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Rational Structure of Cable Truss

V. Goremikins, K. Rocens, and D. Serdjuks

***Abstract*—**One of the main problems of suspended cable structures is initial shape change under the action of non uniform load. The problem can be solved by increasing of weight of construction or by using of prestressing. But this methods cause increasing of materials consumption of suspended cable structure.

The cable truss usage is another way how the problem of shape change under the action of non uniform load can be fixed.

The cable trusses with the vertical and inclined suspensions, cross web and single cable were analyzed as the main load-bearing structures of suspension bridge.

It was shown, that usage of cable truss allows to reduce the vertical displacements up to 32% in comparison with the single cable in case of non uniformly distributed load. In case of uniformly distributed load single cable is preferable.

***Keywords*—**Cable trusses, Non uniform load, Suspension bridge, Vertical displacements.

I. Introduction

ONE of the main problems of suspended cable structures is initial shape change under the action of non uniform load. The problem can be solved by increasing of structural dead weight or by prestressing. But this methods cause increasing of materials consumption and make difficult usage of modern materials with increased specific strength [9].

The cable truss usage is another way how the problem of shape change under the action of non uniform load can be fixed.

The existing types of cable trusses are differed by the shapes of top and bottom chords and by the structure of the web.

The aim of this study is choice of the best, form the point of view of minimization of vertical displacements, type of the cable truss as the main load-bearing structure of suspension prestressed bridge.

Rational structure of the cable truss' web also should be developed.

V. Goremikins is with the Institute of Structural Engineering and Reconstruction, Riga Technical University, Azenes Str.16, Riga, LV 1048 Latvia (phone: 371 29231772; e-mail: goremikin@inbox.lv).

K. Rocens is with the Institute of Structural Engineering and Reconstruction, Riga Technical University, Azenes Str.16, Riga, LV 1048 Latvia (e-mail: rocensk@latnet.lv).

D. Serdjuks is with the Institute of Structural Engineering and Reconstruction, Riga Technical University, Azenes Str.16, Riga, LV 1048 Latvia (e-mail: dmitrijs@bf.rtu.lv).

