CHOICE OF RATIONAL COMPONENTS FOR HYBRID COMPOSITE CABLE WITH INCREASED SPECIFIC STRENGTH

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Abstract. High strength hybrid composite cables with large specific strength on the base of such materials as carbon fiber reinforced plastics (CFRP), glass fiber reinforced plastics (GFRP) and Vectran, are widely used in constructional practice. But using of a steel component enables to increase small relative elongation, decrease brittleness and expand area of application of high strength hybrid composite cables. Steel was investigated in combination with such materials as CFRP, GFRP and Vectran.

Hybrid composite cables with the increased specific strength were considered as materials of several cable groups for a prestressed saddle-shaped cable roof with dimensions 50x50m. Opportunity to decrease the displacements of composite saddle-shaped cable roof by using of cable trusses, which were made from the hybrid composite cable with the increased specific strength was investigated. Rational geometric characteristics of the cable truss were determined by the numerical experiment.

It was shown, that using of hybrid composite cable enables to increase its specific strength up to 2.4 times. Rational components for composite cable with increased specific strength were chosen by the numerical experiment.

Keywords: saddle-shaped roof, cable truss, maximum vertical displacements, effectiveness of cable net materials using.

1. Introduction

Saddle-shaped cable roofs with a compliant supporting contour are rational type of structures from the point of view of materials consumption [1]. But at the same time, saddle shaped cable roofs possess an increased compliance and vertical displacements, which complicate using of this type of structures.

Basing on the results obtained in the [2] and the above mentioned information we can suppose, that the best method to decrease the displacements of the saddle shaped roof is to use the cable trusses made of the materials with increased moduli of elasticity as structures of several groups of the cables. Effectiveness of cable trusses used as tension cables construction was considered in [3].

High strength materials such as FRCC and FRP possess potential for their application as constructional materials in combination with the steel [1]. Carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP) and vectran are examples of such materials. As constructional materials they have following advantages:
- high specific strength;
- good durability in aggressive surrounding;
- CFRP is adaptable to be used in structures not allowed to be magnetic or electric conductive;
- low density.

However, CFRP, GFRP and Vectran have a number of disadvantages, which limit their application as constructional materials. Relatively small elongation at break [1], probability of surface damages and increased cost [2] are most significant disadvantages of CFRP, GFRP and Vectran in comparison with the steel cables.

Small elongation at break significantly decreases safety of construction due to probability of brittle failure during short time growing of the load. This disadvantage could be improved by the adding of steel component, which enables to increase reliability of the cable. Addition of distribution layer, which could be made of glass fiber reinforced plastic (GFRP), significantly decreases the possibility of surface damages of CFRP in hybrid composite cable. Yet the volume fractions of the components should be evaluated.

So, the purpose of the study is evaluation of rational volume fractions for hybrid composite cable components. Effectiveness of cable truss application for the main diagonal cable structure as a method to decrease the displacements of the saddle-shaped cable roof also should be evaluated. Rational geometrical characteristics of the cable truss shall be estimated.

2. Choice of rational components for hybrid composite cable with the increased specific strength

2.1 Material combinations for hybrid composite cable

The main directions of the considered hybrid composite cables application are prestressed nets of saddle-shaped roofs. Here two types of hybrid composite cables with the increased specific strength should be investigated. First of them is a hybrid composite cable with an increased, in comparison with the CFRP ultimate elongation and decreased in comparison with that of steel dead weight. These types of the cables could be used for the tension and suspension cables of the prestressed net. Second is a hybrid composite cable with relatively high ultimate elongation for the stressing cables of the prestressed nets. Combination of high strength and increased ultimate elongation is the main requirement for the first hybrid composite cable type. But the second type, unlike the first, should possess first of all, an increased ultimate elongation.

Thus, the first cable type should obligatorily contain two types of materials: one material with a large limit of strength and the other with an increased ultimate elongation. Third type of materials should be added to transfer perpendicular to the direction of axial force action pressure of the external layer at the surface of the internal one.

