EVALUATION OF MECHANICAL INTERACTION BETWEEN COMPONENTS IN HYBRID COMPOSITE CABLE
MEHĀNISKĀS MIJIEDARBĪBAS NOVĒRTĒŠANA STARP HIBRĪDAS KOMPOZĪTAS VANTS SASTĀVDAĻĀM

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1. Introduction

Hybrid composite cable with increased breaking elongation and low creep at tension on the base of carbon and steel could be used in the prestressed cable nets [1].

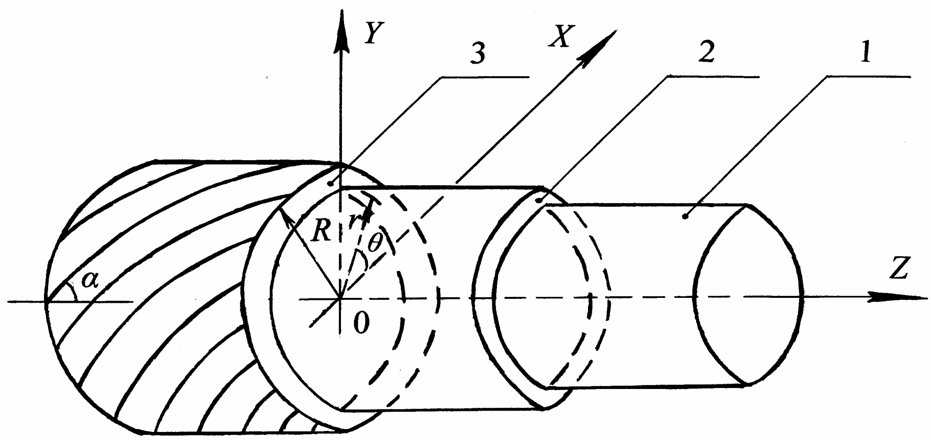

Fig.1. Scheme of hybrid composite cable made of steel, CFCC and GFRP with the cylindrical coordinates system: 1 – CFCC core; 2 – GFRP distributional layer; 3 – steel wire; α – angle of steel wire strands twisting; R – radius of the cable; Z, θ, r – cylindrical coordinates; X – horizontal axis, from which positive direction angle θ is counted; Y – vertical axis.

Hybrid composite cable contains of three layers: carbon fiber composite cable (CFCC) core, glass fiber reinforced plastic (GFRP) distributional layer and steel wire strands. All layers of hybrid composite cable participate in the taking up of tension stresses, acting in the cable during exploitation. But GFRP also distributes perpendicular to the direction of axial force action (axis Z) pressure of steel wire strands at the surface of CFCC core. This pressure has significant value and should be taken into account during the cable design [2].
Perpendicular to the direction of axial force action pressure causes radial and tangential stresses in GFRP and CFCC.
So, the purpose of this study is to evaluate perpendicular to the direction of axial force action pressure of steel wire strands at GFRP distributional layer and that of GFRP distributional layer at the CFCC core in the hybrid composite cable. Radial and tangential stresses in the

GFRP and CFCC also should be determined and compared with compression strengths of the GFRP and CFCC.

2. Approach to the solution of the problem

Evaluation of pressures between steel wire strands, GFRP distributional layer and CFCC core as well as radial and tangential stresses, acting in the GFRP distributional layer and CFCC core of hybrid composite cable was conducted for the tension cable of saddle shape cable roof. The tension cable takes up tension force *N*, acting in the cable during exploitation. Each component of the cable takes up a part of the axial force *N* depending on the value of its modulus of elasticity and volume fraction.

Hybrid composite cable is considered as a system of two cylinders (see Fig.2). Steel wire strands are replaced by the external pressure p_b per unit of external surface area of the GFRP distributional layer.