II. Choice of the Shape of Cable Truss

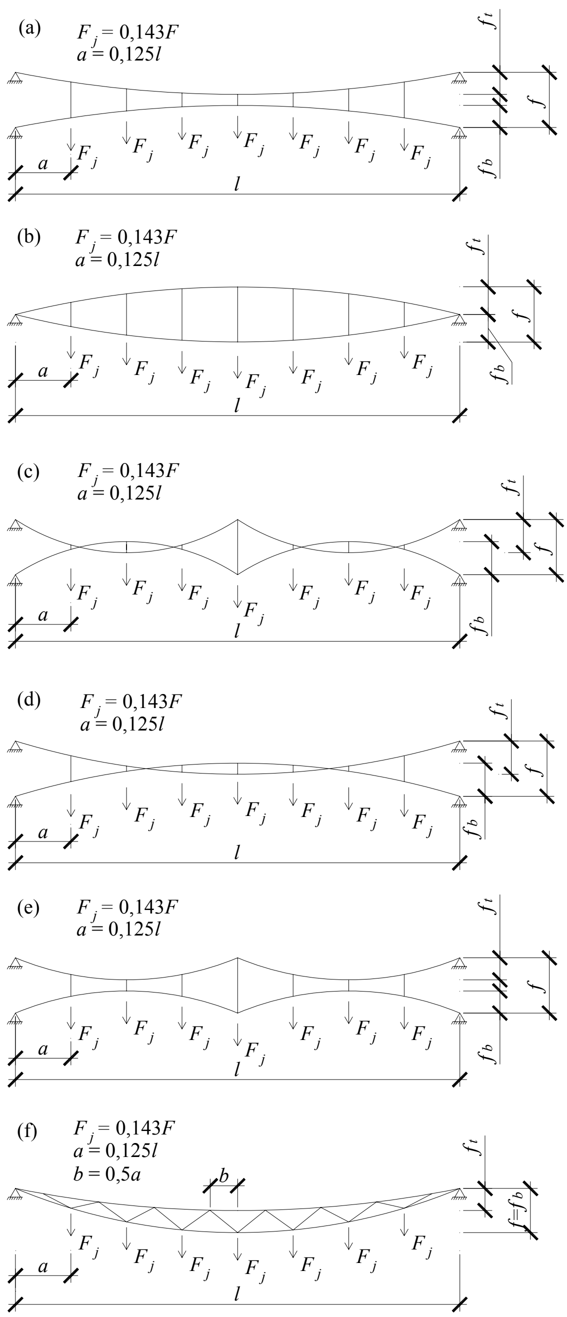


Fig.1 Types of cable trusses. (a) – Cable truss with suspensions; (b) – Cable truss with studs, (c),(d),(e) – Cable truss with suspensions and studs; (f) – Cable truss with tensioned elements. *a* – distance between load, *l* – span, *F* – load; *f* – truss height, f_b – bottom chord camber, f_t – top chord camber

The first task was to consider, which type of cable trusses can better keep the initial shape. To discover that, the shape of initial camber was assumed as cylindrical shape, not parabola, so we can apply uniformly distributed load.

Different types of cable trusses, which were analyzed, are shown in Fig.1 [4], [17], [18].

All considered trusses can't exist without prestressing, because cable elements can't be compressed, expect of truss, where all elements are tensioned without prestressing. So, this type of cable truss is characterized with reduced material consumption in comparison with other cable trusses and it was considered, as an object of investigation.

III. Evaluation of Rational Parameters of Considered Cable Truss

The next step was to find the rational values of main parameters, such as truss bottom chord camber, truss top chord camber, the number of bottom chord joints, so as the rational type of the web of considered cable truss (Fig.2.) [8]. It was assumed, that all constructions are with the same material consumption g, equal load is applied to all construction. The criteria of research are minimal vertical displacements w in the different points. The steel cables with the modulus of elasticity in 167000MPa and class 1960 MPa were considered for cable trusses.

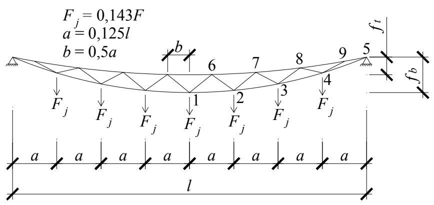


Fig.2 Cable truss with tensioned elements. a – distance between load, l – span, F – load; f – truss height, f_b – bottom chord camber, f_t – top chord camber

All elements of cable truss are tensioned and its cross-sectional area was determined by the (1) [21]:

$$A \geq \frac{1.6 \cdot N}{k \cdot R_{un}} \tag{1}$$

where: A – cross-sectional area of the bottom chord; N – force acting in the bottom chord; R_{un} – tensile strength of the wire; k – coefficient, taking into account the drop in the breaking force of the cable, caused by the inhomogeneity of stress distribution; 1.6 – reliability index of the material.

The coefficient k , taking into account the drop in the breaking force of the cable, caused by the inhomogeneity of stress distribution, was equal to 0.75 [16].

The calculations were done by the FEM programs, such as ANSYS and LIRA. The types of finite elements were LINK10 and КЭ310, respectively[15]. The rational values were found by the computer exhaustive search method [3], [7].

A. The influence of top chord camber on vertical displacements of cable truss

The calculations were made analytically using finite element method [11], [13], [14]. Relative camber of bottom chord was fixed on the level 1/10. The relation of dead weight of bottom chord and total dead weight was equal to 0.69, the relation of dead weight of top chord and total dead weight was equal to 0.25 and the relation of dead weight of the web and total dead weight was equal to 0.06. The number of bottom chord joints is equal to 7. The results of calculations are shown on the Table I.

TABLE I
The Dependence of Top Chord Camber on Displacements of Cable Truss

Relative Camber of Top Chord f_t/l	Vertical Displacements
1/11,4=0,0875	$w_{b,1} = 0,78w_s$
1/13,3=0,075	$w_{b,1} = 0,61w_s$
1/20=0,05	$w_{b,1} = 0,61w_s$
1/40=0,025	$w_{b,1} = 0,94w_s$

w_s – vertical displacements of single cable with the relative camber 1/10l

The dependence of top chord camber on displacements of cable truss under the action of load was obtained (Fig.3). The displacements were compared with displacements of single cable with rational camber 1/10 l. The rational value of top chord camber is within the limits from 1/20 to 1/15 of span or from 1/2 to 2/3 of bottom chord camber.

