suspension structure with the cable truss are smaller than displacements of the structure with the main single cable by 26–30% in the span interval between 50 and 350 m.

The main disadvantages of the cable truss in comparison with the single main cable are increased time and human resources of manufacturing, installation and maintenance processes.

Table 1
Displacements of Prestressed Suspension Structure with Single Main Cable and Cable Truss

Prestressed suspension structure	Load application points	Maximum deck displacements downwards, mm	Maximum deck displacements upwards, mm	Maximum deck total displacements, mm
Single cable	1-20	**629.3**	**291.7**	**921.0**
	1-39	492.0		492.0
Cable truss	1-17	514.5	**122.0**	636.6
	1-34	**623.3**	1.9	625.2
	1-22	572.8	103.1	**675.9**
	1-39	620.8	0.0	620.8

In the third chapter web elements behaviour of the cable truss with cross web was analysed. It was shown that in some loading cases several elements may exclude from the work, while significant internal forces appear at the same elements in other loading cases. However, some elements join in the work only in specific loading case. In this connection, it was stated that removing of elements of the web inclined to the centre of the cable truss simplifies the web. Removing the web elements from 1 to 11 significantly simplifies the web: in this case displacements will increase by 3.5%.

The prestressed suspension structure with the cable truss can be used for a main span of suspension bridge (Fig. 4), where displacements from unsymmetrical load are important. The bridge structure was checked under the action of horizontal and temperature loads and it was stated that the structure confirms the existing standards. Influence of pylon displacements on vertical displacements of the bridge was evaluated. It was stated that depending on the pylon stiffness, the advantage of the cable truss comparing with the single main cable from the point of view of displacements vary from 10 to 35%. The stabilization cable of the structure should be cambered in horizontal plane in the case of horizontal load action. Four stabilization cables allow to decrease displacements from the load applied unsymmetrically in cross direction (Fig. 5).

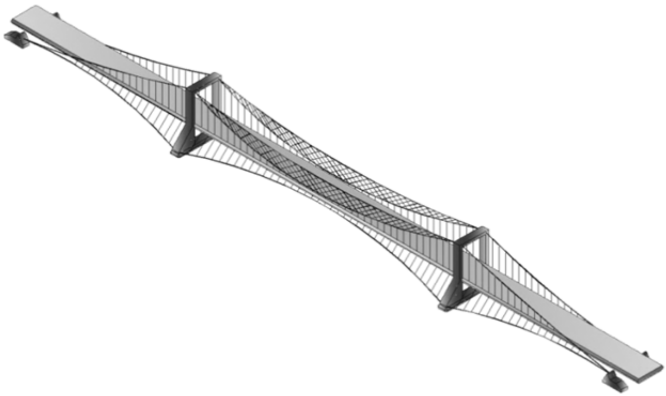


Fig. 5. Prestressed suspension bridge with cable truss

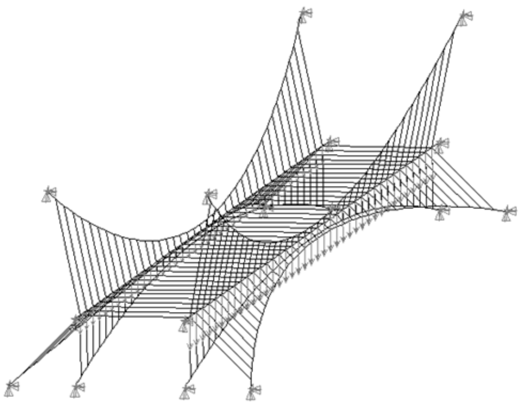


Fig. 5. Position of the main and stabilization cables for decreasing of displacements under the action of unsymmetrical load in cross direction

Composite pultrusion material application for large span load caring structure of deck of the suspension bridge is shown in the third chapter. This structure is designed as trussed beam, where the top chord, made of composite pultrusion profiles, is strengthened with composite pultrusion profile struts and steel cable. It was shown that replacement of vertical struts with inclined allows to minimize material consumption by 5%.

