EFFECT OF THE TYPE OF SUBSTRUCTURE ON CABLE MATERIAL CONSUMPTION

Leonids Pakrastinsh[1], Karlis Rocens[2] and Dmitrijs Serduks[3]

Institute of Structural Engineering and Reconstruction, Riga Technical University,
Azenes Str. 16, Riga LV-1048, Latvia
[1]leonidp@latnet.lv [2]rocensk@latnet.lv [2]dmitrijs@bf.rtut.lv

Abstract. The recently developed Hierarchic Cable Roofs open the opportunities to cover extremely large areas comparing with ordinary structures due to effective use of structural materials with much higher specific strength in combinations with structural systems, where tensile stresses are dominant in their cross-sections, and these structures have a better correlation between the volume and roofed area. The overall material consumption is seriously dependent on structure of the primary repeatable unit which can be made as negative Gaussian bent cable net. The possibility of cable roofs covering with textile-reinforced woven fabric and multiaxially reinforced films based on liquid crystal polymer fibers with regularly oriented aromatic polyester molecules (LCP) was analysed. The main mechanical properties of cladding element based on LCP Vectra basket weave fabric which is covered by the PTFE was evaluated by the engineering approach. Based on two developed calculation models the stress and deformation state of cladding element was evaluated by applying vertical loading as most unfavourable. These models describe the extreme observations of real behavior of cladding, which can be in intermediate position: the first – without any shear stiffness, the second – with full membrane shear stiffness. By applicating of these models the rational steps of load bearing and stressing cables of main structure depending on the constructive conditions in the prevention of rain bags were found. Using the method of substructuring allows to estimate how the type of cladding affects the displacements and material consumption of the whole structures.

Keywords: cable net, hierarchic structures, prestressed fabric, multiaxially reinforced films, LCP, substructuring.

1. Introduction

The recently developed Hierarchic Cable Roofs [1] open the opportunities to cover extremely large areas comparing with ordinary structures due to effective use of structural materials with much higher specific strength in combinations with structural systems, where tensile stresses are dominant in their cross-sections, and these structures have a better correlation between the volume and roofed area. From a constructional point of view, most perspective and most expressive (regarding architectonical aspect), is a pre-stressed cable net with negative Gaussian curvature saddle-shaped hyperbolic surface with a compliant supporting contour known as an anticlastic form covered with reinforced cladding, which is characteristic by kinematic rigidity and smaller deformability under exposure to external loading.

Based on previously accomplished investigations [2-5], it is shown that the ratio between the roofed volume and the area is unacceptable at larger spans as it causes an inexpedient increase of the heated volume. This problem can be solved by application of the saddle – shaped roofing with the compliant supporting contour as standard elements, and by suspending their corners to a higher level cable structure thus obtaining a hierarchic, inter-subordinated large–span cable roofing (Fig.1).

Primary elements of a hierarchic structural square in plan module 4x4 may be combined thus producing larger roofed areas. To reduce the total height of structures, the upper part can be lowered below the level of primary elements, and at the same time lifting the corners of the primary elements by means of vertical latticed post fixed to these cables.

The overall material consumption is seriously dependent on structure of the primary repeatable unit which can be made as negative Gaussian bent cable net. The possibility of cable roofs covering with textile-reinforced woven fabric or multiaxially reinforced films based on liquid crystal polymer with regularly oriented aromatic polyester molecules (LCP) was analysed.

However, the application of this new material requires the knowledge of its mechanical characteristics, in particular, the directional-dependent stiffness and strength, especially in the case of woven fabric.

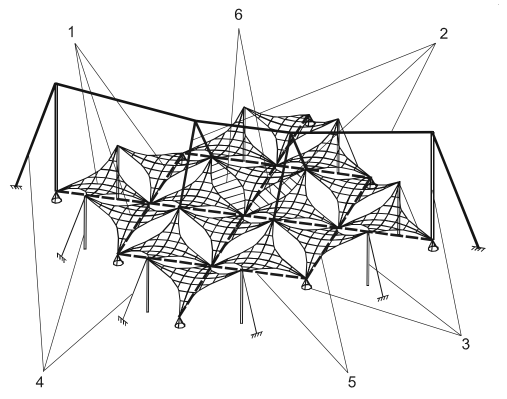

Fig.1. Simplified variant of hierarchic cable structures with slope suspenders.
1 – primary saddle shape elements; 2 – higher level cable structure; 3 – supports; 4 – guy-ropes; 5 – bottom level tie net; 6 – cable trusses.
*Cable trusses for all primary elements have not been conventionally displayed

Cable roofs can be divided into the groups depending on the type of cladding. These can be rigid elements working at bending. Reinforced concrete slabs, profiled metal sheets, several types of composites that are the examples of rigid elements for cable roofs cladding. Such elements mainly are used for the permanent structures and are characterized by the comparably large materials consumption. Tensioned fabric and multiaxially reinforced films are other types of cladding for cable roofs and membrane structures (Fig.2).

