

# Decreasing of Displacements of Prestressed Cable Truss

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

**Abstract**—Suspended cable structures are most preferable for large spans covering due to rational use of structural materials, but the problem of suspended cable structures is initial shape change under the action of non-symmetrical load. The problem can be solved by increasing of relation of dead weight and imposed load, but this methods cause increasing of materials consumption. Prestressed cable truss usage is another way how the problem of shape change under the action of non-symmetrical load can be fixed. The better results can be achieved if we replace top chord with cable truss with cross web.

Rational structure of the cable truss for prestressed cable truss top chord was developed using optimization realized in FEM program ANSYS 12 environment. Single cable and cable truss model work was discovered. Analytical and model testing results indicate, that usage of cable truss with the cross web as a top chord of prestressed cable truss instead of single cable allows to reduce total displacements by 13-16% in the case of non-symmetrical load.

In case of uniformly distributed load single cable is preferable.

**Keywords**—Cable trusses, Non-symmetrical load, Cable truss models, Vertical displacements

## I. INTRODUCTION

THE main advantage of suspended cable structures (Fig.1) is possibility to use in full scale high strength materials, for example steel ropes with tensile strength of wires 1960 MPa, because tensile elements can't lose its stability and stresses are uniformly distributed by cross-section [5], [7] – [10], [14], [25]. But the problem of suspended cable structures is increased deformability or initial shape change, especially in case of non-symmetrical load (Fig.2). The problem is especially important for suspension bridges, where this case of loading is possible [11], [18], [21], [28] and [29]. The problem can be solved by increasing of relation of dead weight and imposed load, which is realized by adding of cantledge (Fig.3) [15], [22]. But this methods cause increasing of material consumption. The prestressed cable truss usage is another way how the problem of shape change under the action of unsymmetrical load can be fixed (Fig.4) [13], [16], [26], [27], [30]. The better results can be achieved if we replace single cable top chord with cable truss with cross web (Fig.5) [6].

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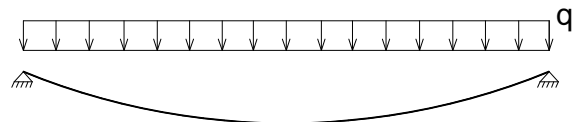


Fig. 1 Suspended cable structure

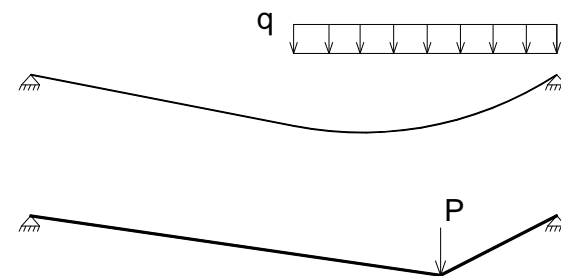


Fig. 2 Initial shape change under the action of non-symmetrical load



Fig. 3 Suspended cable structure stabilization adding cantledge

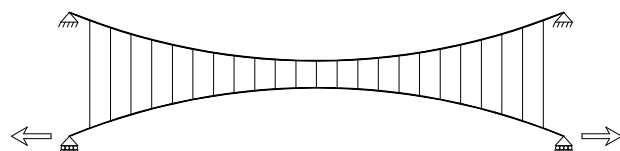


Fig. 4 Suspended cable structure stabilization using prestress

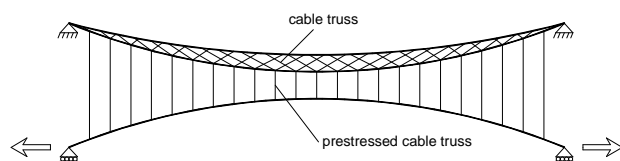


Fig. 5 Suspended cable structure stabilization using prestressed cable truss instead of top chord cable

The aim of this study is to develop rational structure of cable truss for top chord of prestressed cable truss and to

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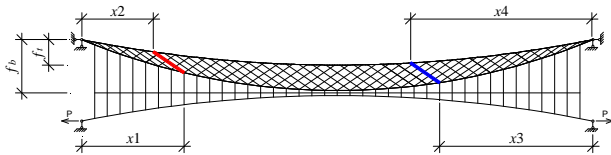


Fig. 8 Position of web elements

The position of web elements, inclined to the edges of cable truss can be expressed by (3), the position of web elements, inclined to the edges of cable truss can be expressed by (4).

$$x_2 = x_1 - (\text{root1} \cdot x_1^2 + \text{root2} \cdot x_1 + \text{root3}), \quad (3)$$

$$x_4 = x_3 + (\text{root4} \cdot x_3^2 + \text{root5} \cdot x_3 + \text{root6}), \quad (4)$$

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

$x_1$  and  $x_3$  – distance from the pylon to the connection of web element and bottom cord;

root1...root6 – roots of the system of equation.