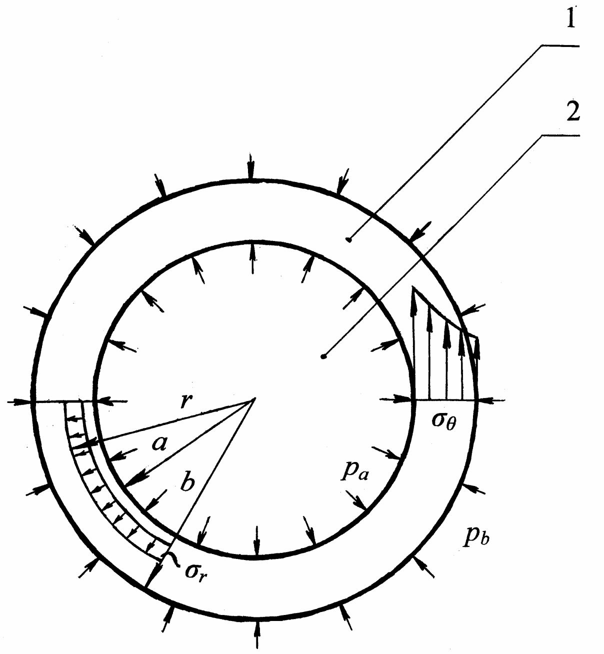

Fig.2 Scheme for determination of pressure at the CFCC core of hybrid composite cable: 1 – GFRP distributional layer; 2 – CFCC core; σ_r – radial stresses; σ_θ – tangential stresses; p_b – external pressure per unit of the surface area of the GFRP (due to the pressure of steel wire strands); p_a – external pressure per unit of the surface area of the CFCC (due to the pressure of GFRP); *a* – radius of the CFCC core of the cable and internal radius of GFRP distributional layer; *b* – external radius of the GFRP distributional layer; other designations as in Fig.1.

The GFRP distributional layer is considered as a hollow cylinder inside which another cylinder, i.e., CFCC core is situated. The GFRP distributional layer has constant internal and external radiuses: *a* and *b*, respectively. The CFCC core has constant external radius, which is equal to *a*.

Interaction between the GFRP distributional layer and CFCC core is considered as a pressure p_a at the unit of the surface area of the CFCC core or at the unit of internal surface area of the GFRP distributional layer.

Pressure p_b at the unit of external surface area of the CFRP distributional layer could be determined by the following equation [2]:

$$p_b = -\frac{ntg^2\alpha}{2\pi aR}, \quad (1)$$

where: n – part of axial force N, which takes up steel wire strands of the cable; α – angle of steel wire strands twisting; a – radius of the CFCC core; R – radius of the cable.

The equation (1) was obtained for the case, when GFRP distributional layer limits the displacements of the steel wire strands in the radial direction.
Pressure p_a per unit of the surface area of the CFCC core and per unit of internal surface area of the GFRP distributional layer could be determined by the equation (2). The equation (2) is obtained due to the equal radial deformations of CFCC core and GFRP distributional layer [3]:

$$\frac{1-\nu_{Grz}}{E_{Gr}}\frac{p_a a^2 - p_b b^2}{b^2 - a^2} r + \frac{1+\nu_{Grz}}{E_{Gr}}\frac{a^2 b^2 (p_b - p_a)}{(b^2 - a^2) r} + \delta_{Gr} = \frac{1-\nu_{Crz}}{E_{Cr}} p_a r + \delta_{Cr}, \quad (2)$$

where: E_{Gr} , E_{Cr} – modulus of elasticity for GFRP and CFCC, respectively, in the radial directions; r – coordinate of the point, where deformations are determined; ν_{Grz} – Poisson's ratio of GFRP; ν_{Crz} – Poisson's ratio of CFCC; a – radius of the CFCC core of the cable and internal radius of GFRP distributional layer; b – external radius of the GFRP distributional layer; δ_{Gr} – radial deformations of GFRP due to the part of axial force, acting in the GFRP component of the cable; δ_{Cr} – radial deformations of CFCC due to the part of axial force, acting in the CFCC component of the cable.