Steel wire strands can be treated as a material with an increased up to 10% ultimate elongation for the first type of the cable. Properties of GFRP (E-glass and epoxy matrix at 60% fiber content), CFRP (AS4/3501-6 graphite fibers and epoxy matrix at a 60% fiber content), Vectran HS 1500 and strands of steel wire are taken in accordance with the sources [4-10]. Moduli of elasticity of steel wire strands, GFRP, CFRP and Vectran are equal to $2 \cdot 10^5$; $0.75 \cdot 10^5$; $1.37 \cdot 10^5$ and $0.65 \cdot 10^5$ MPa, respectively. Limits of strength are equal to 1900; 760; 2100 and 2850 MPa, respectively [4-9]. Ultimate elongations are equal to 10, 2.64; 1.6 and 3.3 %, respectively.

Basing on the above mentioned materials properties, two following materials combinations can be considered for the first type of hybrid composite cable: steel, GFRP, CFRP and steel, Vectran, CFRP (Fig.1).

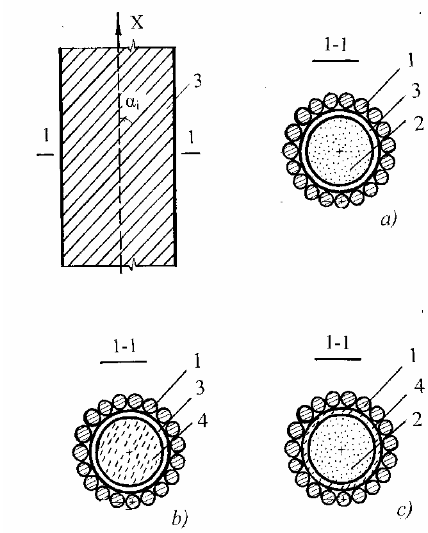

Fig.1. Hybrid composite cables on the base of steel, CFRP, GFRP and Vectran: 1 – steel component; 2 – CFRP component; 3 – GFRP component; 4 – Vectran component; *a)* –variant on the base of steel, GFRP and CFRP; *b)* – variant on the base of steel, GFRP and Vectran; *c)* – variant on the base of steel, Vectran and CFRP; α_i – angle of steel wire strands twisting; X – longitudinal axis of the cable.

Second type of the cables should be based on the material with the increased ultimate elongation and limit of strength, which is enough to take up tension forces, acting in the stressing cables of the net. Combination of steel, Vectran and GFRP, probably, enables to obtain hybrid composite cables with such properties.

2.2 Evaluation of mechanical properties of hybrid composite cables

The behaviours of hybrid composite cables are determined by the dependence of proportional components summing on the base of behaviors of separate components. Generally known dependence of proportional components summing was used for the engineering evaluation of modulus of elasticity of the hybrid composite cable.

Modulus of elasticity of the steel component of the hybrid composite cable was evaluated by the method of Kumar and Cochran [10].

Specific strength and load-bearing capacity were obtained for three variants of composite cables with the area of cross-sections equal to 0.001 m^2. Empty space was not taken into account. Angle of steel wire strands twisting was equal to 12 degrees for all the variants of hybrid composite cables. Specific strength of the cables was determined as a relation of ultimate strength of the cable and its density.

$$Y = \frac{R}{\rho}, \qquad (1)$$

where: *Y*- specific strength of the cable; *R* – ultimate strength of the cable; ρ – density of the cable.

Ultimate strength of the cable was found as a relation of maximum axial force, which can be taken by the cable and area of it cross-section. Volume fraction of steel changes within the limits of 0.1 to 0.7.

Increase of volume fraction of steel from 0.1 to 0.7 causes growing of moduli of elasticity from $1.25 \cdot 10^5$ to $1.57 \cdot 10^5$ MPa for the cable on the base of steel, GFRP and CFRP. For the cables on the base of steel, GFRP and Vectran and steel, Vectran and CFRP the increase of volume fraction of steel from 0.1 to 0.7 causes growing of moduli of elasticity from $0.94 \cdot 10^5$ to $1.53 \cdot 10^5$ and $1.27 \cdot 10^5$ to $1.6 \cdot 10^5$ MPa, correspondingly.

Three variants of the hybrid composite cables next will be mentioned as first, second and third variant, correspondingly.

The values of maximum axial forces, which can be taken up by the cables are given in the Table 1 for three variants of hybrid composite cables.

It is shown, that increase of volume fraction of steel from 0.1 to 0.7 enables to increase by 20.4 %, 20% and 1.63 times maximum axial forces, which can be taken up by the hybrid composite cables for first, second and third variant, respectively.