In **Fourth Chapter** the advantages of cable truss in comparison with the single main cable were experimentally verified. Two small scale models of the prestressed suspension structure with the single main cable and the cable truss (Fig. 6) were constructed. The span of the models is equal to 2.1 m. The structures were prestressed up to the level of 1000 kgf (0.4 of design tensile strength of stabilization cable). The models were loaded up to the load of 2755 kgf (half of the design tensile strength of the main cable) in symmetrical loading case and up to the load of 1495 kgf (Fig. 7) in unsymmetrical loading case. The displacements of the models depending on the applied load in the case of symmetrical and unsymmetrical load are shown in Fig. 8 and Fig. 9 respectively. The experimental results show that the replacement of the single main cable by the cable truss allows to minimize displacements upwards by 16% and downwards – by 12% in the case of unsymmetrical loading. Total displacements are reduced by 13% in this case. Experimental results confirm to the analytical ones, which confirm validity of the developed design methods and algorithms of the cable truss. The dependence between temperature change and displacements, as well as the prestressing level change was determined. It was experimentally determined that in the case of initial prestressing of the model up to the level that is larger by 20% than design level, and reducing the level up to design level after one day, the loss of the prestressing level was only 0.5% at the period of time of 88 days.

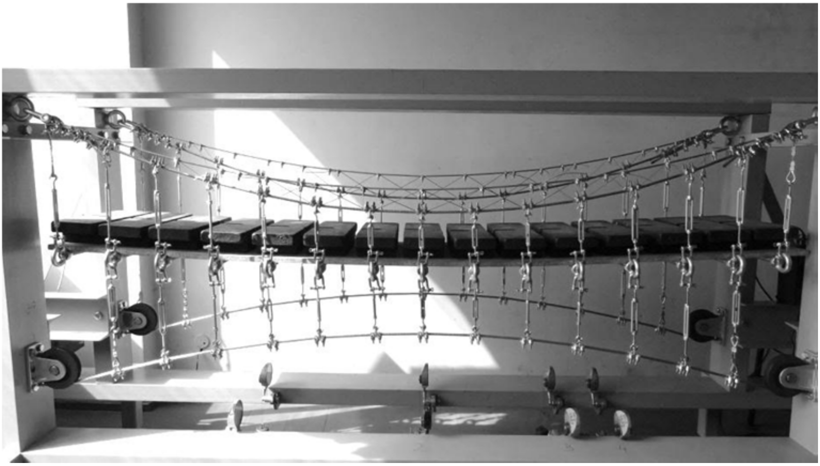


Fig. 6. Physical model of prestressed suspension structure with cable truss

Fig. 7. Unsymmetrically loaded model

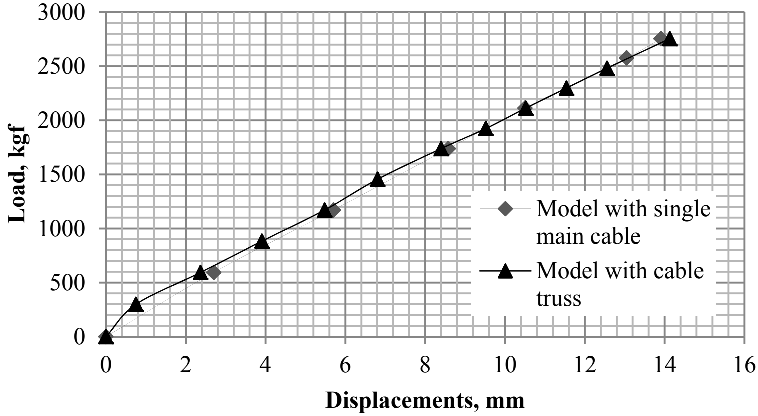


Fig. 8. Results of models of prestressed suspension structure testing in symmetrical loading case