The roots of the polynomial equation for web elements inclined to the edges of cable truss were found solving system (5).

$$\begin{cases} s_1 = \text{root1} \cdot a_1^2 + \text{root2} \cdot a_1 + \text{root3} \\ s_2 = \text{root1} \cdot a_2^2 + \text{root2} \cdot a_2 + \text{root3} \\ s_3 = \text{root1} \cdot a_3^2 + \text{root2} \cdot a_3 + \text{root3} \end{cases}, \quad (5)$$

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  $x_1 = a_3$ .

$a_1$  – 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.

Distances  $s_1$ ,  $s_2$  and  $s_3$  were found by optimization.

The system of equations is solved by Ansys, using matrix method (6) - (10).

$$\Delta = a_1^2 \cdot a_2 - a_1^2 \cdot a_3 - a_1 \cdot a_2^2 + a_1 \cdot a_3^2 + a_2^2 \cdot a_3 - a_2 \cdot a_3^2. \quad (6)$$

$$\Delta_1 = s_1 \cdot a_2 - s_1 \cdot a_3 - a_1 \cdot s_2 + a_1 \cdot s_3 + s_2 \cdot a_3 - a_2 \cdot s_3. \quad (7)$$

$$\Delta_2 = a_1^2 \cdot s_2 - a_1^2 \cdot s_3 - s_1 \cdot a_2^2 + s_1 \cdot a_3^2 + a_2^2 \cdot s_3 - s_2 \cdot a_3^2. \quad (8)$$

$$\begin{aligned} \Delta_3 = & a_1^2 \cdot a_2 \cdot s_3 - a_1^2 \cdot s_2 \cdot a_3 - a_1 \cdot a_2^2 \cdot s_3 + \\ & + a_1 \cdot s_2 \cdot a_3^2 + s_1 \cdot a_2^2 \cdot a_3 - s_1 \cdot a_2 \cdot a_3^2. \end{aligned} \quad (9)$$

$$\begin{aligned} \text{root1} &= \Delta_1 / \Delta; \\ \text{root2} &= \Delta_2 / \Delta; \\ \text{root3} &= \Delta_3 / \Delta. \end{aligned} \quad (10)$$

where  $\Delta$  – determinant.

The roots of the polynomial equation for web elements inclined to the center of cable truss can be founded by the same method.

Top chord point coordinates for one half of span for web elements inclined to the edges of cable truss is expressed by (11).

$$\begin{cases} x_2 = x_1 - (\text{root1} \cdot x_1^2 + \text{root2} \cdot x_1 + \text{root3}) \\ y = -\frac{4 \cdot f_t \cdot x_2 \cdot (l - x_2)}{l^2} + h_p \end{cases}, \quad (11)$$

were  $x_1 = a \cdot i$ ;

$i$  changes from 1 to  $(l/a)/2$ ;

$f_t$  – top chord camber;

Top chord point coordinates for one half of span for web elements inclined to the center of cable truss is expressed by (12).

$$\begin{cases} x_4 = x_3 + (\text{root4} \cdot x_3^2 + \text{root5} \cdot x_3 + \text{root6}) \\ y = -\frac{4 \cdot f_t \cdot x_4 \cdot (l - x_4)}{l^2} + h_p \end{cases}, \quad (12)$$

were  $x_3 = a \cdot i$ ;

$i$  changes from 1 to  $(l/a)/2$ .

Top chord point coordinates for other half of span can be founded by the same method.

As the points are not sorted, it is not possible to connect them. Grouping of points of top chord, so the point with first number has the smallest horizontal coordinate, but the point with last point has the largest horizontal coordinate, should be done. To order array on point numbers and coordinates by coordinate, bubble sort is used (Fig.9). Bubble sort works by repeatedly stepping through the list to be sorted, comparing each pair of adjacent items and swapping them if they are in the wrong order. The pass through the list is repeated until no swaps are needed, which indicates that the list is sorted [31].

