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PECULIARITIES OF BEHAVIOURS OF COMPOSITE MATERIALS IN SADDLE-SHAPED CABLE ROOF

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Abstract: *Peculiarities of behaviours of composite materials in saddle-shaped cable roof were investigated.*
Hybrid composite cables with the steel component were considered as materials of several cable groups for a prestressed saddle-shaped cable roof.
Cladding element for saddle-shaped cable roofs on the base of the PoliTetraFluoroEthylene copolymer foil, which is reinforced by the Vectran fabric, was investigated.
Opportunity to decrease the displacements and dead weight of composite saddle-shaped cable roof by using of hybrid composite cables with steel component for several groups of cables and composite cladding element was investigated.
Keywords: load bearing elements, hybrid composite cable, cladding element, maximum vertical displacements.

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 the steel. Carbon fiber reinforced plastic (CFRP), glass fiber reinforced plastic (GFRP) and Vectran are examples of such materials. Saddle-shaped cable roof is a type of constructions where such high strength constructional materials could be used on the full scale, because nearly all the load bearing elements are tensioned.
However, the most significant disadvantage of the saddle-shaped cable roofs supported by the tensioned cables is the increased compliance. One of the eventual methods to decrease the compliance of the cable roofs is using of
the cables with the increased moduli of elasticity.
Hybrid composite cable on the base of steel, CFRP, GFRP and Vectran can be considered as an example of such a cable (Figure 1).

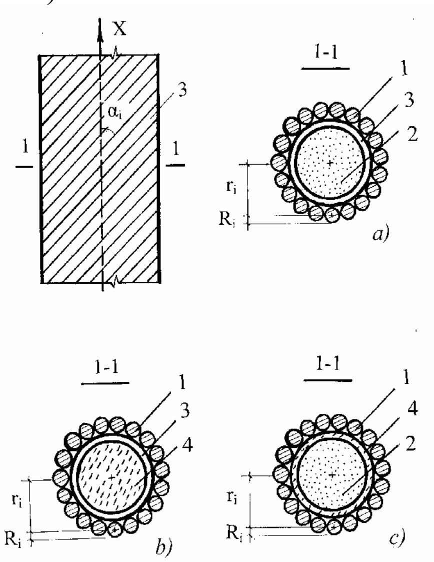

Fig.1. Hybrid composite cables on the base of steel, CFRP, GFRP and Vectran: 1 – steel component; 2 – CFRP component; 3 – GFRP component; 4 – Vectran component; *a)* –variant on the base of steel, GFRP and CFRP; *b)* – variant on the base of steel, GFRP and Vectran; *c)* – variant on the base of steel,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

Another method is to decrease the dead weight of cable net and cladding. PoliTetraFluoroEthylene (PTFE) copolymer foil, reinforced by the Vectran fabric is the probable material for such tensioned cladding element. Using of tensioned cladding element enables to obtain increased mobility [1].

The purpose of this study is to consider behaviour of hybrid composite cable on the base of steel, CFRP, GFRP, Vectran. Opportunity to decrease the displacements of the composite saddle-shaped cable roof by using of hybrid composite cables for several groups of cables and tensioned composite cladding element should be investigated.

2. COMPOSITE MATERIALS IN SADDLE-SHAPED CABLE ROOF

2.1 Material Combinations for Hybrid Composite Cables

The main directions of the considered hybrid composite cables application are prestressed nets of saddle-shaped roofs. Two types of hybrid composite cables should be investigated.

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, GFRP (E-glass and epoxy matrix at 60% fiber content), CFRP (AS4/3501-6 graphite fibers and epoxy matrix at 60% fiber content), and Vectran HS 1500 considered as materials for both types of hybrid composite cables. The moduli of elasticity of the materials 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. Breaking elongations are equal to 10, 2.64, 1.6 and 3.3%, respectively [2–7]. The values of materials characteristics are given in the longitudinal direction X.

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.

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 Characteristics of Materials for Tensioned Fabric Claddings

Polymer foils, reinforced by the fabrics, is one of the tensioned fabrics types (Figure 2).

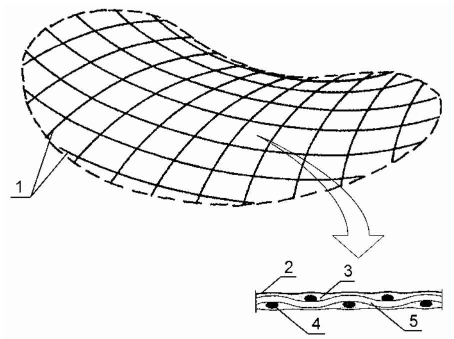

Fig. 2. Typical section of cladding of the cable net: 1 – cable net; 2 – lacquering; 3 – coating; 4 – warp threads; 5 – weft threads.