The left and right parts of the equation (2) are radial deformations of GFRP and CFCC components, respectively, due to the pressures p_b and p_a. Radial deformations of GFRP and CFCC components δ_{Gr} and δ_{Cr} due to the parts of axial force, acting in the components also are taken into account. Values of radial deformations of GFRP and CFCC components δ_{Gr} and δ_{Cr} were determined basing on the consumption that components work in the elastic stage.
Radial and tangential stresses act in the GFRP and CFCC due to the pressure p_b. The values of radial and tangential stresses could be determined by the equations, which were obtained for the cylinder with the hole in the center, which is loaded by uniformly distributed by the internal and external surfaces pressures p_a and p_b, respectively [2]. The values of radial and tangential stresses acting in the GFRP component of the hybrid composite cable could be determined by the following equations:

$$\sigma_{Gr} = \frac{a^2 b^2 (p_b - p_a)}{(b^2 - a^2)}\frac{1}{r^2} + \frac{p_a a^2 - p_b b^2}{b^2 - a^2}, \quad (3)$$

$$\sigma_{G\theta} = -\frac{a^2 b^2 (p_b - p_a)}{(b^2 - a^2)}\frac{1}{r^2} + \frac{p_a a^2 - p_b b^2}{b^2 - a^2}, \quad (4)$$

where: σ_{Gr} and $\sigma_{G\theta}$ – stresses acting in the GFRP component of hybrid composite cable in the radial and tangential directions.

For determination of radial and tangential stresses acting in the CFCC component of the hybrid composite cable the following equation could be used:

$$\sigma_{Cr} = -p_a = \sigma_{C\theta}, \tag{5}$$

where: σ_{Cr} and $\sigma_{C\theta}$ – stresses acting in the GFRP component of hybrid composite cable in the radial and tangential directions.

Equation (5) was obtained from the equations (3) and (4) when the internal radius of the cylinder (CFCC core) is equal to zero, external radius of the cylinder is equal to a, and external pressure per unit of the surface area of the CFCC (due to the pressure of GFRP) is equal to p_a.

3. Determination of pressures on the components of hybrid composite cables

The dependence of pressure at the CFCC core of hybrid composite cable on the axial force N and angle of wire twisting α was developed by the example of tension cable of saddle shape cable roof with dimensions in plan 30x30m.
Cable, which is loaded by the uniformly distributed load, is considered as a scheme for analysis. The cable has rational from the point of view of materials consumption initial deflection
f_1 = 5,7 m. The uniformly distributed load with intensity q = 21 kN/m loads the cable. Mechanical properties of hybrid composite cable components are given in Table 1 [4,5].

Table 1. Mechanical properties of hybrid composite cable components

Components of hybrid composite cable	E_z, MPa	ν_{zr}	R_{uz}, MPa	E_r, MPa	ν_{rz}	R_{tr}, MPa
Steel wire strand	130000	0,3	1568	–	–	–
GFRP	75000	0,19	1765	9200	0,05	78
CFCC	137000	0,3	1000	8670	0,014	186

In Table 1 R_{uz} are the limits of strengths of components in the direction Z; R_{tr} are the compression strengths of components in the radial direction.

The values of moduli of elasticity correspond to the elastic stages of the materials work. Volume fractions of fibers in GFRP and CFCC are 0,6. The fibers are oriented in the direction of axial force action [4,5].
Volume fractions of steel wire, GFRP and CFCC are 0,4 ; 0,2 and 0,4, respectively. Total area of cross sections for hybrid composite cable was equal to 0,00097 m^2.
The value of the axial force N, acting in the cable due to the uniformly distributed load, could be determined by the equations of cable calculation without taking into account elastic elongation of the cable [6].