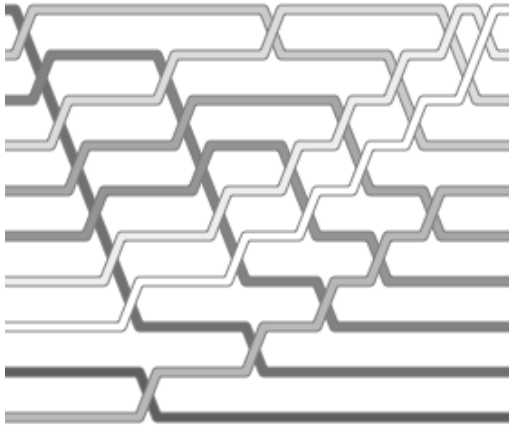


Fig. 9 A visual representation of how bubble sort works [31]

When the sorting is done, points can be connected with lines.

#### D. Definition of cross-section parameters

For LINK10 elements we need to define cross-section area and initial strain.

In this work the whole mass of structure is given, the distribution of material consumption for each element of the truss was found by optimization. The material consumption for all elements is expressed, as a part of whole truss material consumption.

The prestressing of structure is organized in stabilization cable by applying initial strain.

When the preprocessor operations are done, calculations can be launched [17], [19], [23].

#### IV. RATIONAL PARAMETERS OF CABLE TRUSS

Rational parameters of cable truss were founded.

Rational relation of top chord camber and bottom chord camber:  $f_t/f_b=0.71$ .

Rational relation of bottom chord material consumption and material consumption of whole truss:  $g_b/g=0.6$

Rational relation of web elements material consumption and material consumption of whole truss:  $g_w/g=0.05$

Rational number of web elements inclined to the center of cable truss is achieved removing element from 5 to 11 from both sides.

Rational position of web elements inclined to the edges of cable truss is expressed by rational value of distance  $x_2$  of each web element on distance  $x_1$  from the pylon in the form of polynomial equation (13).

$$x_2 = x_1 - (6.783 \cdot 10^{-4} \cdot x_1^2 + 0.1817 \cdot x_1 + 2.108), (13)$$

where  $x_1$  – distance from the pylon to the bottom chord's node,

$x_2$  – distance from the pylon to the top chord's node

Position of web elements inclined to the center of cable truss was founded by mirroring elements inclined to the edges of cable truss.

#### V. COMPARISON OF SINGLE CABLE AND CABLE TRUSS FOR TOP CHORD OF PRESTRESSED CABLE TRUSS

Cable truss top chord of prestressed truss was compared with single cable top chord of cable truss. Shape of displacements in non-symmetrical loading case is shown on the Fig.10. Loaded part of structure displace to the downwards direction, but unloaded part – to the upper direction. Total displacements are calculated as sum of upwards and downwards displacements. The results of displacements in symmetrical and non-symmetrical loading case are shown in Table I. The difference between single cable and cable truss displacements upwards is 34%, the difference between single cable and cable truss displacements downwards is 8% and difference between single cable and cable truss total displacements is 16%.

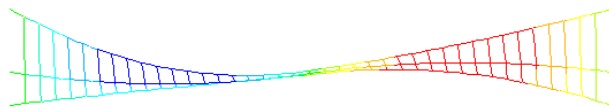


Fig. 10 Shape of displacements in non-symmetrical loading case

TABLE I  
DISPLACEMENTS OF PRESTRESSED CABLE TRUSS WITH SINGLE CABLE AND CABLE TRUSS TOP CHORD

Displacement direction	Single cable		Cable truss	
	Symmetrical load	Non-symmetrical load	Symmetrical load	Non-symmetrical load
Deck displacements downwards, mm	0.4965 m	0.6684 m	0.5498 m	0.6157 m
Deck displacements upwards, mm		0.3039 m		0.1995 m
Deck displacements total, mm	0.4965 m	0.9723 m	0.5498 m	0.8152 m

#### VI. EXPERIMENTAL MODEL TESTING

Two models were constructed to compare behaviors of single cable and cable truss for top chord of prestressed cable truss. (Fig.11 and Fig.12).



Fig. 11 Model of single cable top chord



Fig. 12 Model of cable truss top chord

The span of the models of cable truss is equal to 2.1 m. Top chord camber is equal to 22 centimeters. The deck is connected to main load carrying structure by suspensions in 15 points (Fig.13).