Glass and polyester fabrics are the most widely used types of reinforcement. The Vectran fabric take intermediate position between polyester and glass ones. Comparison of mechanical properties of fibers, which are initial components of tensioned fabrics shows, that the Vectra fibers have density 1.82 times less than that of Glass fibers (1.40 and 2.55 g/cm^3 respectively). Vectra and Glass fibers have nearly equal strength at tension – 3200 and 3500 MPa, respectively. But strength at tension of Vectra fibers is 2.46 times larger, than that of polyester fibers [6–7]. Vectran fibers possess one more significant advantage – absence of creep. It allows us to consider Vectran fabric as a material for prestressed claddings.

PTFE copolymer foils cause the biggest interest as a matrix material due to the row of advantages. Water and thermo resistance, low thermal conductivity, good insulating properties, resistance to UV and IR radiation are the most significant of them. Next will be considered cladding element, which is PTFE copolymer foil reinforced by the Vectran fabric.

3. EVALUATION OF MECHANICAL PROPERTIES OF SADDLE-SHAPED CABLE ROOF'S UNITS

3.1 Peculiarities of behaviours of hybrid composite cables

Generally known dependence of proportional components summing was used for the engineering evaluation of modulus of elasticity of the hybrid composite cable. The dependences are given for the variant of the hybrid composite cable on the base of steel, GFRP and CFRP.

$$E = \Omega_C E_C + (1 - \Omega_C - \Omega_S)E_G + \Omega_S E_S \qquad (1)$$

where

$$\Omega_C = \frac{A_C}{A}, \Omega_S = \frac{A_S}{A} \qquad (2)$$

$$E_S = \frac{\sum_{i=1}^{n} m_i A_i E_i \cos\alpha_i \left[1 - (1+\nu) p_i \cos^2 \alpha_i\right]}{A_S} \qquad (3)$$

$$A_i = \pi r_0^2 \qquad (4)$$

$$p_i = \left(1 - \nu \frac{R_i}{r_i} \sin^2 \alpha_i\right) \times \left[1 - \frac{R_i^2}{4r_i^2}\left(1 - \frac{\nu}{1+\nu}\sin^2 \alpha_i\right)\sin^2 \alpha_i\right] \qquad (5)$$

where: E − modulus of elasticity of hybrid composite cable; A − cross-sectional area of hybrid composite cable; A_C, A_S − cross-sectional areas of CFRP and steel components, respectively; E_C, E_G, E_S − moduli of elasticity of CFRP, GFRP and steel components, respectively; m_i − amount of steel wires in the i-th strand; A_i − cross-sectional area of the separate steel wire in the i-th strand; r_0 − radius of separate steel wire; E_i − modulus of elasticity of steel wire; α_i− angle of i-th steel wire strands twisting; ν − Poison's ratio of steel wire; R_i − radius of i-th steel wire strand; r_i − distance between the centres of i-th steel wire strand and cable.

Modulus of elasticity of the steel component of the hybrid composite cable was evaluated by the method of Cumar and Cochran [8].

The dependence of strain ε on the force N, acting in the cable, was 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. The dependence was obtained on the base of stress-strain curves of separate components [3–4,7]. The following consumption were considered. The steel wire and GFRP are working in the elastic stage up to the strains, which are equal to 0.95 and 1 %, respectively. Then occurs yielding up to the ultimate strains of 10 and 2.64 %, respectively. The CFRP and Vectran components are working in the elastic stage till the ultimate strains of 1.6 and 3.3 %, respectively. Volume fraction of steel for each variant changes within the limits of 0.1 to 0.7. Volume fractions of GFRP in the two first variants and Vectran in the third variant of hybrid composite cables were constant and equal to 0.2. Angle of steel wire strands twisting was adopted equal to 12 degrees.

The dependence of strain ε on the force N, acting in the cable, for hybrid composite cable on the base of steel, GFRP and CFRP (Figure 3) illustrates, that increase of volume fraction of steel from 0.1 to 0.7 enables the increase by 20.4 % of the value of the force, which can be taken up by the cable. The value of the force corresponds to 0.95 % value of the strain. Modulus of elasticity of the cable grows from $1.25 \cdot 10^5$ to $1.57 \cdot 10^5$ MPa at the same time.

