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Hybrid Composite Cable Based on Steel and Carbon

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Combination of steel and carbon enables to obtain a hybrid composite cable with increased strain in comparison with the carbon composite cables and decreased dead weight in comparison with the steel cables.

Hybrid composite cable contains three layers: carbon fiber composite cable (CFCC) core, glass fiber reinforced plastic (GFRP) and steel wire strands. CFCC core and steel wire strands take up tension stresses, acting in the cable during the exploitation. The functions of GFRP are distribution of transversal pressure of steel wire strands at the carbon fiber core, and taking up of tension stresses.

Volume fractions of steel and carbon are determined basing on the assumption, that in an emergency, when the strain of carbon fiber exceeds the ultimate value and these fibers are disrupted, strands of steel wire must be able to take up tension stresses, acting in the cable.

The principle of hybrid composite cable work was illustrated on the example of separate cable. Opportunity to decrease dead weight of the cable is stated.
Keywords: hybrid composite cable, steel wire strands, carbon fiber composite cable.

1. INTRODUCTION

High strength materials such as fiber reinforced composite cables (FRCC) and fiber reinforced plastics (FRP) possess potential for their application as constructional materials in combination with steel [1]. Carbon fiber composite cable (CFCC) and carbon fiber reinforced plastic (CFRP) are examples of such materials. As constructional materials they have following advantages:

- high tensile strength;
- good durability in hostile environment;
- CFCC is adaptable to be used in structures not allowed to be magnetic or electric conductive;
- low density.

However, CFCC has a number of disadvantages, which limits its application as constructional material. Relatively small elongation at break [1], probability of surface damages and increased cost [2] are most significant disadvantages of CFCC 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 development of hybrid composite cable, which has decreased in comparison with the steel dead weight, and increased in comparison with CFCC elongation at break. Addition of distribution layer, which could be made of glass fiber reinforced plastic (GFRP), significantly decreases probability of surface damages of CFCC in hybrid composite cable.

Increased cost of CFCC in comparison with the steel cables could be partially compensated by the application of CFCC in economic, from the point of view of material consumption, constructions. One of CFCC utilization in practice is using as tendons for the cable bridges [1]. Saddle shape cable roof is another probable example of CFCC using as a constructional material. Saddle shape cable roof is a type of constructions where such high strength constructional materials as CFCC could be used in the full scale, because nearly all the load bearing elements are tensioned [3].

The purpose of this study is to consider behavior of hybrid composite cable on the base of steel, CFCC and GFRP, and to evaluate rational from the safety point of view volume fractions of each component.

2. EXPERIMENTAL

2.1. Hybrid composite cable based on steel and carbon

Hybrid composite cable with increased breaking elongation and low creep at tension could be elaborated for pre-stressed cable net on the base of carbon and steel [4]. Hybrid composite cable contains three layers: CFCC core, glass fiber reinforced plastic (GFRP) and steel wire strands (Fig. 1).

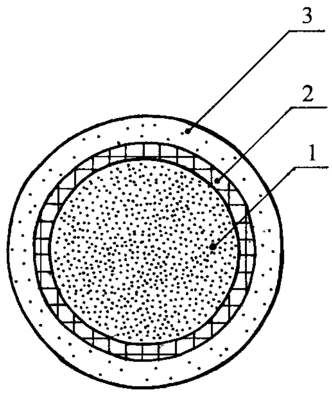

Fig. 1. Scheme of hybrid composite cable made of steel, CFCC and GFRP: 1 – CFCC core, 2 – GFRP distribution layer, 3 – steel wire

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All layers of hybrid composite cable take up tension stresses, acting in the cable during exploitation. But GFRP has second function - distribution of transversal pressure of steel wire strands at CFCC core.

A larger breaking elongation of the hybrid composite cable in comparison with the CFCC provides increased safety. In an emergency, when the strain exceeds the limiting value for carbon (1.6 %) and glass (2.64 %) fibers and these are excluded from the work, the steel wire must completely take up tensile stresses, which are significantly decreased due to the elongation of the cable.

The working stages of hybrid composite cable are shown in Fig. 1. Deflection f_1 corresponds to the stage, when all components of the cable work jointly. Deflections f_2 and f_3 corresponds to the stages, when GFRP and CFCC are excluded from the work. The big elongation of the cable and significant growing of the cables deflections characterize the last stage of cable work. Strain of steel component could grow till 10 % in the process of yielding. Growing of the cable deflection, decreases tension stresses, acting in the steel component of the cable. When tension stresses become less, than limit of yielding of steel component process of cable elongation stopped.