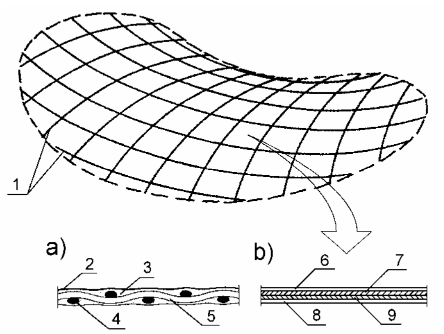

Fig.2. Typical section of cladding of the cable net
a) woven fabric; b) multiaxially reinforced film.
1 – cable net; 2 – laqueering; 3 – coating; 4 – warp threads; 5 – weft threads; 6,7,8,9 – 0/+45/-45/90° oriented layers.

Tensioned fabrics can be coated or uncoated. Uncoated fabrics have short service lives and their applications is limited by the temporary membrane and cable structures. Coating a fabric gives the following benefits:

- protecting the yarns against different sources of damages (UV, abrasion, atmosphere);
- proofing the membrane against rainwater and atmospheric moisture;
- stabilizing what might otherwise be an unstable fabric geometry;
- providing material to permit heat-sealed seams.

More precisely a membrane consists of different layers combined with the fabric: a prime coat, a top coat and a surface treatment for sealing or painting as shown in Fig.1 [6]. Tensioned fabrics are used for permanent or temporary cable and membrane structures and enable to decrease materials consumption in comparison with the rigid elements of the cladding.

Almost all permanent fabric structures built today are entirely synthetic. The most common fibers used for the membranes and cable roofs are glass and polyester fibers. Special attention should be added to LCP (liquid crystal polymer based on aromatic polyester) yarns [6]. Using of other kinds of fibers is limited by the increased costs (carbon, kevlar fibers), increased dead weight and possibility of corrosion (metal fibers) and relatively low modulus of elasticity (cotton, hempen fibers). But glass and polyester fibers possess a number of disadvantages: Glass fibers deteriorate when exposed to moisture and polyester degrades when exposed to sunlight.

Probability of waves development at some parts of structure after design vertical load application is a serious problem for fabric claddings. Other parts of cladding can be overstrengthened in this case. Development of element of the cladding with the increased compliance and enough strength is a potential way to fix the problem together with the cladding's prestressing.

In the case of multiaxially reinforced films based on liquid crystal polymer, they have a controlled molecular orientation due to processing conditions. One embodiment includes a multi-component LCP sheet in which particles of a higher melting LCP are imbedded in a matrix of a lower melting LCP. These LCP components are formed into sheet at a temperature between the melting point of the lower melting matrix LCP and the higher melting reinforcing LCP, so that the imbedded LCP particles might maintain their shape, orientation, and mechanical characteristics while the matrix LCP component flows around the particles and forms a solid sheet. In another embodiment, LCP particles are melt consolidated to form a single article in which a significant amount of LCP orientation is retained. A sheet of this invention may be formed by a variety of processes, and may be made from recycled scrap LCP. Due to the particular molecular structure of thermotropic liquid crystal polymers, LCP film can be molecularly oriented in the melt phase. After the extruded LCP cools and solidifies, the molecular orientation is maintained [7].

One main consequence of this morphology is that the structure and properties of the material are highly anisotropic. The morphology is crudely similar to that of a fiber reinforced polymer, but where the reinforcement is oriented molecules of the matrix material; they are often called self-reinforcing polymers (SRP) as a result. Design approaches based on the use of fiber reinforced polymers (FRP) can be applied, up to a point, to SRP's.

The aim of the investigation is to develop element of cladding for the cable roofs with the increased compliance and enough strength. Behavior of the element after design vertical load application should be investigated.

2. Characteristics of materials for tensioned claddings

Fabrics can be divided into the following groups depending on the type of yarns [8]:

- organic (cotton, hempen);
- mineral (glass, carbon);
- metal (steel, copper, bronze);
- synthetic (polyamide, polyester, acryl, kevlar).