The dependence of strain ε on the force N, acting in the cable, for hybrid composite cable on the base of steel, GFRP and

Vectran (Figure 4) illustrates, that increase of the volume fraction of steel from 0.1 to 0.7, increases by 1.63 times the value of the force, which can be taken up by the cable. Modulus of elasticity of the cable grows from $0.94 \cdot 10^5$ to $1.53 \cdot 10^5$ MPa at the same time.

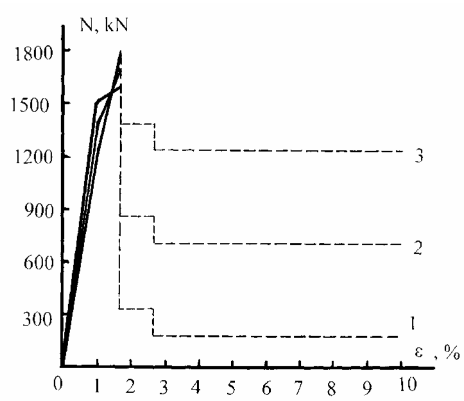

Fig. 3. Strain of hybrid composite cable on the base of steel, GFRP and CFRP ε vs. the force N, acting in the cable: 1,2,3 – the dependences, which were obtained at volume fractions of steel, equal to 0.1; 0.4; 0.7, respectively; (_____) − stage, when all the components of the cables work commonly; (------) − stage, when some components are disrupted.

The dependence of strain *ε* on the force *N*, acting in the cable, for the hybrid composite cable on the base of steel, vectran and CFRP has a property, which is analogous to the dependences shown in Figure 3 and Figure 4.

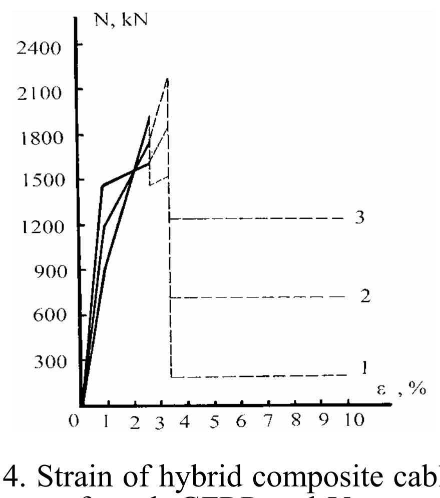

Fig. 4. Strain of hybrid composite cable on the base of steel, GFRP and Vectran ε vs. the force N, acting in the cable: 1,2,3 – the dependences, which were obtained at volume fractions of steel, equal to 0.1; 0.4; 0.7, respectively; (_____) − stage, when all the components of the cables work commonly; (------) − stage, when some components are disrupted.

The value of force, which can be taken up by the cable, changes from 1212.5 kN to 1517.8 kN, when the volume fraction of steel changes from 0.1 to 0.7. Modulus of elasticity of the cable grows from $1.27 \cdot 10^5$ to $1.6 \cdot 10^5$ MPa at the same time.

Comparison of the dependences of strain *ε* on the force *N* for three variants of hybrid composite cables indicates, that maximum strain (2.64%) without any components disruption possesses a variant on the base of steel, GFRP and Vectran. But the value of the force, which can be taken up by the cable, is a minimum for all the variants and equals to 1453.6 kN.

3.2 Evaluation of mechanical properties of cladding element

Modulus of elasticity of cladding element and the tensile strengths in warp and weft directions were considered as the main mechanical properties. Mechanical properties of cladding elements were determined basing on the assumption, that the properties are mainly determined by the characteristics of the base fabric.

Base fabrics are generally woven ones obtained by inserting weft yarns between two layers of warp yarns at 90º to the warp yarns, following a construction designed by the number of yarns per cm and weave pattern. The weave patterns used in considered cladding element is basket weave. The considered cladding element has the following parameters: thickness 1.1 mm, reinforcing ratio 0.45 and surface weight 1720 g/m^2. Cladding element was prestressed in warp and weft directions by the forces at 0.04 and 0.045 from tension strength of fabric, respectively.

Tensile strength of fabrics are equal to 105/90 kN/m in warp and weft directions. Initial moduli of elasticity of fabric are equal to 50.8/39.0 GPa in warp and weft directions respectively at the same time.

4. EXAMPLE OF APPLICATION OF COMPOSITE MATERIALS IN SADDLE-SHAPED CABLE ROOF

Hybrid composite cable on the base of steel, CFRP, GFRP and Vectran was considered as a material for the tension and main diagonal suspension cables of the saddle shaped cable roof since characteristics of the cables have significant influence on the compliance of the structure [9]. The cable roof was square in plan with dimensions 50x50 m. The initial deflections of the suspension, stressing and tension cables were equal to 20 and 8.6 m, respectively. The distance between the suspension and stressing cables was equal to 1.414 m [9].