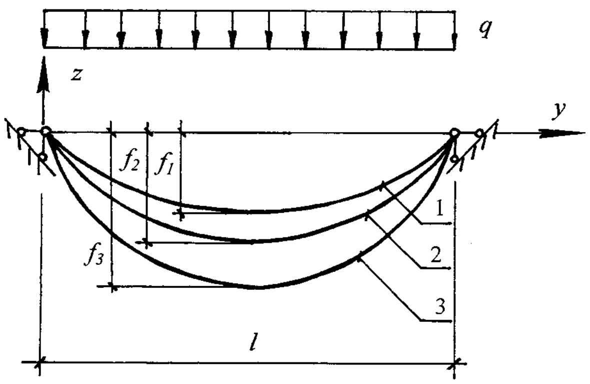

Fig. 2. Scheme of hybrid composite cable work: 1 – steel wire, GFRP and CFCC work commonly, 2 – GFRP is excluded from the work, 3 – GFRP with CFCC are excluded from the work and steel wire works alone, q – design vertical load, acting at the cable, f_1 – deflection of the cable, which corresponds to the stage, when steel wire, GFRP and CFCC work commonly, f_2 – deflection, which corresponds to the stage, when GFRP is excluded from the work and steel wire works commonly with CFCC, f_3 – deflection, which is corresponds to the stage, when GFRP and CFCC are excluded from the work and steel wire works alone, l – span of the cable

Decreased dead weight is obtained by the using materials (CFCC and GFRP) with a smaller density than steel. It means, that hybrid composite cable should contain such amount of steel, which could provides safety of the cable from one side and minimum dead weight from other.

2.2. Practical example of hybrid composite cable work

The above-mentioned principles of hybrid composite cable work could be illustrated by the example of separate cable with span $l = 38.42$ m and initial deflection $f_1 = 5.7$ m.

Scheme, which is shown in Fig. 2, could be considered as analyze scheme of the cable. The uniformly distributed load with intensity q = 21 kN/m loads the cable. Volume fractions of steel wire, GFRP and CFCC are 0.4, 0.2 and 0.4 respectively. Elastic modulus for steel, CFCC and GFRP were equal to 1.3×10^5, 1.37×10^5 and 0.75×10^5 MPa, respectively. The values of modulus of elasticity correspond to the elastic stages of the materials work. Volume fraction of carbon fibers in CFCC is 0.6 [1].

Limits of strength of steel, CFCC and GFRP were equal to 1568, 1765 and 1000 MPa, respectively. Total area of cross sections for hybrid composite cable was equal to 0.00097 m^2.

Dependence of the force in hybrid composite cable on the initial deflection of the cable is shown in the Fig.3. The dependence was obtained by the equations of cable calculation, without taking into account elastic elongation of the cable [5]:

$$n = \sqrt{H^2 + V^2}\ , \tag{1}$$

$$H = \frac{ql^2}{8f}\ , \tag{2}$$

$$V = \frac{ql}{2}\ , \tag{3}$$

where H is the horizontal force of the cable, V is the vertical support reaction of the cable, q is the load, acting on the cable, l is the span of the cable, f is the initial deflection of the cable.

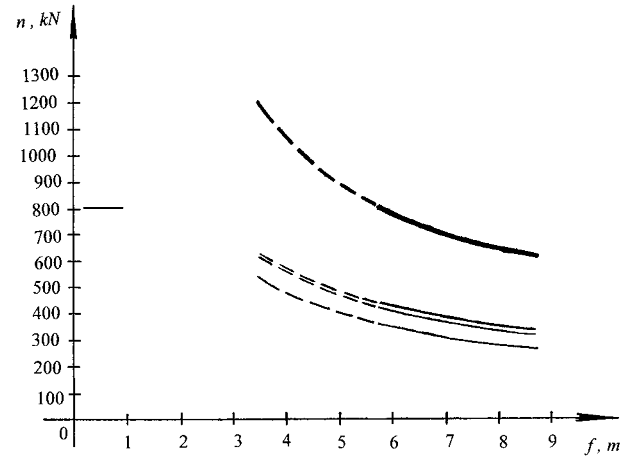

Fig. 3. Force in the hybrid composite cable, n as a function of the initial deflection f: dependences (▬▬), (──) and (══) were obtained by the values $1.6\,n/A \le 1568$ MPa for the whole cable, steel wire and CFCC, respectively; dependences (▬ ▬), (– –) and (= =) were obtained by the values $1.6\,n/A \ge 1568$ MPa for the whole cable, steel wire and CFCC, respectively; A – area of cross-section of the cables

The dependence shows, that decreasing of initial deflection of the cable from 8.7 to 2.7 m causes growing of forces by 2 times in the hybrid composite cable.