Ethylene-tetrafluoroethylene copolymer foils (ETFE) also have taken a special position between tensioned claddings. The main characteristics of fibers, which are initial components of tensioned fabrics, are given by [6-10] and shown in Table 1.

Table 1. The main characteristics of fibers, which are initial components of tensioned fabrics

Materials	Density g/cm^3	Strength at tension, MPa	Elongation at break, %	Modulus of elasticity, MPa
Steel	7,86	2200	1,1	210000
Bronze	8,50	320-1100	10-35	96000-120000
Aramid (Kevlar, Twaron)	1,45	till 2700	2,0-4,0	130000-150000
Carbon fibers (CFC, Celion, Carbolon, Thornel)	1,7-2,0	2000-3000	<1	200000-500000
Polyamides (Nylon, Perlon)	1,14	till 1000	15-20	5000-6000
Glass	2,55	till 3500	2,0-3,5	70000-90000
Vectra (LCP)	1,40	3200	3,3	65000
Polyesters (Trevira, Dacron, Diolen)	1,38-1,41	1000-1300	10-18	10000-15000
Ethylene and politeratftorethylene copolymer foils (ETFE, Tefzel, Dyneon)	1,70-1,76	48-234	45-650	900-3500

Fabrics on the base of materials, which are given in the Table 1. are used for the permanent fabric structures.

Vectra (LCP) yarns, as it is shown in Table 1, take intermediate position between polyester and glass ones. It means that Vectra (LCP) yarns can be used as components of tensioned fabrics for membrane and cable structures. Practical absence of creep allows us to consider Vectra (LCP) yarns as a material for prestressed structures.

Coated fabrics can be divided into the following groups depending on the type of coatings [6]:

- PVC coatings;
- PTFE coatings;
- Silicone coatings.

PTFE coatings cause the greatest interest due to the row of advantages. Since PTFE upper limit of continuous service temperature is +260 ºC it can be used in hot climatic zones. The lower limit of the continuous service temperature is -200 ºC. Temperature variations have no influence on the lifespan. PTFE has a low thermal conductivity (0,25-0,50 W/Km) and good insulating properties. PTFE under normal conditions is inflammable, and is resistant against the strongest corrosive substances. PTFE is not soluble in most common solvents.

Because of its hydrophobic properties, PTFE is an excellent protection for the textile reinforcement of the membrane. PTFE is totally resistant to UV and IR-radiation. PTFE membranes show no ageing or embrittlement due to UV/IR radiation [6].

Next will be considered cladding element on the base of Vectra (LCP) yarns and PTFE coating.

3. Evaluation of mechanical properties of woven cladding element

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 main weave patterns used in membrane are basket weave or 2-2 basket weave [6]. Next we will consider the basket weave case only.

Modulus of elasticity of cladding element both as the tensile strengths in warp and weft directions were considered as the main mechanical properties. Modulus of elasticity of cladding element in warp and weft directions were evaluated by the following equations:

$$E_{f,x} = E_1 \cos^4 \beta_x, \quad (1)$$

$$E_{f,y} = E_1 \cos^4 \beta_y, \quad (2)$$

where

$\cos \beta_x = 1 - 0.001 a_x,$

$\cos \beta_y = 1 - 0.001 a_y.$

Here $E_{f,x}$; $E_{f,y}$ - moduli of elasticity of cladding element in warp and weft directions, respectively; E_c - modulus of elasticity of PTFE coating, E_1- modulus of elasticity of separate yarn, β_x, β_y – angles of yarns inclinations in warp and weft directions, respectively, a_x, a_y- runner length (run-in) of fabric in warp and weft directions respectively.

The tensile strength of cladding element was determined on the base of the scheme [11], which is shown in Fig.3 for the basket weave case.

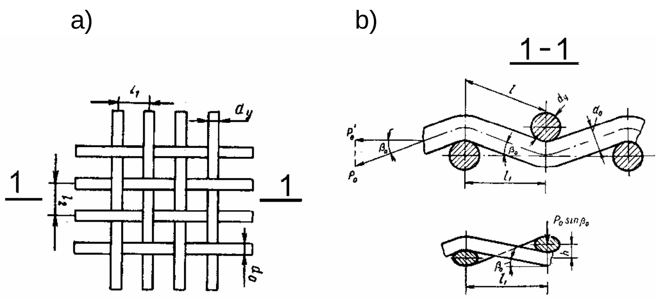

Fig.3. Scheme of tensioned fabric loading:
a) – in warp direction, b) in weft direction.
β_x- angles of yarns inclinations in warp direction.