Table 1. Maximum axial forces for three variants of hybrid composite cable, kN.

Variant of hybrid composite cable	Volume fraction of steel		
	0.1	0.4	0.7
1. Variant (Steel;GFRP;CFRP)	1191	1343	1496
2. Variant (Steel;Vectran;CFRP)	1212	1365	1518
3. Variant (Steel; GFRP;Vectran)	892	1173	1454

The dependences of specific strengths of the cables on the volume fractions of steel are given in Fig.2.

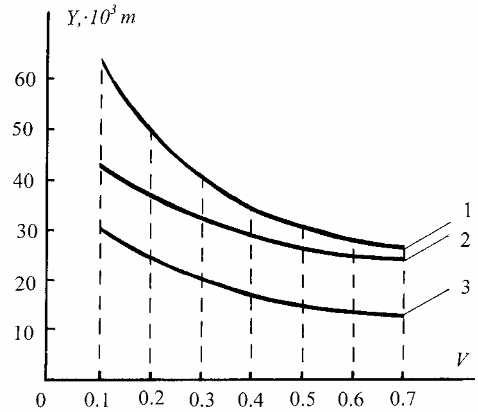

Fig.2. Dependence of specific strengths of the cables *Y* vs. the volume fraction of steel V: 1 – variant of hybrid composite cable on the base of steel, GFRP and CFRP; 2 – variant of hybrid composite cable on the base of steel, Vectran and CFRP; 3 – variant of hybrid composite cable on the base of steel, GFRP and Vectran.

The dependence illustrates, that increase of volume fraction of steel from 0.1 to 0.7 causes the decrease of specific strengths of the cables 2.40; 2.17 and 1.75 times for the first, second and third veriants of the cables, respectively.

2.3 Evaluation of rational volume fractions of steel

Thus increase of volume fraction of steel causes the increase of load bearing capacity of the cable and the decrease of it specific strength from other side. Yet there is a minimum volume fraction of steel, which enables to prevent failure of single cable or cable net in the case of emergency, when all the components of hybrid composite cable, excluding the steel, are disrupted. The minimum volume fraction of steel was considered as a rational.

Diagonal suspension cable of saddle-shaped cable roof with dimension 50x50 m was considered as an object for evaluation of rational volume fraction of steel for three variants of hybrid composite cables. Design scheme of diagonal suspension cable was a prestressed simple cable with the supports at one level, which is loaded by the uniformly distributed load.

Initial deflection and span of the cable were equal to 20 and 70.71 m, accordingly. Intensity of uniformly distributed load was equal to 1.97 kN/m. The value of prestressing is assumed as a 20% from the tension force, which acts in the cable due to the vertical design load. Three above mentioned variants of hybrid composite cable were considered. Volume fraction of steel changes within the limits of 0.1 to 0.7 from the initial area of cross-section. The dependences of stresses, acting in the steel component of hybrid composite cables after other components disruption on the volume fraction of steel, are given in Fig.3.

The deppendence illustrates, that the minimum volume fraction of steel, which prevents failure of the cable in the case, when other components are disrupted, is equal to 0.23, 0.28 and 0.29 for the first, second and third variants of hybrid composite cable, respectively. So, the hybrid composite cables with the rational volume fraction of steel possess following mechanical properties.

Moduli of elasticity are equal to $1.32\cdot10^5$; $1.35\cdot10^5$ and $1.36\cdot10^5$ MPa, for the first, second and third variant of the hybrid composite cable, respectively. Maximum axial forces, which can be taken up by the cables, are equal to 1242; 1313 and 1294 kN, for the first, second and third variant of the hybrid composite cable, respectively. Specific strengths are equal to $43.00\cdot10^3$; $41.00\cdot10^3$ and $40.50\cdot10^3$ m, for the first, second and third variant of the hybrid composite cable, respectively.