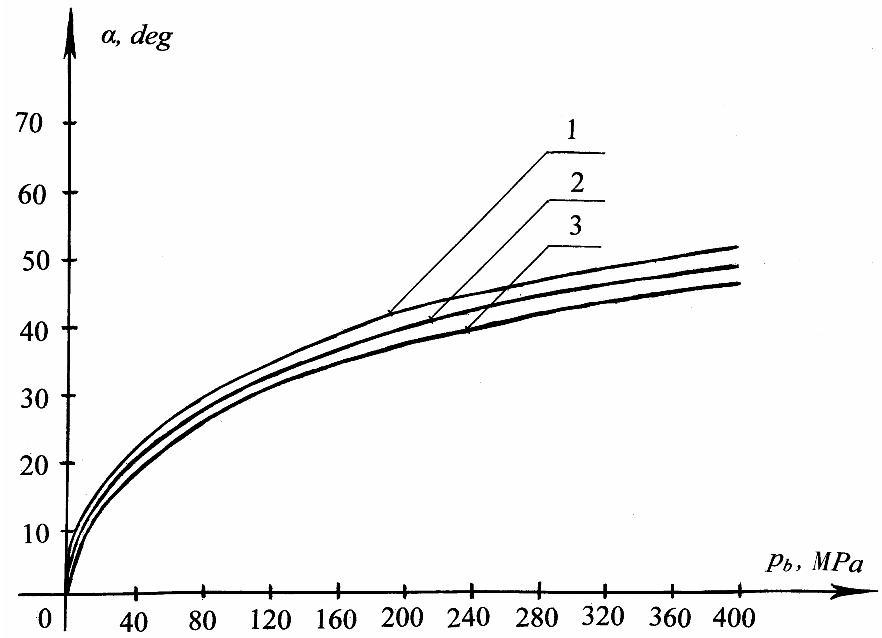

Fig.3 Dependences of pressure p_b on the angle of steel wire strands twisting α: 1– dependence, which is obtained at N = 750 kN; 2 – dependence, which is obtained at N = 650 kN; 3 – dependence which is obtained at N = 550 kN.

The dependences of pressure, which acts in the direction that is perpendicular to the direction of axial force action, at the GFRP distributional layer of hybrid composite cable p_b on the axial force N and angle of steel wire strands twisting α were developed when the angle α changes from10 to 70 degrees (see Fig.3). The value of axial force N changes from 550 to 750 kN.
The dependence of pressure p_a on the axial force N and angle of steel wire strands twisting α is shown in Fig.4.

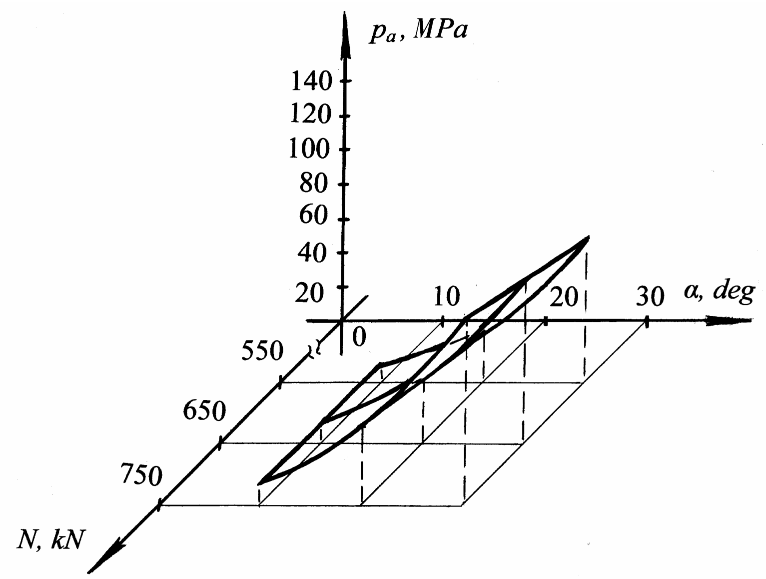

Fig.4 Dependence of pressure p_a on the axial force N and angle of steel wire strands twisting α.

The value of angle of steel wire twisting α was taken within the limits of 10 to 30 degrees because its increasing over 30 degrees causes quick growing of external pressure per unit of GFRP area (see Fig.3).
The value of the axial force N, acting in the cable, changes within the limits of 550 to 750 kN. The following values of the axial forces are considered because with the growing of the axial force value exceeding 750kN, the GFRP component of the cable is excluded from the work [1]. Each component of the cable takes up part of the force N depending on the area and modulus of elasticity.
The dependences, which are shown in Fig.4 illustrate, that the angle of the steel wire strands twisting α is the most significant factor, which influences the external pressure per each unit of the surface area of the GFRP (due to the pressure of steel wire strands) p_b.