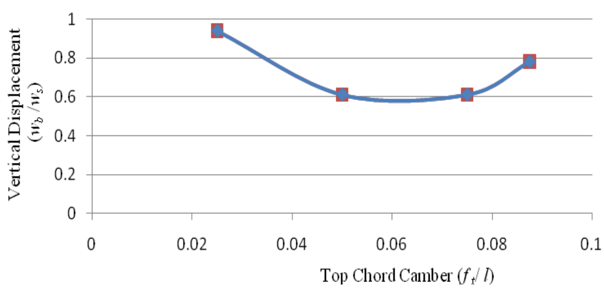


Fig.3 The dependence of top chord camber on displacements. w_b – vertical displacements of cable truss, w_s – vertical displacements of single cable, f_t – top chord camber, l – span

B. The influence of bottom chord camber on vertical displacements of cable truss

The calculations were made analytically using finite element method. The relation of top chord camber and bottom chord camber was fixed on the level 2. The relation of dead weight of bottom chord and total dead weight was equal to 0.69, the relation of dead weight of top chord and total dead weight was equal to 0.25 and the relation of dead weight of the web and total dead weight was equal to 0.06. The number of bottom chord joints is equal to 7. The results of calculations are shown on the Table II.

TABLE II
THE DEPENDENCE OF BOTTOM CHORD CAMBER ON DISPLACEMENTS OF CABLE TRUSS

Relative Camber of Bottom Chord f_b/l	Vertical Displacements
1/8=0,125	$w_{b,1} = 0{,}41w_s$
1/10=0,1	$w_{b,1} = 0{,}61w_s$
1/13,3=0,075	$w_{b,1} = 0{,}995w_s$
1/20=0,05	$w_{b,1} = 2{,}05w_s$

w_s – vertical displacements of single cable with the relative camber 1/10l

The dependence of bottom chord camber on displacements of cable truss under the action of load was obtained (Fig.4). The displacements were compared with displacements of single cable with rational relative camber 1/10 l. It was shown, that the displacements are smaller reducing bottom chord camber, but further camber increasing is limited by construction usage.

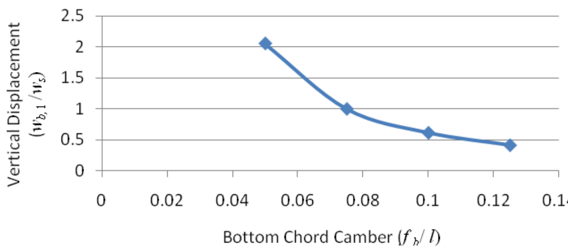


Fig. 4 The dependence of bottom chord camber on displacements. w_b – vertical displacements of cable truss, w_s – vertical displacements of single cable, f_t – top chord camber, l – span

C. The influence of the number of bottom chord joints on vertical displacements of cable truss

The calculations were made analytically using finite element method. Relative camber of bottom chord was fixed on the level 1/10, the relation of top chord camber and bottom chord camber was fixed on the level 2. The relation of dead weight of bottom chord and total dead weight was equal to 0.69, the relation of dead weight of top chord and total dead weight was equal to 0.25 and the relation of dead weight of the web and total dead weight was equal to 0.06. The results of calculations are shown on the Table III.

The dependence of the number of bottom chord joints on displacements of cable truss under the action of load was obtained (Fig.5). The displacements were compared with displacements of single cable. The rational value of the number of bottom chord joints is within the limits from 6 to 7 joints.

TABLE III
THE DEPENDENCE OF THE NUMBER OF BOTTOM CHORD JOINTS ON DISPLACEMENTS OF CABLE TRUSS

Number of Bottom Chord Joints: n	Vertical Displacements
3	$w_{b,1} = 0{,}73w_s$
5	$w_{b,1} = 0{,}63w_s$
7	$w_{b,1} = 0{,}61w_s$
9	$w_{b,1} = 0{,}66w_s$

w_s – vertical displacements of single cable with the relative camber 1/10l

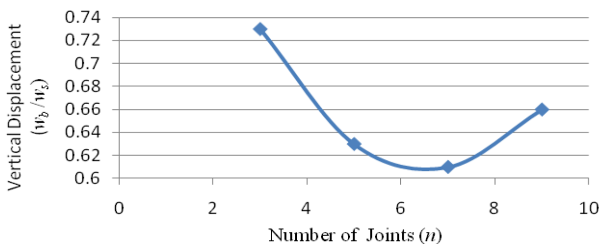


Fig. 5 The dependence of the number of bottom chord joints on displacements. w_b – vertical displacements of cable truss, w_s – vertical displacements of single cable, f_t – top chord camber, l – span

D. Rational type of the web

Different types of web were analyzed (Fig.6). The numerical results of vertical displacements depending on the web type are shown on the Table IV. The best results can be achieved using cable trusses (d),(e), (f), but types (g) and (h) allow to simplify the web.