The structure was calculated for the basic combination of loads (1.39 kPa) – the dead weight of the structure and the weight of snow – evenly distributed on the horizontal projection of the roof. The design load in the form of point wise forces was applied to the nodes of the cable net.

The maximum vertical displacements of the cable roof were determined by the computer program "ANSYS/ED 5.3". The existence of two symmetry planes allows us to regard, as a design scheme, a quarter of the cable net of the saddle-shaped cable roof with a compliant supporting contour. Three quarters of the cable roof were replaced by the bonds imposed on its one-quarter part. The cable net was modeled by the finite element of LINK 10 type, with three degree of freedom for each node. Steel cables with an elastic modulus of $1.3 \cdot 10^5$ MPa were assumed as a material for the suspension and stressing cables, excluding the main diagonal ones.

The dependences of the maximum vertical displacements of the cable net on the volume fraction of the steel component in the hybrid composite cables were obtained (Figure 5).

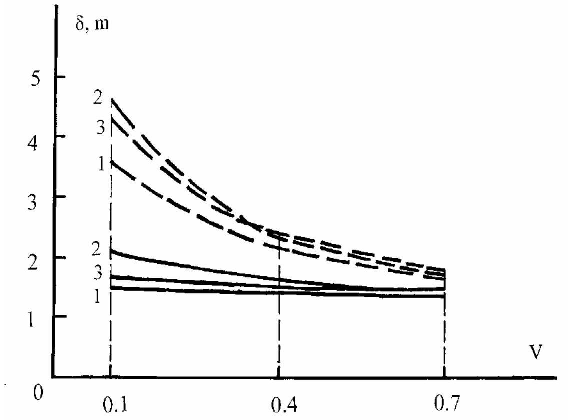

Fig. 5. Dependence of the maximum vertical displacements of the cable roof δ on the volume fraction of steel in hybrid composite cables V: 1 − variant on the base of steel, GFRP and CFRP; 2 − variant on the base of steel, GFRP and Vectran; 3 − variant on the base of steel, Vectran and CFRP; (_____) − stage, when all the components of the cables work commonly; (------) − stage, when all the components, excluding the steel, are disrupted.

In the case, when all the components of the hybrid composite cable work commonly, the increase of volume fraction of the steel from 0.1 to 0.7 causes the decrease of the maximum vertical displacements of the cable roof by 9.31 and 8 % for the variants, when the hybrid composite cable is on the base of steel, GFRP and CFRP, steel, GFRP and Vectran and steel, Vectran and CFRP, respectively.

In the case, when all the components, excluding the steel, are disrupted, the increase of volume fraction of the steel from 0.1 to 0.7 causes decrease of the maximum vertical displacements of the cable roof by 2.21, 2.78 and 2.46 times for the variants, when hybrid composite cable is on the base of steel, GFRP and CFRP, steel, GFRP and Vectran and steel, Vectran and CFRP, respectively.

Maximum vertical displacements of the cable roof are equal to 4.562 m. The value is 1.9 times less, than the distance up to the surface of the ground. But in the case of using of tensioned cladding element on the base of PTFE copolymer foil, reinforced by the Vectran fabric, the maximum vertical displacements are equal to 3.923 m. So, we can suppose that the steel component of hybrid composite cable can prevent failure of the cable roof in emergency, when the strain of CFRP, Vectran and GFRP exceeds the ultimate values and these components are disrupted. The using of CFRP, GFRP and Vectran components enables to decrease the dead weight of the cables by 44 – 47 % when the volume fraction of steel is equal to 0.4 at the same time.

5. CONCLUSIONS

Hybrid composite cables on the base of steel, GFRP, CFRP and Vectran, which differ by the components and volume fractions, were considered.

It was stated that the increase of volume fraction of the steel from 0.1 to 0.7 causes the decrease of the maximum vertical displacements of the cable roof by 9.31 and 8% for the variants, when the hybrid composite cable is on the base of steel, GFRP and CFRP, steel, GFRP and Vectran and steel, Vectran and CFRP, respectively.

The using of CFRP, GFRP and Vectran components enables to decrease the dead weight of the cables by 44 – 47 % in comparison with the steel ones.

It was shown that the using of tensioned cladding element on the base of PoliTetraFluoroEthylene (PTFE) copolymer foil, reinforced by the Vectran fabric, enables to increase mobility and decrease up to 1720 g/cm^2 the dead weight of cladding of the saddle shaped cable roof.

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