When the stresses, acting in the cable reach limits of strength of components, GFRP and CFCC are excluded from the work, but the steel start to yield. Yielding of steel is accompanied by its elongation and decreasing of tension force, acting in the steel component. This process is stopped when the stresses, acting in the steel component of the cable become less than temporary strength of steel wire.

Thus the dependence of force, acting in the steel component of the cable, from the displacement in the middle of the span, during changing of initial deflection, and excluding from the work of CFCC and GFRP components is shown in Fig. 4 in combination with the dependence of force, acting in the steel component of the cable from the strain.

These dependences show, that strengthening of steel occurs in the process of deformation of steel component of hybrid composite cable and steel component at the determined value of Δf is able to take up forces, acting in the cable (Fig.4).

The dependence of force, acting in the steel component of the cable, from the strain of steel component was obtained basing on the data of literature source [1], which were received for steel wire strand with diameter 12.5 mm. The dependence shows, that proportion limit of steel wire occur when the strain is equal to 0.9 %. Yielding of steel wire starts when the value of strain reaches 1.2 %.

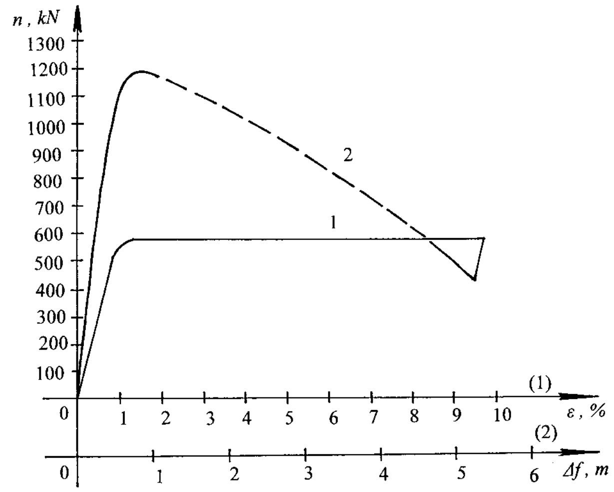

Fig. 4. Force in the hybrid composite cable, n and its steel component as a function of the strain ε (1) and displacement in the middle of the span Δf (2): dependence (——) was obtained by the values $1.6\,n/A \leq 1568$ MPa; dependence (— — —) was obtained by the values $1.6\,n/A \geq 1568$ MPa; 1 – dependence was obtained for whole hybrid composite cable; 2 – dependence was obtained for steel component of hybrid composite cable

The dependences in Fig. 4 show, that after excluding from the work of CFCC and GFRP components, steel wire alone is able to take forces, acting in the cable.

2.3. Evaluation of rational volume fractions of steel, CFCC and GFRP for hybrid composite cable

Rational from the point of view of materials consumption and condition of safety volume fractions of steel, GFRP and CFCC for hybrid composite cable were determined by the numerical experiment. Numerical experiment is joined with determination of forces, acting in the hybrid composite cable and strains of steel component.

Cable, which is loaded by the uniformly distributed design vertical load (Fig. 2), is considered as an object of investigations.