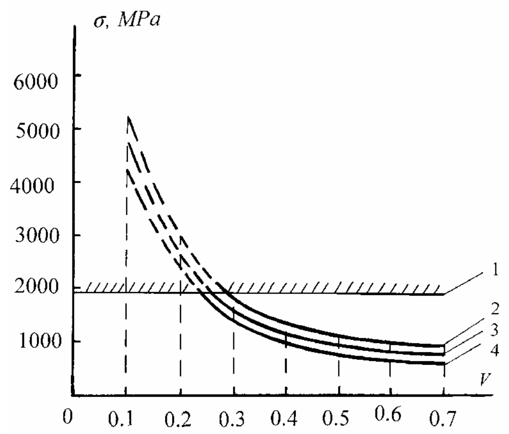

Fig.3. Evaluation of rational volume fraction of steel (at constant vertical load): 1 – limit of strength of steel; 2 – dependence for variant of hybrid composite cable on the base of steel, GFRP and CFRP; 3 – dependence for variant of hybrid composite cable on the base of steel, Vectran and CFRP; 4 – dependence for variant of hybrid composite cable on the base of steel, GFRP and Vectran; σ - stresses, acting in the steel component of hybrid composite cables after other components disruption; V - volume fraction of steel.

However a single cable can not characterise behaviours of the cable roof in the full scale. So, hybrid composite cable on the base of steel, GFRP and CFRP was considered as a material of tension and diagonal suspension cables of saddle shaped cable roof with dimensions 50x50 m. The behaviours of the cable roof were evaluated for the diagonal suspension and tension cables in the cases, when all the components of hybrid composite cables, excluding the steel, were disrupted. Parameters of cable roof and methodology of numerical experiment are explained in chapter 3.

It was stated, that the maximum vertical displacements of the cable roof grows by 3 mm in the case of GFRP and CFRP components disruption of diagonal suspension cable. Maximum growing of the stresses from 899 to 1110 MPa took place in the suspension cables, which are neighbouring to the diagonal suspension cables. The maximum vertical displacements of the cable roof grows by 1.37 m in the case of GFRP and CFRP components disruption of tension cables. Maximum growing of stresses from 897 to 1050 MPa took place in the diagonal suspension cable. Still the growing of stresses and maximum vertical displacements did not cause failure of any more cables.

3. Using of composite cable for increasing of saddle-shaped cable roof rigidity

Let us to consider how the using of hybrid composite cable in combination with the cable truss application enables to increase the rigidity of saddle-shaped cable roof.

A saddle-shaped cable roof 50x50 m in the plan was investigated. The existence of two symmetry planes allows us to regard, as a design scheme, a quarter of the cable net of a saddle-shaped cable roof with a main stressing cable as the shape of the cable truss, which is subjected to the prestressing and vertical design load (Fig.4).

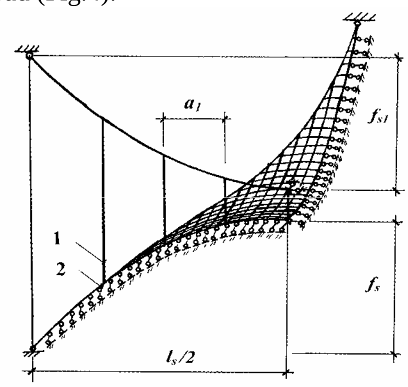

Fig.4. Design scheme of cable roof:1– cable truss; 2 – cable net; f_{s1} – initial deflection of top chord of cable truss; f_s – initial deflection of main stressing cable; a_1 – distance between the support points of tee-bars.

Three quarters of the cable roof are replaced by the bonds imposed on its one-quarter part. Hybrid composite cables on the base of steel, GFRP and CFRP with an elastic modulus of $1.32 \cdot 10^5$MPa were assumed as a material of cable truss elements. Steel cables with an elastic modulus of $1.3 \cdot 10^5$MPa were assumed as a material for the suspension , stressing (excluding main diagonal) and tension cables.

From the viewpoint of material consumption, the saddle-shaped cable roof has rational geometrical characteristics: the initial deflection of the contour cables was 8.6 m, the initial deflection of suspension and stressing cables 20 m, and the step in plan of the latter ones was 1.414 m [11,12].

The structure was calculated for the basic combination of loads – the dead weight of the structure (0.27kPa) and the weight of snow (1.12kPa) – evenly distributed on the horizontal projection of the roof. The design load in the form of pointwise forces was applied to the nodes of the cable net. The roof had the following layers: a glass net coated with polymer resin (2 mm), foam plastic, reinforced with a glass net (120 mm), and saddle-shaped plywood sheets (6 mm) [13].

