EVALUATION OF THE BEHAVIOR OF TENSIONED COMPOSITE CLADDING ELEMENT FOR CABLE ROOFS

NOROBEŽOJOŠA STIEPTA KOMPOZĪTA ELEMENTA DARBĪBAS NOVĒRTĒŠANA VANŠU PĀRSEGUMIEM

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Keywords: tensioned fabric, large displacements, Vectra LCP.

Introduction

Cable roofs can be divided into the groups depending on the type of cladding. It can be rigid elements working at bending. Reinforced concrete slabs, profiled metal sheets, several types of composites that is the examples of rigid elements for cable roofs cladding. Such elements mainly are used for the permanent structures and are characterized by the comparably big materials consumption. Tensioned fabric is other type of cladding for cable roofs and membrane structures (Fig.1).

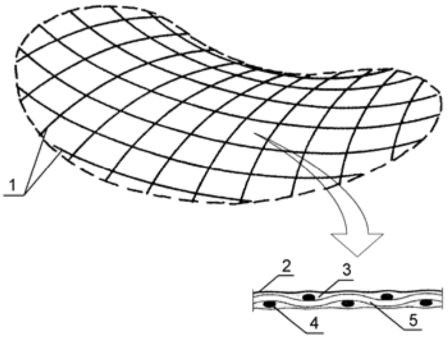

Fig.1. Typical section of cladding of the cable net..
1 – cable net; 2 – laqueering; 3 – coating; 4 – warp threads; 5 – weft threads

Tensioned fabrics can be coated or uncoated. Uncoated fabrics have short service lives and it applications is limited by the temporary membrane and cable structures. Coating a fabrics 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 the Fig.1 [1]. 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 [1]. 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 deteriorates 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 probable way to fix the problem together with the cladding's prestressing.

So, the aim of the paper 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.

Characteristics of materials for tensioned fabric claddings

Fabrics can be divided into the following groups depending on the type of yarns [2]:

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

Ethylene-tetrafluoroethylene copolymer foils (ETFE) also took a special position between tensioned claddings.

The main characteristics of fibers, which are initial components of tensioned fabrics, are given by [1-4] and shown in the 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 the 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 [1]:

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

PTFE coatings cause the biggest 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 is under normal conditions 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 embritlement due to UV/IR radiation [1].

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

Evaluation of mechanical properties of 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 [1]. Next we will consider the basket weave case only.

Modulus of elasticity of cladding element so 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:

$$E_{cf,x} = \mu_x E_{f,x} + (1-\mu_x)E_c \approx E_{f,x}, \qquad (1)$$

$$E_{cf,y} = \mu_y E_{f,y} + (1-\mu_y)E_c \approx E_{f,y}, \qquad (2)$$

where

$E_{f,x} = E_1 \cos^4 \beta_x$, $E_{f,y} = E_1 \cos^4 \beta_y$,

$\cos\beta_x = 1 - 0{,}001 a_x$, $\cos\beta_y = 1 - 0{,}001 a_y$.

Here $E_{cf,x}$; $E_{cf,y}$ - moduli of elasticity of cladding element in warp and weft directions respectively; μ_x; μ_y - volume fractions of yarns 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 [5], which is shown on Fig.2 for the basket weave case.

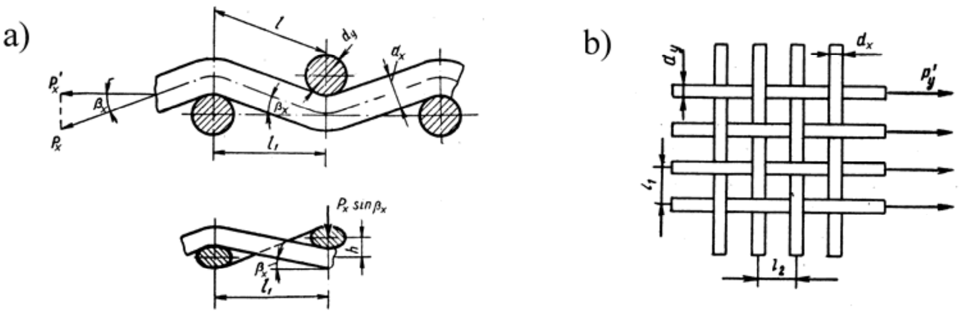

Fig.2. Scheme of tensioned fabric loading: a) – in warp direction, b) in weft direction.
β_x- angles of yarns inclinations in warp direction.