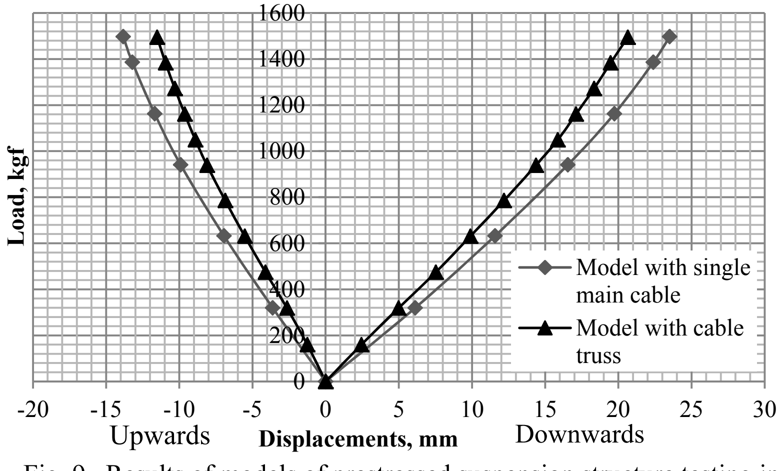


Fig. 9. Results of models of prestressed suspension structure testing in unsymmetrical loading case

In **Fifth Chapter** the approximate determination method of natural frequencies of prestressed suspension structure was developed. Equations of determination of natural frequencies of 1, 3, … mode shapes (7) and 2, 4, …

mode shapes (8) were composed:

$$\omega_{v,i} = \sqrt{\alpha_1 + \frac{\alpha_2 + \alpha_4}{2} + \frac{\alpha_3 + \alpha_5}{2}}, \tag{7}$$

$$\omega_{v,i} = \sqrt{\alpha_1 + \frac{\alpha_2 + \alpha_4}{2}}, \tag{8}$$

where α_1 – component depending on stiffness girder;

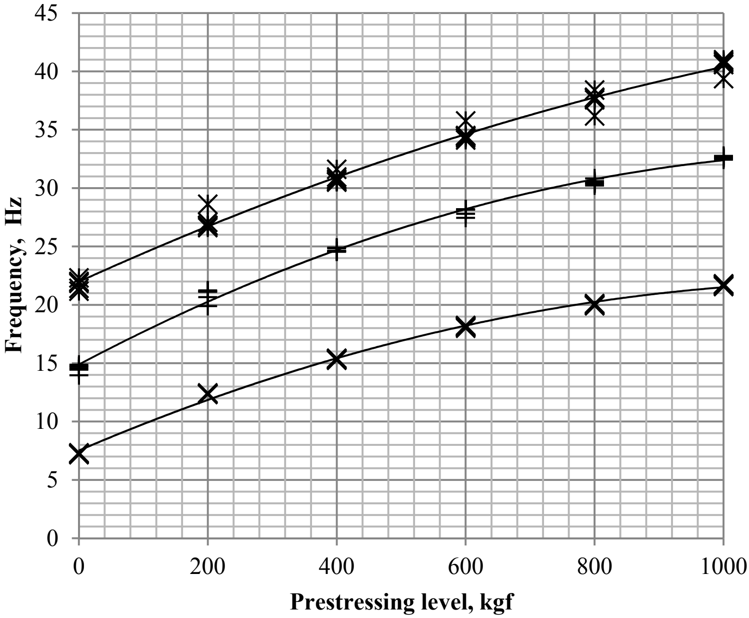
α_2 – component depending on support reaction of the main cable;

α_3 – component depending on characteristics of the main cable;

α_4 – component depending on support reaction of the stabilization cable;

α_5 – component depending on characteristics of the stabilization cable.

The developed methodology was validated by prestressed suspension structure model testing. Natural frequencies and mode shapes of the model were determined for different prestressing levels. The dependence between the prestressing level and the natural frequency, as well as approximation curves and polynomials are shown in Fig. 10. The difference between the experimental results and the results obtained by the developed method is 18% that is acceptable for dynamic preliminary analyses.



× 1st natural frequency - $y = -7E\text{-}06x^2 + 0.0251x + 21.978$
$R^2 = 0.9916$

+ 2nd natural frequency - $y = -1E\text{-}05x^2 + 0.0292x + 14.888$
$R^2 = 0.995$

⋇ 3rd natural frequency - $y = -1E\text{-}05x^2 + 0.0236x + 7.5182$
$R^2 = 0.9966$

Fig. 10. Dependence between the prestressing level and natural frequency

CONCLUSIONS

The rational solution of the large span prestressed two-chord cable structure, where top chord is developed as the cable truss, where all elements are tensioned only, was developed. The shape and topology of this cable truss were optimized to find the solution with material consumption equivalent to the main cable, but providing considerably larger structural stiffness. The computing and optimization algorithms of the suggested cable truss were developed. The advantages of the cable truss in case of its application for the large span bridge structure instead of the single main cable were evaluated.