The cable net was prestressed by applying tension forces to the suspension and stressing cables, such that the residual tension forces in the stressing cables were equal to 20% from their initial values under the vertical design load. Two variants of support points of the main diagonal suspension cables fixation were considered:

- the displacements of the cable net at the support points were restricted by the deformation of the guys;
- the relations excluding any displacements were imposed on the support points of the cable net.

The cross-sectional areas of the cables occuring in the symmetry plane (the main diagonal cables), as well as the pointwise forces applied to the nodes of these cables, were divided by two. The pointwise force applied to the intersection node of the main diagonal cables was divided by four.

The relations between the initial deflection of the top chord of the cable truss, the distance between the support points of tie-bars and effectiveness of cable net materials usied for maximum vertical displacements decrease were determined in the form of second power polynomial functions applying the method of experimental design [14]. The effectiveness of cable net materials usied for maximum vertical displacements decrease was determined from the formula:

$$Э = \frac{\Delta\delta}{V/A} \quad , \qquad (2)$$

where $\Delta\delta$ is maximum vertical displacements decrease, V/A is the volume of the material of the cable net per unit of the covered area (relative volume).

The coefficients of the second power polynomial functions were found from the results of a numerical experiment, which was joined with the determination of forces in the net cables, which are necessary to select the cable cross-section, calculate the relative volume of the material of the cable net, and maximum vertical displacements of the cable net. The numerical experiment was conducted with the values of initial deflection of top chord of the cable truss, changing from 4 to 16 m and values of the distance between the nodes of cable truss, changing from 2.8 to 8.4 m.

The cross-sectional areas of the cables were found according to the recommendations given in [15], from the formula:

$$F \geq \frac{1{,}6N}{kR} \ , \tag{3}$$

where F is the cross-sectional area of the cable, N is the design force in the cable, k is a coefficient, taking into account the drop in the breaking force of the cable caused by the inhomogenity of stress distribution, R is the ultimate strength of the cable material, and 1.6 is the reliability index of the material.

The area, covered by the roof was found with regard to the initial deflections of tension cables.

Using a computer program "ANSYS/ED 5.3" for WINDOWS the numerical experiment was carried out. The program enables to calculate values of the tension forces acting in the cables of the net and maximum vertical displacements of the cable net. In calculating a cable net, the program uses the iteration method, which consists of the division of the applied vertical design load into several parts in an ascending order. The cable net was modeled by finite elements of LINK10 type, with three degrees of freedom for each node. Each finite element was divided into two parts of the same length. The judicious values of the basic geometrical characteristics of the cable truss were found from the system of equations (4). The first and second equation of the system was obtained by taking of partial derivations from the second power polinomial functions, by the initial deflection of top chord of the cable truss and distance between support points of tie-bars, respectively.

$$\begin{cases} \dfrac{\partial Э}{\partial a_1} = \theta_0 + \theta_1 a_1 + \theta_2 f_{s1} = 0, \\ \dfrac{\partial Э}{\partial f_1} = \psi_0 + \psi_1 a_1 + \psi_2 f_{s1} = 0 \, , \end{cases} \tag{4}$$

where $Э$ is effectiveness of cable net materials using for maximum vertical displacements decrease, f_{s1} is initial deflection of top chord of the cable truss, a_l is distance between the support points of tie-bars.

Coefficients of the equations are given in Table 2.

Table 2. Coefficients of the equations.

Coefficients of the equations	* Values of coefficients
θ_0	0.0090/0.013
θ_1	0.000041/0.00023
θ_2	-0.00066/-0.00093
ψ_0	0.012/0.0087
ψ_1	0.000041/0.00023
ψ_2	-0.0032/-0.0029

*Values, which are given in the numerator, are obtained for the case, when the displacements of the cable net were restricted by the deformations of the guys.

The values of the initial deflection of top chord of the cable truss and distance between support points of tie-bars are equal to 15 and 4 m, respectively.

4. Investigation of displacements decrease

Maximum vertical displacements of the cable roof for all combinations of the main geometrical characteristics of the cable truss were determined as a maximum difference in the vertical coordinate of the cable net nodes before and after application of design vertical load. The dependence of the maximum vertical displacements of cable net on the initial deflection of top chord of the cable truss and distance between the support points of tie-bars is shown in Fig.5.