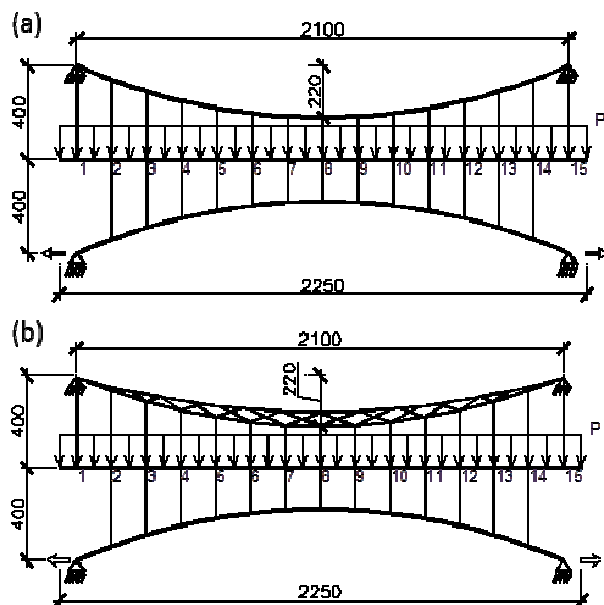


Fig. 13 Scheme of the cable truss models.(a) – scheme of the model with single cable; (b) – scheme of the model with cable truss

#### A. Elements of the Models

The elements of the cable truss and single cable top chord for prestressed cable truss models are made from steel cables. Two types of cables are used: 6x7+WSC (wire steel core) and 6x19+WSC (Fig.14). Both cables have ordinary left hand lay (Zs). Tensile strength of wires for both cables is 1770 MPa. The modulus of elasticity was experimentally obtained and is 60000 MPa. The diameters of elements are shown in Table II. With selected diameters of elements was achieved that cable truss has the same cable material consumption as single cable, what is important for comparison of models.

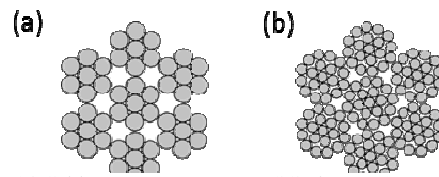


Fig. 14 Cable types: (a) – 6x7+WSC, (b) – 6x19+WSC

TABLE II  
DIAMETERS OF ELEMENTS OF MODELS

Elements	Cable type	Diameter	Breaking force
Single cable top chord			
Main cable	6x19+WSC	10.0 mm	63.0 kN
Stabilization cable	6x19+WSC	8.0 mm	40.3 kN
Cable truss top chord			
Bottom chord	6x19+WSC	8.0 mm	40.3 kN
Top chord	6x19+WSC	5.5 mm	17.8 kN
Web elements	6x7+WSC	2.0 mm	2.7 kN
Stabilization cable	6x19+WSC	8.0 mm	40.3 kN

The prestressing is organized in stabilization cable and is developed by rotating a screw and moving a bar. To allow cable to move, it is supported by the block (Fig.15).

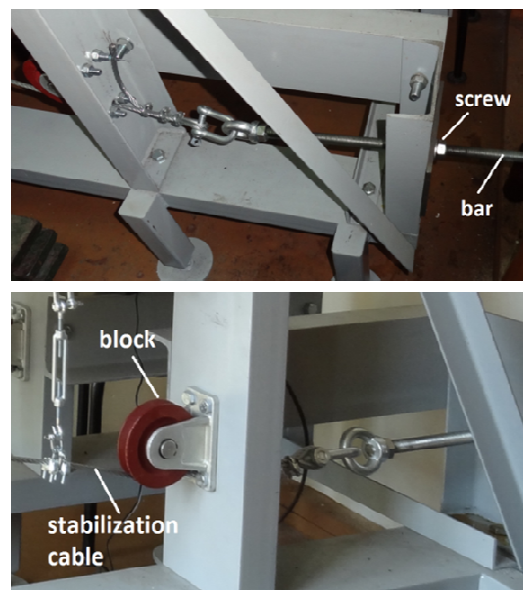


Fig. 15 Prestressing mechanism

The deck of the models is made from wood oriented strand board (OSB). Due to OSB good deformability, it does not take load, but only distribute it among suspensions. The deck is not connected to suspensions in horizontal plane.