TABLE IV
THE DEPENDENCE OF WEB TYPE ON THE DISPLACEMENTS OF CABLE TRUSS

Web Type	Vertical Displacements
(a)	$w_{b,1} = 0{,}61w_s$
(b)	$w_{b,1} = 1{,}07w_s$
(c)	$w_{b,1} = 0{,}59w_s$
(d)	$w_{b,1} = 0{,}51w_s$
(e)	$w_{b,1} = 0{,}46w_s$, $w_{b,3} = 0{,}50w_s$
(f)	$w_{b,1} = 0{,}26w_s$, $w_{b,3} = 0{,}55w_s$
(g)	$w_{b,1} = 0{,}44w_s$, $w_{b,3} = 0{,}56w_s$
(h)	$w_{b,1} = 0{,}51w_s$

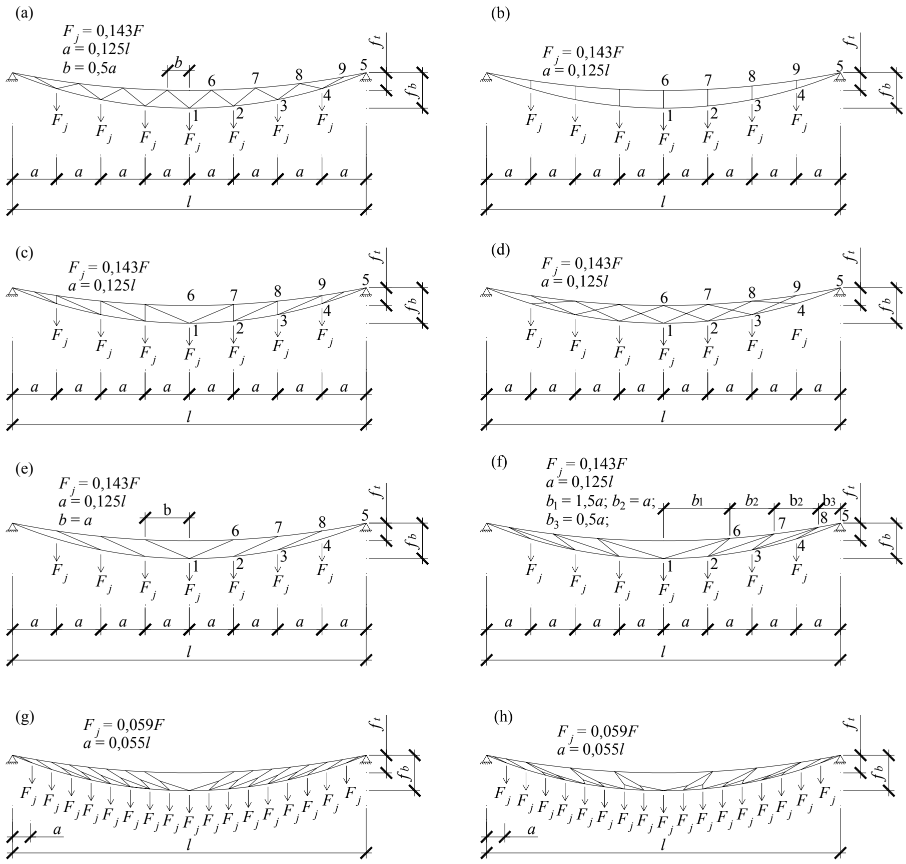


Fig. 6 Different types of the web of cable truss

IV. Behavior of Considered Cable Truss in Suspension Bridge

A. General structure of the bridge

The next step of the work is modeling of suspension prestressed bridge structure.