Kvasi instantaneous tensile strength of cladding element at 1 meter length in warp and weft directions was determined by the following equations:

$$\tilde{N}_{f,x} = 0.5 K_x n_x P_x \quad (3)$$

$$\tilde{N}_{f,y} = 0.5 K_y n_y P_y \quad (4)$$

where

$$P_x = P_y = \eta_0 m_0 p_0 (1 + \frac{\nu}{\eta_0} \cos \beta_c \sin \beta_c),$$

$tg\beta_c = 0.67 \pi d_1 t_1$; $\tilde{N}_{f,x}; \tilde{N}_{f,y}$ - kvasi instantaneous tensile strength of fabric in warp and weft directions; P_x; P_y – breaking force of single yarn in warp and weft directions; K_x; K_y – coefficients of yarns strength using in warp and weft directions; n_x, n_y – amount of yarns in warp and weft directions at 1 meter; ν – friction coefficient of yarn; η_0 – non-simultaneous breaking coefficient of parallel yarns; m_0 – amount o fibers in the yarn cross section; p_0 – breaking force of single fiber; β_c – angles of fiber inclinations in the yarn; d_1– outer diameter of the yarn; t_1 – amount of twists of yarn per millimeter.

Precision of the above mentioned approach was checked by the practical example. Kvasi instantaneous tensile strengths of several types of coated fabrics, which are used for the claddings of cable and membrane structures, were determined by the equations (3) - (6). The coated fabrics are PVC coated polyester fabric, PTFE coated glass fabrics and silicone coated glass fabric. Comparison of tensile strengths of coated fabrics, which are given in [6] and determined by the equations (3) - (6) is shown in Table 2.

Table 2 Comparison of tensile strengths of coated fabrics [6]

Type of coated fabric	PVC coated polyester fabric	PTFE coated glass fabric	Silicone coated glass fabric
Tensile strength warp/weft (kN/m) by [6]	115/102	124/100	107/105
Tensile strength warp/weft(kN/m) by the equations (3)-(4)	107/97	121/109	121/109

Comparison of the results show, that maximum difference is equal to 13 %. So, the equations (3)-(6) can be used for evaluation of tensile strengths for covered fabrics. The values of tensile strength and modulus of elasticity of PTFE covered LCP fabric were determined for the case, when surface density of the fabrics changes within the limits of 800 to 1450 g/m^2. The dependence of tensile strength in warp and weft directions from the surface density of fabrics is shown in Fig.3.

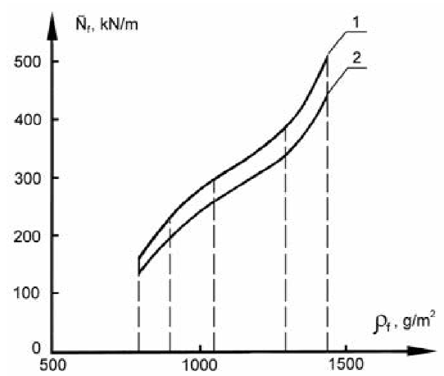

Fig.4. The dependence of tensile strength in warp and weft directions from the surface density for LCP fabrics: 1– in warp direction; 2 – in weft direction; $\tilde{N}_f$ – tensile strength of fabric; ρ_p – surface density of fabrics.

The maximum tensile strength of fabrics are equal to 512/456 kN/m in warp and weft directions respectively. Initial modulus of elasticity of fabric are equal to

50,8/39,0 GPa in warp and weft directions respectively at the same time.

4. Evaluation of stress state and deformed condition of cladding element

Evaluation of stress and deformed condition of cladding element on the base of LCP (Vectra) fabric, which is covered by the PTFE and the multiaxially reinforced LCP films were determined on the base of following structure: saddle-shaped cable roof with dimensions in plan 45x45m. The structure is formed by orthogonally crossing concave load bearing and convex stressing cables with identical Initial deflection value as 1/10 parts of the span in conformity with our previous investigations. In accordance with the literature recommendations the step of the cable net is assumed 1,77 m and identical level of prestressing for all the cables proposed, which make 22,5% from the tensile strength of cables (1/2 from the design strength). The structure is loaded by the vertical load at 1,60 kN/m^2 as most unfavourable, which consists of deadweight of structures and negative wind load with twice wind speed, which exceed by intensity the snow load values of a valid Latvian building codes.