The numerical experiment was accomplished by the program "ANSYS/ED 5,3" for WINDOWS. The program is based on the Newton - Raphson iterative method during the analysis of the cable. The cable is modeled by LINK10 type finite element, which has three degree of freedom in each node. Displacements of the cable nodes, as well as horizontal cable force were determined by the equations (4) – (6), which are written for the cable and each node.

$$\nabla_k \left[dH \frac{\Delta y}{L} \right] = -dP_y \ , \tag{4}$$

$$\nabla_k \left[H \frac{\Delta w}{L} + dH \frac{\Delta(z_0 + z_1)}{L} \right] = -dP_z \ , \tag{5}$$

$$dH = H_0 + \frac{EA}{S} \left[\Delta^* dv \frac{\Delta^* y}{S} + \sum_1^m \frac{\Delta(z_0 + z_1)\Delta dw}{L} \right] , \tag{6}$$

where: y, z are the coordinates of the cables nodes (z – vertical axis); P_y, P_z are the external loads, applied to the nodes of the cable in the directions y, z, respectively; v, w are the displacements of the cable nodes in the directions y, z, respectively; ∇ is the difference operator to k-th node; Δ is the difference between the initial and final mean of the value; H is the horizontal cable force; H_0 is the prestressing force of the cable; S is the length of the cable; L is the distance between neighbouring nodes of the cable; A is the area of cross-section of the cable; m is the number of elements in the cable.

Correlation between the volume fraction of steel in hybrid composite cable, the strain of steel fraction after excluding from the work of GFRP and CFCC and the weight of the cable, related to its span, was determined. Rational volume fraction of steel was determined by this correlation as a minimum amount of steel, which takes up forces, acting in the cable after excluding from the work of CFCC and GFRP components.

The numerical experiment was performed with the span and initial deflection equal to 38.42 and 5.7 m, respectively [6 – 8]. Intensity of uniformly distributed load, acting in the cable, was equal to 21 kN/m.

The numerical experiment was carried out for the values of volume fractions for steel, GFRP and CFCC, which are given in Table 1.

Table 1. Volume fractions of steel, GFRP and CFCC for hybrid composite cable

Volume fraction of steel	0.1	0.2	0.3	0.4	0.5	0.6	0.7
Volume fraction of GFRP	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Volume fraction of CFCC	0.7	0.6	0.5	0.4	0.3	0.2	0.1

The dependences of final strain of steel fraction and weight of the cable, related to its span on the volume fraction of steel for hybrid composite cable are given in Fig. 5.

The dependences were obtained with the values of density equal to 7.8, 1.5, 2.02 g/cm^3 for steel, CFCC and GFRP, respectively.

Dependences, which were obtained at volume fractions of steel smaller than 0.4, also have linear character.

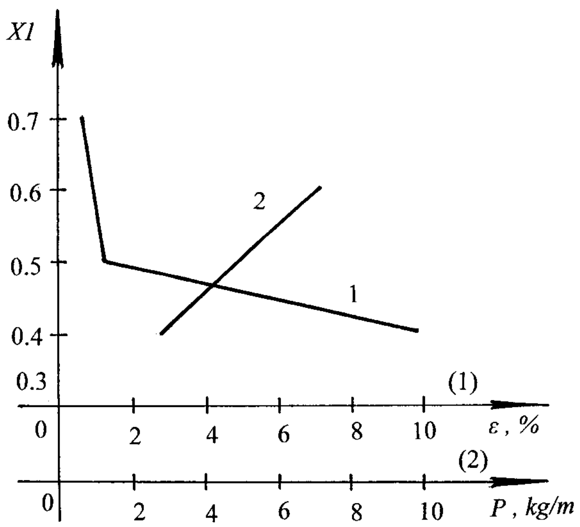

Fig. 5. Volume fraction of steel in hybrid composite cable X1 as a function from final strain of steel ε, after excluding from the work of CFCC and GFRP (1), and relative weight of the cable P (2).

The turning point on the dependence of volume fraction of steel component in hybrid composite cable on its strain is joined with the stresses acting in the steel component of the cable. If volume fraction of steel is bigger or equal to 0.5, values of stresses, acting in the steel component of the cable, are less than the limit of yielding of steel wire, and strains of steel component are relatively small. If volume fraction of steel is smaller than 0.5, value of these stresses are bigger or equal to the limit of yielding of steel wire, and character of dependence changes due to increased strains of steel component.

The dependences illustrate, that most rational from the point of view of materials consumption and safety volume fraction of steel and CFCC are equal to 0.4.

3. CONCLUSIONS

1. Hybrid composite cable on the base of steel, GFRP and CFCC with decreased dead weight and increased safety was considered.
2. It was stated by numerical experiment that most rational from the point of view of materials consumption and safety volume fraction of steel, GFRP and CFCC are 0.4, 0.2, and 0.4, respectively.
3. Opportunity to decrease dead weight of the hybrid composite cable by 1.6 times in comparison with the steel one was determined.

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