The bridge span is equal to 200 m. Bridge pylon height is equal to 21 m (Fig.7.). Bridge has two lines in each direction and two pedestrian lines. Bridge load caring construction is made from cables or cable trusses. Deck is connected to cables by suspensions [10] and is made from pultrusion composite trussed beam with step 5 m, pultrusion composite beams with height 300 cm and step 1 m and composite pultrusion plank with height 40 mm (Fig.8) [2], [5], [6]. The bridge is characterized with reduced dead weight of the deck in comparison with existing bridges [12], [17], [19], [20]. It was assumed that deck do not have stiffness in longitudinal direction. The bridge is loaded by the load model LM:1 (Fig.9.) and load model LM:3 [1].

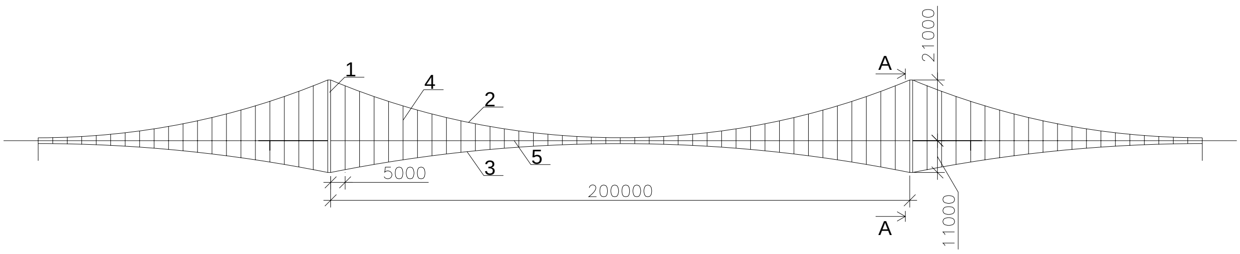


Fig.7 The bridge longitudinal view. 1 – Pylon of the bridge, 2 – Main load caring cable, 3 – Stabilization cable, 4 – Suspensions, 5 – Deck

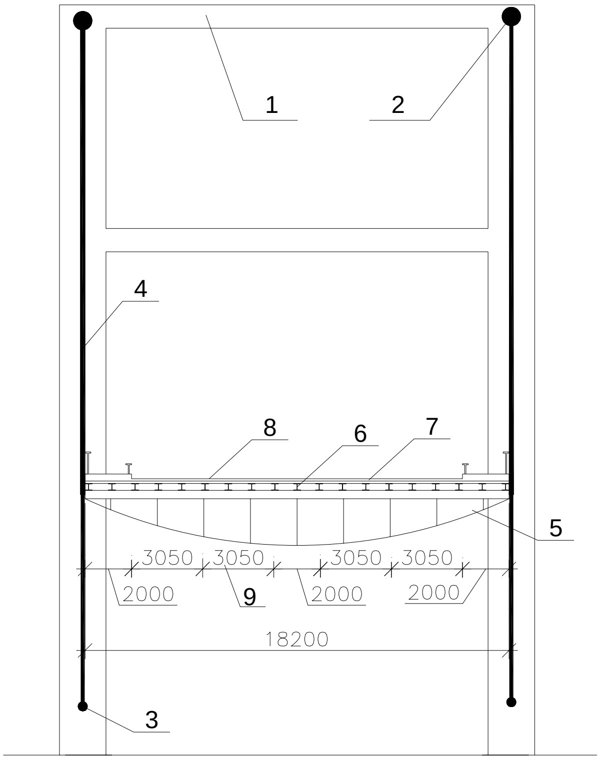


Fig. 8 The bridge cross-section A-A. 1 – Pylon of the bridge, 2 – Main load caring cable, 3 – Stabilization cable, 4 – Suspensions, 5 – Composite trussed beam, 6 – Composite I type beams, 7 – Composite plank, 8 – Cover of the bridge, 9 – Lines of the bridge

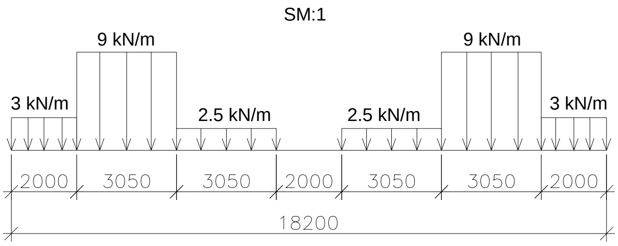


Fig.9. Applied load to the bridge.