To connect a deck to load bearing cable, adjustable suspensions are used, that allow leveling the deck. Suspensions are connected to the cables using U-bolt clips to prevent moving them along the cable (Fig.16).



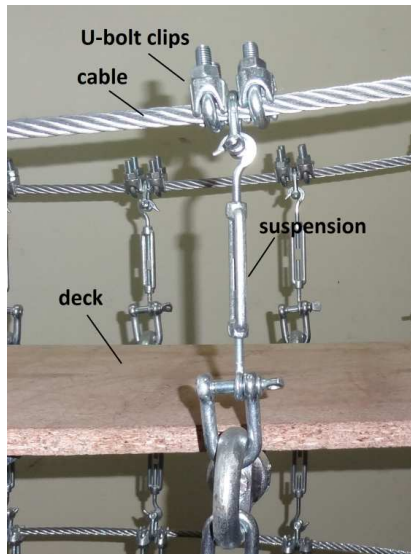


Fig. 16 Deck connection to the cable using of suspensions

Web elements of cable truss are connected to the chords by contact connection (Fig.17), where web elements are pressed to the chord. This type of connection showed enough strength and it was possible to make small elements of the web with this type of connection.

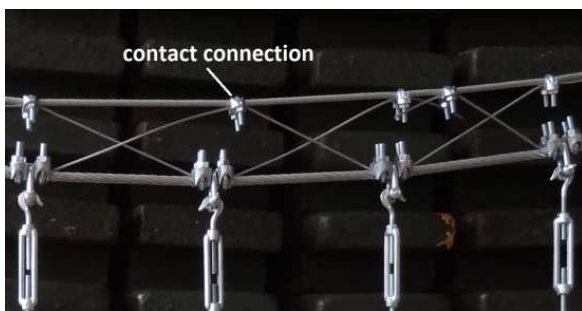


Fig. 17 Cable truss web element connection

#### B. Measurement Instruments

The tensile force in stabilization cable was measured by electronic dynamometer Scaime IPB50 (Fig.18) and self-made mechanical dynamometer (Fig.19). Electronic dynamometer work principle is based on changes of electrical bridge resistance. The precision of measurements for electronic dynamometer is 0.25 kg. Mechanical dynamometer work principle is based on measurements of spring displacements and converting them to forces using dependences. The precision of measurements for mechanical dynamometer is 0.5 kg.

Displacements were measured in 8 points by Aistov deflectometers, which allow to measure displacements in wide range (Fig.20). Deck displacements were measured.



Fig. 18 Electronic dynamometer



Fig. 19 Mechanical dynamometer



Fig. 20 Displacements measuring

#### C. Process of model testing

To remove free displacements and to stabilize modulus of elasticity, initial extension should be done for cable structures. The models were initially extended by the load, which is by 20% larger than designed load.

The model was at first prestressed by load 1000 kg for each side. Two types of loading were applied to model: symmetrical and non-symmetrical. The load was applied to the deck by placing iron weight 20 kg each. In symmetrical loading case, both models were loaded up to load 2755 kg with step 285 kg (Fig.21). In non-symmetrical loading case the models were loaded up to load 1495 kg with step 155 kg (Fig.22).



Fig. 21 Applying symmetrical load to the model



Fig. 22 Applying non-symmetrical load to the model

#### D. Models testing results

The models were tested under the action of symmetrical and non-symmetrical loads. In non-symmetrical loading case loaded part moves downwards, but unloaded part moves upwards (Fig.23). Therefore in non-symmetrical loading case displacements upwards and downwards are decisive. Total displacements were calculated as sum of upward and downward displacements. In symmetrical loading case maximum vertical displacements downwards are decisive.



Fig. 23 Displacements in non-symmetrical loading case

The results of displacements in symmetrical loading case for single cable and cable truss suspension bridge models are

shown on the Fig.24. Results of displacements in non-symmetrical loading case are shown on the Fig.25. It was shown that displacements in non-symmetrical loading case are large, than in symmetrical loading case for load with the same intensity. The displacements from symmetrical load are almost the same for single cable and cable truss models, but displacements from non-symmetrical load are smaller for cable truss model.