- 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 two-chord cable structure with the proposed cable truss are smaller by 26–30% than displacements of the structure with the single main cable for span interval from 50 to 350 m. The computing algorithm of the cable truss by FEM program ANSYS automatically calculates the cable truss by given characteristics, as well as can be quickly transformed for solving of different tasks, connected with the cable truss analyses. The optimization algorithm of the cable truss developed in MatLAB programming environment quickly finds rational characteristics of the structure in the case of large variable factor number. Rational characteristics of the cable truss with spans 50, 200 and 350 m and bottom chord camber 1/10 of span from the point of view of structural stiffness are the following: the relation between the top and bottom chords chambers is 0.429, 0.510 and 0.536, the relation between bottom chord material consumption and material consumption of the whole truss is 0.587, 0.451 and 0.468, respectively.

- Replacement of the steel single main cable of prestressed two-chord cable structure by the hybrid composite cable with CFRP (Carbon Fibre Reinforced Polymer) middle layer and steel external layers with cross-section variable by the cable length considerably decrease dead weight of the cable. In the case of static load and 200 m span the dead weight is decreased three times. Rational distribution of steel by the cable length, which provides practically uniform stresses distribution in cable components by length, is one of the reasons of the decrease of dead weight. Furthermore the structure of the cable ensures functioning of the structure in case of the middle CFRP layer destruction. In this case the camber of the main cable instantly increases, but internal forces decrease due to steel yielding. Rational steel distribution by the cable length is evaluated in the form of second order polynomial and coefficients of the polynomial were determined by the genetic algorithm. Steel layer cross-section area should be increased by 58% and CFRP layer cross-section area should be decreased twice in case of taking into account of dynamic effects comparing with static load.
- The application of prestressed structure with the cable trusses for suspension bridges makes possible of light composite materials application for stiffness girder structure and ensures the safe service of the structure in case of horizontal loads. Rational position of the main and stabilization cables of this structure in cross direction ensures required stiffness in case of unsymmetrical load in cross direction, which is typical for bridges.

- Experimental testing of the physical models of the prestressed suspension cable structures confirms the accuracy of the numerical models with 10% precision. The advantages of the cable truss from the point of view of displacements comparing with the single main cable were experimentally approved by small scale physical models. Displacements of the model with the cable truss are smaller by 13% than displacements of the model with the single main cable. Displacements and prestressing change caused by temperature change are evaluated as important factors, which should be taken into account in design of prestressed suspension structures. In case of the model initial prestressing up to the level that is larger by 20% than the design level, and reducing the level down to the design level after one day, the loss of the prestressing level was only 0.5% during the experiment time (88 days) and practically constant temperature (20 ± 3 °C), which is evaluated as unimportant factor.
- The difference between results, which were calculated by the developed simplified determination method of natural frequencies of prestressed suspension structures and experimentally achieved by the model testing, does not exceed 20%. Therefore the method is applicable for preliminary dynamic analyses of structures. Natural frequencies of the prestressed suspension structure, which were determined by the developed method, correspond to the existing bridge design standards (natural period is not in dangerous interval from 0.3 to 1 s).

DOCTORAL THESIS NOMINATED TO OBTAIN DOCTORAL DEGREE OF ENGINEERING SCIENCES IN RIGA TECHNICAL UNIVERSITY

Defence of the doctoral thesis will take place in the assembly hall of RTU Civil Engineering Faculty, Azenes street 16, Riga at 2.15 p.m. April 5, 2013.

OFFICIAL REVIEWERS

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CONFIRMATION

I confirm that I worked out this doctoral thesis, which is submitted for consideration of obtaining of doctoral degree of engineering sciences in Riga Technical University. The doctoral thesis is not submitted in any other university for obtaining of doctoral degree.

Vadims Goremikins …………………………….(Signature)

Date: ………………………

The doctoral thesis is written in Latvian and consists of general description, five chapters, conclusions and references. The volume of the work is 155 p., 157 figures and 152 references.