The aim of this research was to find the best construction of main load caring element (cable or cable truss) under the action of non uniformly distributed load. So only half of the bridge span was loaded by the load model LM:1. Load is symmetrical in cross direction.

B. Evaluation of Rational Parameters of Considered Cable Truss

Cable truss with inclined suspensions was chosen as the main load bearing element for suspension bridge. The rational parameters of the top chord camber, distribution of material consumption for truss elements and the placement of the web elements where found. The rational relation of top chord camber and bottom chord camber is equal to f_t/f_b=0.71. The rational relation of bottom chord material consumption and material consumption of whole truss is equal to gb/g=0.6. The rational placement of web elements is evaluated in the form of the second order polynomial equation (2):

$$x_1 = x - 6.783 \cdot 10 - 4 \cdot x^2 + 0.1817 \cdot x + 2.108 \qquad (2)$$

where x – distance from the pylon to the bottom chord joint, x1 – distance from the pylon to the top chord pylon (Fig.10).

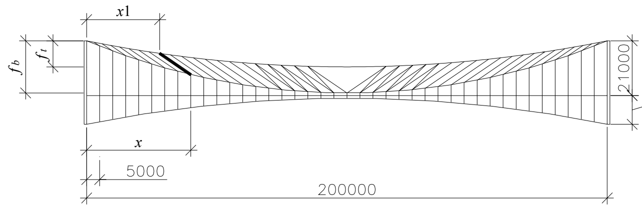


Fig.10 Parameters of cable truss

C. Comparison of Different Types of Trusses when Prestression was Organized in Stabilization Cable

Different types of cable trusses where analyzed (Fig.11). In first case the initial strain was in stabilization cable. The aim was to decrease displacements to the upper direction, because it will summaries with construction raise. The results are shown on the table 5. At the table we can see, that displacements are large, when non uniformly distributed load is applied. It was shown, that usage of cable trusses allow to decrease displacements by 17 % or by 32 % according to selected type of cable truss.

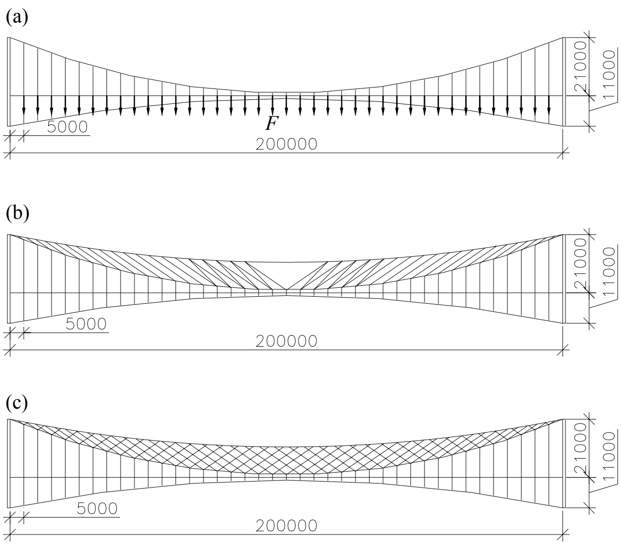


Fig.11 Types of constructions. (a) – Single cable, (b) – Cable truss with inclined elements of the web, (c) – Cable truss with the cross web

TABLE V
VERTICAL DISPLACEMENTS OF CABLE TRUSSES

Construction type	Uniformly distributed load	Non uniformly distributed load
(a) – Single cable	w^-=0.4965 m	w^+=0.3039 m w^-=-0.6684 m
(b) – Cable truss with inclined elements of the web	w^-=0.6912m	w^+=0.2522 m w^-=-0.6798 m
(c) – Cable truss with the cross web	w^-=0.5560m	w^+=0.2076 m w^-=-0.6141 m

D. Comparison of Different Types of Trusses when Prestression was Organized in Suspensions

Variant (b) on Fig.10 was checked when the initial strain was in suspensions. The initial strain is different in each suspension depending on suspension displacement and is evaluated in the form of the second order polynomial equation (3):

$$\varepsilon = a \cdot x^2 + b \cdot x + c \tag{3}$$

where x – distance from the pylon to the bottom chord joint,
ε – initial strain,
a, b, c – coalitions of the equation.