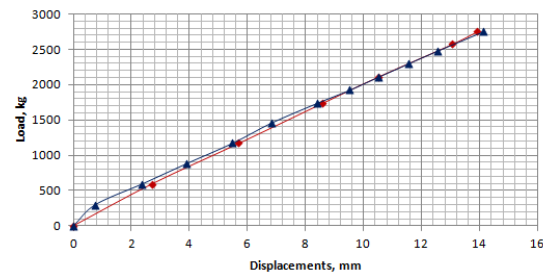


Fig. 24 Model testing results in symmetrical loading case

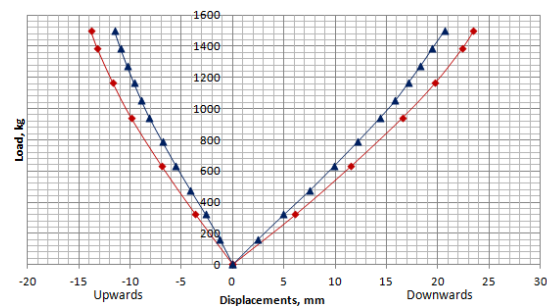


Fig. 25 Model testing results in non-symmetrical loading case

The displacements were calculated analytically by FEM program Lira 9.6 [24] and were compared with experimental results. Scheme of deformation of cable truss model is shown on the Fig.26.

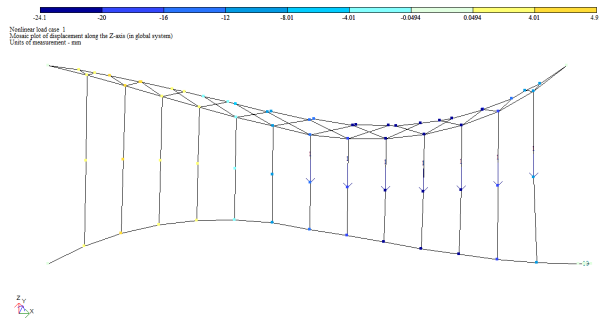


Fig. 26 Scheme of cable truss deformation

The maximum vertical displacements are generalized in Table III. Difference between displacements of model of prestressed cable truss with single cable top chord and prestressed cable truss model with cable truss top chord or cable truss advantage for experimental and analytical results are shown in Table IV.

TABLE III  
EXPERIMENTAL AND ANALYTICAL (IN BRACKETS) RESULTS OF DISPLACEMENTS OF THE MODELS

Loading scheme	Single cable			Cable truss		
	Deck displacements downwards, mm	Deck displacements upwards, mm	Deck displacements total, mm	Deck displacements downwards, mm	Deck displacements upwards, mm	Deck displacements total, mm
Symmetrical load	<b>14.71 (14.09)</b>			<b>15.06 (14.15)</b>		
Non-symmetrical load	<b>23.81 (22.41)</b>	<b>13.83 (12.43)</b>	<b>37.64 (34.84)</b>	<b>21.04 (19.33)</b>	<b>11.61 (8.95)</b>	<b>32.65 (28.28)</b>

TABLE IV  
DIFFERENCE BETWEEN SINGLE CABLE SUSPENSION BRIDGE MODEL AND CABLE TRUSS SUSPENSION BRIDGE MODEL DISPLACEMENTS

	Experimental results	Analytical results
Symmetrical load		
Deck displacements downwards	-2.4%	-0.4%
Non-symmetrical load		
Deck displacements upwards	16.1%	28.0%
Deck displacements downwards	11.6%	13.8%
Deck displacements total	13.3%	18.8%

The displacements for cable and cable truss in symmetrical loading case are equal to 15 mm, but in unsymmetrical case total displacements are 37 and 32 mm for single cable and cable truss respectively. The results of our experiment are close to analytical results. The experimental results shown, that replacing single cable with cable truss with cross web allows to decrease vertical displacements upwards by 16% and downwards by 12%, total displacements by 13%, that is a little bit smaller, than by analytical calculations. That can be described by not accurate web element placement.

## VII. CONCLUSIONS

Rational structure of the cable truss for prestressed cable truss top chord was developed. It was stated, that usage of cable truss with the cross web as a top chord of prestressed cable truss instead of single cable allows to reduce vertical displacements upwards by 34%, downwards by 8% and total displacements by 16% in the case of non-symmetrical load.

Single cable and cable truss model work was discovered. Achieved results are close to analytical ones. Model testing results indicate, that usage of cable truss with the cross web as a top chord of prestressed cable truss instead of single cable allows to reduce vertical displacements upwards by 16%, downwards by 12% and total displacements by 13% in the case of non-symmetrical 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".

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