4. Determination of radial and tangential stresses, acting in the components of hybrid composite cable

The dependence of maximum radial σ_{Gr} and tangential stresses $\sigma_{G\theta}$, acting in the CFCC component of the hybrid composite cable on the axial force N is shown in Fig.5.
The values of the radial and tangential stresses are equal for the CFCC component of hybrid composite cable.
Maximum value of the radial and tangential stresses in the CFCC and GFRP components of hybrid composite cable were obtained, when the value of axial force was equal to750 kN and angle of the steel wire strands twisting α was 30 degrees.

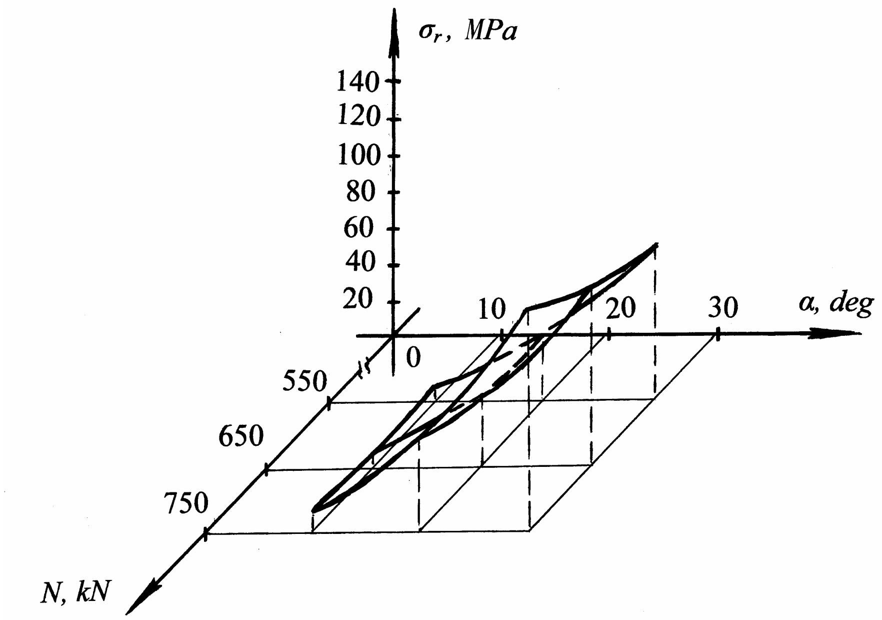

Fig.5 Dependence of the radial σ_{Gr} and tangential $\sigma_{G\theta}$ stresses acting in the CFCC on the pressure p_a and angle of steel wire strands twisting α.

Comparison of the maximum radial stresses, acting in the CFCC components of the hybrid composite cable with their strengths shows, that the stresses are 1,65 times less, than the strength values, but the maximum value of tangential stresses are 13,79 times less, than the strength value. Maximum values of radial stresses were compared with the compression strength of CFCC in the direction perpendicular to the direction of fiber orientation, which is equal to 186 MPa [5]. Tangential stresses were compared with the compression strength of

CFCC in the direction corresponding to the direction of fiber orientation, which is equal to 1558 MPa [5].
The maximum values of radial σ_{Gr} and tangential $\sigma_{G\theta}$ stresses acting in the GFRP component of hybrid composite cable are given in Table 2 in depending on the angle of steel wire strands twisting α. The maximum values of radial and tangential stresses were obtained when the axial force N, acting in the cable, was equal to 750 kN and $r = a$.

Table 2 Maximum radial and tangential stresses, acting in the GFRP component of hybrid composite cable

Angle of steel wire strands twisting α, degrees.	σ_{Gr} , MPa.	$\sigma_{G\theta}$, MPa.
10	10,77	21,29
20	45,02	44,85
30	114,81	93,32

Comparison of the maximum tangential stresses, acting in the GFRP components of the hybrid composite cable with their strengths shows, that the stresses are 5,25 times less than the strengths values. Maximum radial stresses are 1,47 times bigger than the strength value. So, the maximum angle of steel wire twisting for the considered case is 20 degrees, when the radial stresses are equal to 45,02 MPa, which are 1,73 times less than the strength value.
Radial stresses were compared with the compression strength of GFRP in the direction perpendicular to the direction of fiber orientation, which is equal to 78 MPa [4]. Tangential stresses were compared with the compression strength of CFCC in the direction corresponding to the direction of fiber orientation, which is equal to 490 MPa [4].