The results are shown on the table 6. It is shown, that displacements can be reduced by 16% in the case of usage cable truss instead of single cable.

TABLE VI
Vertical Displacements of Cable Trusses

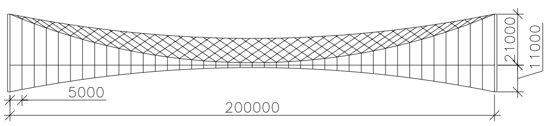
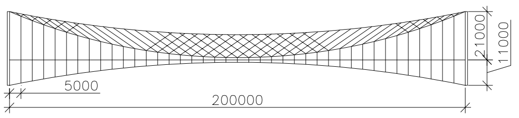
Construction type	Non uniformly distributed load
(a) – Single cable	w^+=0.5530 w^-=-0.8866
(b) – Cable truss with the cross web	w^+=0.4619 w^-=-0.8183

E. Simplification of the Web of Cable Truss

The next step of the task was to simplify the web of cable truss by removing some elements of the web.

The results are shown on the table 7. It was shown that removing of some elements allow decrease displacements and to simplify the web.

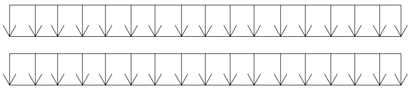
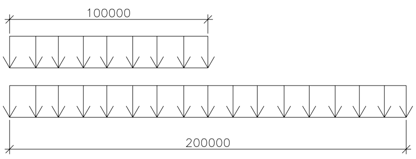
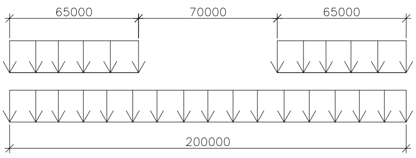
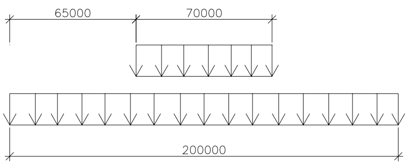
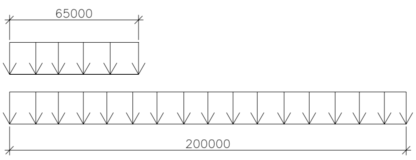
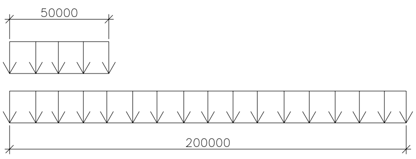
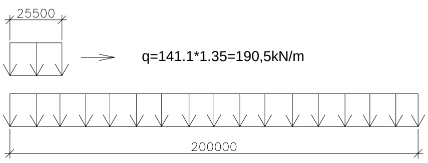
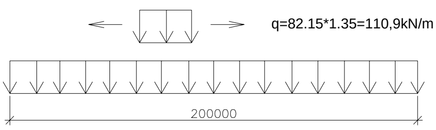
TABLE VII
SIMPLIFICATION OF WEB ELEMENTS

Scheme of cable truss	Removing element number	Non uniformly distributed load		Uniformly distributed load
		Displacements upwards	Displacements downwards	Displacements downwards
	0-0	w^+=0.2076 m	w^-=-0.6141 m	w^-=0.5560m
	2-11	w^+=0.2053 m	w^-=-0.6214m	w=-0.5500 m
	3-11	w^+=0.2031 m	w^-=-0.6194 m	w=-0.5497 m
	4-11	w^+=0.2010 m	w^-=-0.6174 m	w=-0.5496 m
	5-11	w^+=0.1995 m	w^-=-0.6157 m	w=-0.5498 m
	6-11	w^+=0.2008 m	w^-=-0.6144 m	w=-0.5502 m
	7-11	w^+=0.2039 m	w^-=-0.6138 m	w=-0.5506 m
	8-11	w^+=0.2073 m	w^-=-0.6141 m	w=-0.5510 m
	5-10	w^+=0.1999 m	w^-=-0.6139 m	w=-0.5520 m
	5-12	w^+=0.2003 m	w^-=-0.6182 m	w=-0.5476 m
	3-12	w^+=0.2033 m	w^-=-0.6214 m	w=-0.5469 m
	3-13	w^+=0.2051 m	w^-=-0.6260 m	w=-0.5430 m

F. Behavior of Cable Truss Types under the Action of Different Types of Load

The last task was to check the construction under the action of different types of load. The bridge were loaded by the half, one third, two thirds, quarter, moving load and the worth variant. Variants with full web and simplified web were checked and compared with single cable. The results are shown on the table 8. It was shown, that the cable truss works better in all cases, expect the case, when uniformly load is applied.