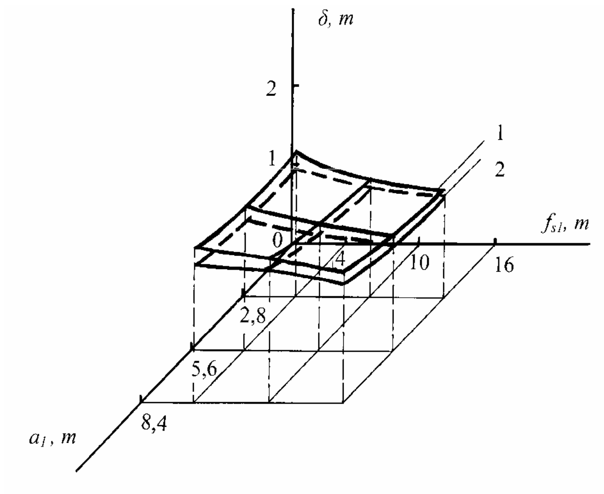

Fig.5. Maximum vertical displacements δ v.s. the initial deflection f_{s1} of top chord of cable truss and distance a_1 between the support points of tie-bars: 1– displacements of the cable net at the support points are restricted by the deformations of the guys; 2 – the support points of the cable net are fixed.

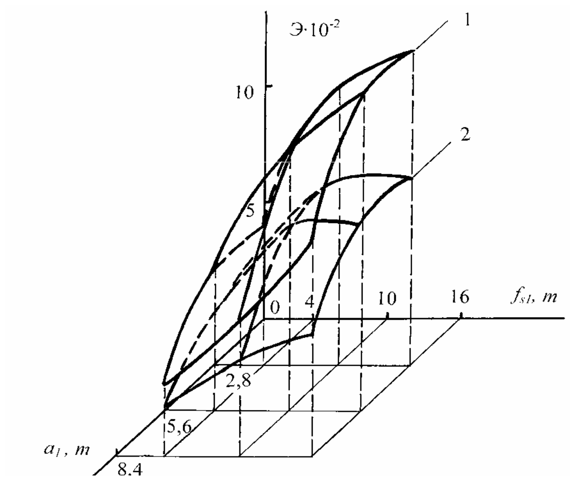

Fig.6. Effectiveness of the cable net materials use for maximum vertical displacements decrease *Э* v.s. the initial deflection f_{s1} of top chord of cable truss and distance a_1 between the support points of tie-bars: 1–displacements of the cable net at the support points are restricted by the deformations of the guys; 2 – the support points of the cable net are fixed.

The dependence shows, that the minimum values of vertical displacements of cable net were obtained, when the initial deflection of top chord of cable truss was equal to 16 m and distance between the nodes of the cable truss was equal to 2.8 m for both variants of support points fixation.

The dependence of the effectiveness of cable net materials using for maximum vertical displacements decrease on the initial deflection of the top chord of cable truss and distance between the cable truss nodes is shown in Fig.6.

The dependence shows, that decrease by 31% of maximum vertical displacements values is joined with the growing by 24% of relative volume of cable net materials expenditure for the variant, when the displacements of the cable net at the support points are fixed. Maximum vertical displacements decrease by 38% in the case, when displacements of cable net were restricted by the deformations of the guys. Relative volume of the cable net materials consumption grows by 27% in the case.

The maximum value of the cable net materials consumption was obtained, when the initial deflection of top chord of cable truss was equal to 16 m and distance between the nodes of the cable truss was equal to 2.8 m.

5. Conclusions

Rational components for hybrid composite cable with the increased specific strength were chosen. It was shown, that the minimum volume fraction of steel component is within the limits of 0.23 to 0.29 for the cables on the base of steel, CFRP, GFRP and Vectran.

Opportunity to decrease the displacements of composite saddle-shaped cable roof by the using of cable trusses as the main stressing diagonal cable structure was investigated.

It was shown by the numerical experiment, that the rational initial deflections of top chord of the cable truss and distance between the support points of tie-bars for the cable roof with dimensions in plan 50x50 m was equal to 15 and 4 m, respectively.

It was shown, that the using of cable truss as a structure of main stressing diagonal cable enables to decrease by 31–38% the maximum vertical displacements of the cable net and to increase by 24–27% the relative volume of the cable net materials consumption in the case, when the main stressing diagonal cable is strengthened by the truss, which is made of hybrid composite cable but suspension and tension cables are made of steel.

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