5. Conclusions

The dependence of external pressure per unit of the surface area of the GFRP (due to the pressure of steel wire strands) p_b of hybrid composite cable on the axial force N and angle of steel wire strands twisting α was obtained.
It was shown, that increasing of angle of wire twisting α from 10 to 30 degrees causes growing of external pressure per unit of the area of CFCC by 14,61 times when the axial force increases from the 550 to 750 kN.
Tangential and radial stresses for GFRP and CFCC components of hybrid composite cable were obtained. It was shown, that the maximum angle of steel wire strands twisting α is equal to 20 degrees for the considered hybrid composite cable.
It was shown, that maximum radial stresses σ_{Gr} acting in the GFRP component of hybrid composite cable, when the angle of the steel wire twisting α was equal to 20 degrees, and the axial force N was equal to 750 kN, was 1,73 times less than the strengths of GFRP.

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Serdjuks D., Rocēns K. Mehāniskās mijiedarbības novērtēšana starp hibrīdas kompozītas vants sastāvdaļām.
Izmantojot inženieraprēķina metodes, analizēts spriegumstāvoklis hibrīdas kompozītas vants sastāvdaļās, kas sastāv no tērauda, stiklaplasta un ogļekļaplasta. Hibrīdās kompozītās vants katra komponente saņem daļu no stiepes garenspēka atkarībā no elastības moduļa un tilpuma frakcijas lieluma.
Noteikti radiālie un tangenciālie spriegumi vants komponentēs, (tērauda stieplēs, stiklaplastā un ogļēkļaplastā) gadījumam, ja tā kalpo par stiepto atbalsta kontūru sedlveida pārsegumam ar izmēriem plānā 30x30 m, un 40% no vants šķērsgriezuma laukuma ir ogļekļaplasts, 20 % - stiklaplasts, 40% - tērauda stieples.
Konkrētajos apstākļos ir noteikts tērauda stieples maksimālais pinuma leņkis.

Serdjuks D., Rocens K. Evaluation of mechanical interaction between components in hybrid composite cable.
Mechanical interaction between components in hybrid composite cable on the base of steel, glass fiber reinforced plastic and carbon fiber composite cable is considered in the paper. Each component of hybrid composite cable takes part of the axial force depending of the value of its modulus of elasticity and volume fraction.
Evaluation of the pressure between components of hybrid composite cable, radial and tangential stresses, acting in the glass fiber reinforced plastic and carbon fiber composite cable components was conducted for the tension cable of the saddle shape cable roof with dimensions 30x30 m. The volume fractions for the components are 0,4;0,2;0,4 for steel, glass fiber reinforced plastic and carbon fiber composite cable respectively.
Maximum available angle of the steel wire twisting was determined.

Сердюк Д., Роценс К. Оценка механического взаимодействия между компонентами в гибридной композитной ванте.
В статье рассматривается механическое взаимодействие между компонентами в гибридной композитной ванте, выполненной из стали, стеклопластика и углепластика. Каждая компонента гибридной композитной ванты воспринимает часть растягивающей продольной силы в зависимости от модуля упругости и объемной фракции.
Оценка давления между компонентами вследствие действия продольной силы, а так же радиальных и тангенциальных напряжений, действующих в стеклопластиковой и углепластиковой компонентах гибридной композитной ванты, произведена для контурной ванты квадратного в плане седловидного вантового покрытия с размером 30x30 м. Объемные фракции компонентов составили 0,4;0,2;0,4 для стали, стеклопластика и углепластика соответственно.
Установлен максимальный для данных условий угол свивки прядей стальной проволоки.