Cladding element on the base of LCP (Vectra) fabric was modeled by two square 1,77m segment patterns between the load bearing and stressing cables, which are shown in Fig.4.

The first (Fig.5.) is considered as totality of yarns in warp and weft directions modeled by the universal nonlinear spatial cable finite element with specific bilinear stiffness matrix, which defines that the element works in tension only without bending stiffness [14]. The modulus of elasticity of yarns in warp and weft directions is assumed as determined in the previous chapter.

The second cladding element based on multiaxially reinforced (0/+45/-45/90° oriented layers) LCP films (Fig.6.) is assumed as 3-D Shell nonlinear element having membrane in-plane stiffness but no out-of-plane stiffness with tension-only options. This nonlinear option acts like a cloth materials in that tension loads are supported but compression loads will cause the element to wrinkle. The material properties for this element are assumed the same as in the first case and in-plane (XY) shear modulus is assumed as 1,7 GPa.

For each model were made two calculations with coarse and twice smaller steps of yarns (coarse and fine mesh of membrane) with accordingly adopted cross sections of elements to be satisfied that the finite element model has adequate accuracy.

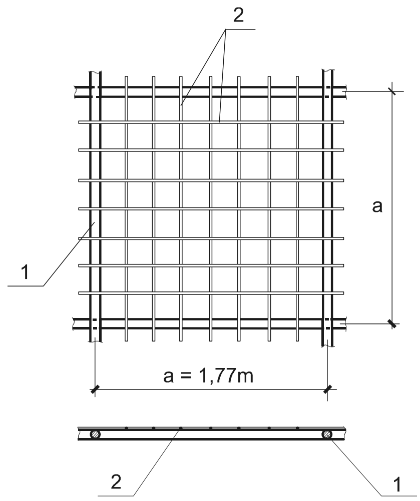

Fig.5. Woven cladding element modeled by totality of yarns
1 – steel cables of the roof (cable net); 2 – cladding element.

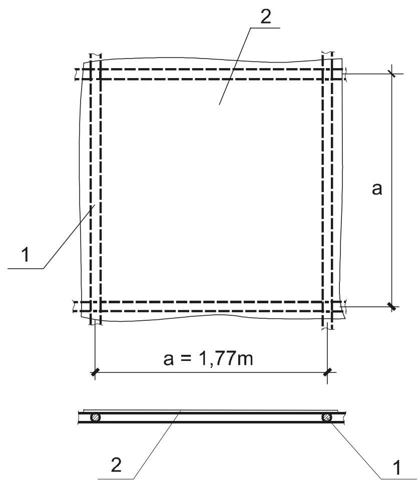

Fig.6. Multiaxially reinforced film cladding element modeled by membrane
1 – steel cables of the roof (cable net); 2 – cladding element.

The example of deformed shape for the first model is shown in Fig.7. The deformed shape of the second model is similar.

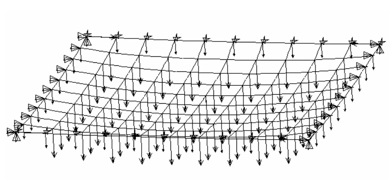

Fig.7. Deformed shape of cladding element.

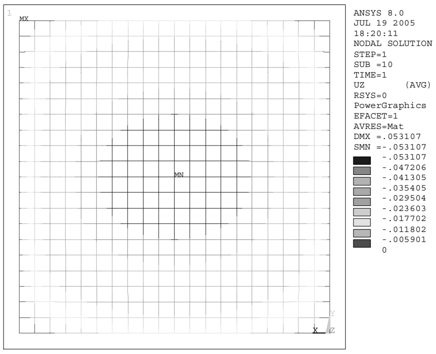

Fig.8. Vertical nodal displacements [m] of fabric cladding element modeled by totality of yarns

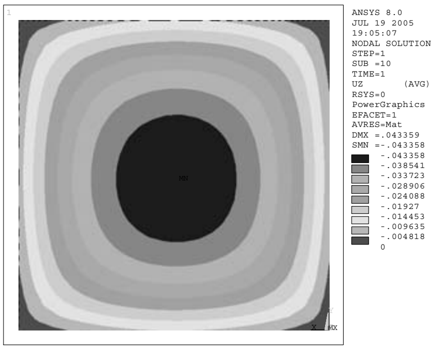

Fig.9. Vertical nodal displacements [m] of reinforced film cladding element modeled by membrane.

The strain and stress distribution examples in the multiaxially reinforced films cladding element are shown in Fig.10. and Fig.11.