TABLE VIII
VERTICAL DISPLACEMENTS OF MAIN LOAD BEARING STRUCTURE OF CABLE BRIDGE UNDER THE DIFFERENT TYPES OF LOADING

Loading scheme	Full web cable truss		Simplified wed cable truss		Single cable	
	w^-,m	w^+, m	w^-,m	w^+, m	w^-,m	w^+, m
 q=82,15*1.35=110,9kN/m g=57,1*1.35=77,1kN/m	-0.5552		-0.5502		-0.4956	
 q=82,15*1.35=110,9kN/m g=57,1*1.0=57,1kN/m	-0.6128	0.2083	-0.6144	0.2008	-0.6670	0.3044
 q=82,15*1.35=110,9kN/m g=57,1*1.0=57,1kN/m	-0.3161		-0.3531		-0.3378	0.0464
 q=82,15*1.35=110,9kN/m g=57,1*1.0=57,1kN/m	-0.5168	0.0365	-0.5242	0.0460	-0.5645	0.0785
 q=82,15*1.35=110,9kN/m g=57,1*1.0=57,1kN/m	-0.4842	0.1721	-0.5123	0.1652	-0.5553	0.2324
 q=82,15*1.35=110,9kN/m g=57,1*1.0=57,1kN/m	-0.3852	0.1295	-0.4245	0.1231	-0.4451	0.1694
 q=141.1*1.35=190,5kN/m g=57,1*1.0=57,1kN/m	-0.4599	0.1425	-0.4852	0.1355	-0.5368	0.1960
 q=82.15*1.35=110,9kN/m g=57,1*1.0=57,1kN/m	-0.6279	0.2092	-0.6262	0.2009	-0.6693	0.3044

V. Conclusions

Different types of cable trusses where compared under the action of the uniformly and non uniformly distributed load and uniformly distributed load. It was shown, that the best from the point of view of minimization of maximum vertical displacements, is cable truss with the cross web. It was stated, that usage of cable truss with the cross web instead of single cable allows to reduce maximum vertical displacements up to 32% in the case of non uniformly distributed load in the case, if prestressing is applied by the stabilization cable. Maximum vertical displacements can be reduced up to 16% in the case, if prestressing is applied by the suspensions.

Rational structure of the cable truss' web was developed. It was shown, that the cross web can be replaced by the inclined suspensions in part of the span.

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Vadims Goremikins was born in Riga, Latvia on 6th February 1986. He is a doctoral study student. He received his professional master degree (M.Sc.Ing) in Civil Engineering from the Riga Technical University, Latvia in 2009. He graduated as a civil engineer and holds a professional bachelor degree in civil engineering (B.Sc.Ing) from the Riga Technical University on 2008.

He currently works as Assistant of scientific work at the Riga Technical University, and as Assistant in the Building Structures department at the Riga Technical University. He was Internal Control Specialist, Guarantee repair Specialist, Civil engineer assistant at "MTK Construction" Ltd.

M.Sc.Ing., Goremikins is a member of the Association of Latvian Young Scientists.

Karlis Rocens was born in Riga, Latvia on 3rd March 1939. He is a professor of structural engineering and director of the Institute of Structural Engineering and reconstruction at the Riga Technical University, Latvia. He is a Full member of Latvian academy of sciences and participant from Latvia in COST C25 "Sustainability of Constructions: Integrated Approach to Life Time Structural Engineering". Author of 5 monographs and more than 250 scientific articles. His research interests include the modern structures, technological mechanics of wood and composite materials and structural material science.

Dmitrijs Serdjuks was born in Riga, Latvia on 23rd March 1971. He is Civil Engineer, Dr.sc.ing. (2001), asoc. prof.. RTU Faculty of Building and Civil Engineering (1995). M.sc.ing. (1997). RTU B. F. Division of Building Constructions, assistant (1998-2001), lecturer (2001-2004), docent (2004-2008), associated professor (since 2008).

Subjects: metal structures, timber and plastic structures, structural optimization. Investigations in field of steel and composite structures. Publications: ~ 50 scientific and methodological works.