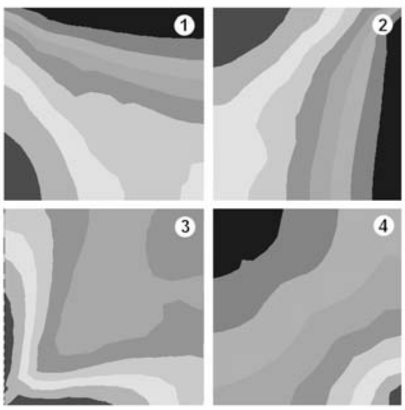

Fig.10. Strain distribution* example in the reinforced film cladding element

*The strains are given for the quarter of cladding element in the corresponding directions: 1 - ε_x; 2 - ε_y; 3 - ε_{xy}; 4 - ε_z.

These two models describe the extreme observations of real behavior of cladding, which can be in intermediate positions: the first – without any shear stiffness, the second – with full membrane shear stiffness. The calculation results show that the maximal displacements for cladding element on the base of the multiaxially reinforced LCP films with shear stiffness for examined case are by 25% smaller then ones without it.

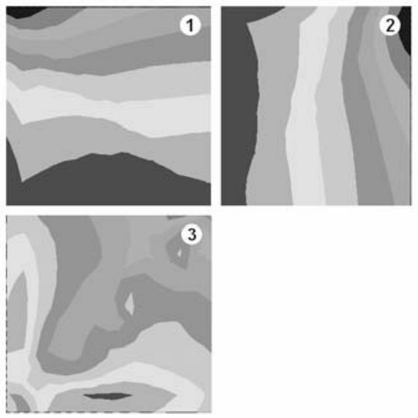

Fig.11. Stress distribution* example in the reinforced film cladding element

*The stress are given for the quarter of cladding element in the corresponding directions: 1 - σ_x; 2 - σ_y; 3 - σ_{xy}.

Also it can be mentioned, that second membrane model is more susceptible to fineness of mesh and require much more computing time comparing with first model of totality of yarns.

By using the method of substructuring was made the calculations series to estimate how the displacements of the whole structures affect the cladding stress-strain condition. For these types of structures [12,13] the vertical displacements of the cladding element are determinant. The calculations show that these displacements substantially do not affect the stress and deformed state of the cladding element.

5. Conclusions

By analysis of existent types of tensioned fabric and reinforced films claddings suitable for covering of cable roofs and membrane structures it is considered that a special attention should be given to liquid crystal polymer based on regularly oriented aromatic polyester molecules along the longitudinal direction. Practical absence of creep allows to consider that this material is very applicable as a component of tensioned fabric or multiaxially reinforced films for prestressed cable structures.

To evaluate the main mechanical properties of cladding element based on LCP basket weave fabric was made the calculations of modulus of elasticity and tensile strength of this element in warp and directions on the basis of the assumption that the properties of cladding are mainly determined by the properties of the base fabric. By using of this calculation technique the tensile stress is obtained as 512/456 kN/m and initial modulus of elasticity is 50,8/39,0 GPa in warp and weft directions, respectively.

To estimate the precision of the above-mentioned approach there was determined the tensile stress of several existent types of coated fabric and compared with experimental testing data. Comparisons show that the maximum differences do not exceed 13%.

Stress-strain state of cladding element was evaluated on the base of two developed calculation models for the case of vertical loading as most unfavorable. These models describe the extreme observations of real behavior of cladding, which can be in intermediate position: the first – without any shear stiffness, the second – with full membrane shear stiffness. The calculation results show that the maximal displacements for cladding element on the base of the multiaxially reinforced LCP films with shear stiffness for examined case are by 25% smaller then ones without it. This allows to reduce the pre-stressing reserve [12,13] and reduce the cable material consumption for overall hierarchic covering.

In the future experiments these cladding must be developed and compared with experimental testing results to obtain more accurate displacements and reliable stress. Using of multiaxially reinforced LCP films with shear stiffness allows to reduce steps of load bearing and stressing cables of main structure depending on the constructive conditions to prevent the development of rain bag, because the fabric or some other kinds of tiling in cable net structures mainly provide the transfer of external loading to the cable net.

Using of multiaxially reinforced LCP films with method of substructuring allows to estimate how the displacements of the whole structures affect the cladding stress-strain condition, that in its turn provide the chance to reduce the safety factor and accordingly reduce the material consumption and expenses of long span coverings.

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