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

$$\widetilde{N}_{cf,x} = \mu_x \widetilde{N}_{f,x} + (1-\mu_x)\widetilde{N}_c \approx \widetilde{N}_{f,x}, \qquad (3)$$

$$\widetilde{N}_{cf,y} = \mu_y \widetilde{N}_{f,y} + (1-\mu_y)\widetilde{N}_c \approx \widetilde{N}_{f,y}, \qquad (4)$$

where $\widetilde{N}_{cf,x};\widetilde{N}_{cf,y}$ - kvasi instantaneous tensile strength of cladding element in warp and weft directions; $\widetilde{N}_{f,x};\widetilde{N}_{f,y}$ - kvasi instantaneous tensile strength of fabric in warp and weft directions; $\widetilde{N}_c$ - tensile strength of PTFE covering.

Kvasi instantaneous tensile strength of fabric in warp and yarn directions (kN/m) were determined by the recommendations [6] depending on the breaking force of fabric in both directions.

$$\widetilde{N}_{f,x} = 0{,}5K_x N_x P_x, \qquad (5)$$

$$\widetilde{N}_{f,y} = 0{,}5K_y N_y P_y, \qquad (6)$$

where P_x and P_y - breaking force of yarns in warp and weft directions; K_x and 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.

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 [1] and determined by the equations (3) - (6) is shown in the Table 2.

Table 2 Comparison of tensile strengths of coated fabrics [1]

Type of coated fabric	PVC coated polyester fabric	PTFE coated glass fabric	Silicone coated glass fabric
Tensile strength warp/weft (kN/m) by [1]	115/102	124/100	107/105
Tensile strength warp/weft(kN/m) by the equations (3)-(6)	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 from 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.

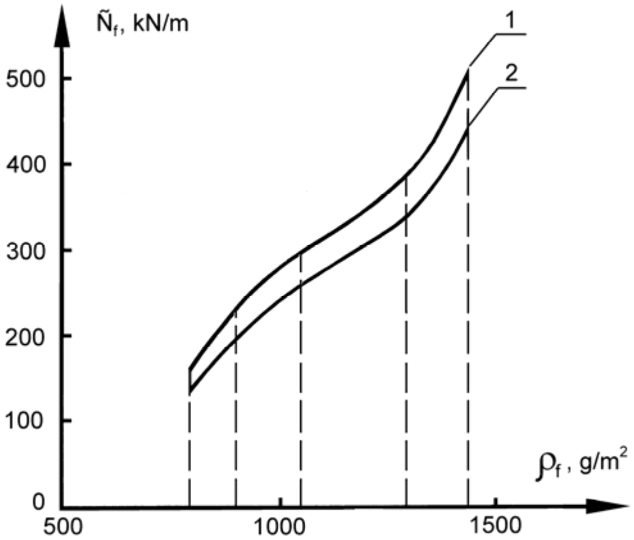

Fig.3. The dependence of tensile strength in warp and weft directions from the surface density for LCP fabrics: 1– in warp direction; 2 – in weft direction; $\tilde{N}_f$– tensile strength of fabric; ρ_p – surface density of fabrics.

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.

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 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 the 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 unfavorable, 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 was modeled by two square 1,77m segment patterns between the load bearing and stressing cables, which are shown in Fig.4. The first (a) 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 [6]. The modulus of elasticity of yarns in warp and weft directions is assumed as determined in previous chapter.

The second (b) 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 will be supported but compression loads will cause the element to wrinkle. The material properties for this elements is assumed as orthotropic accordingly warp and weft directions as determined in previous chapter and in-plane shear modulus is assumed as 1,7 GPa.

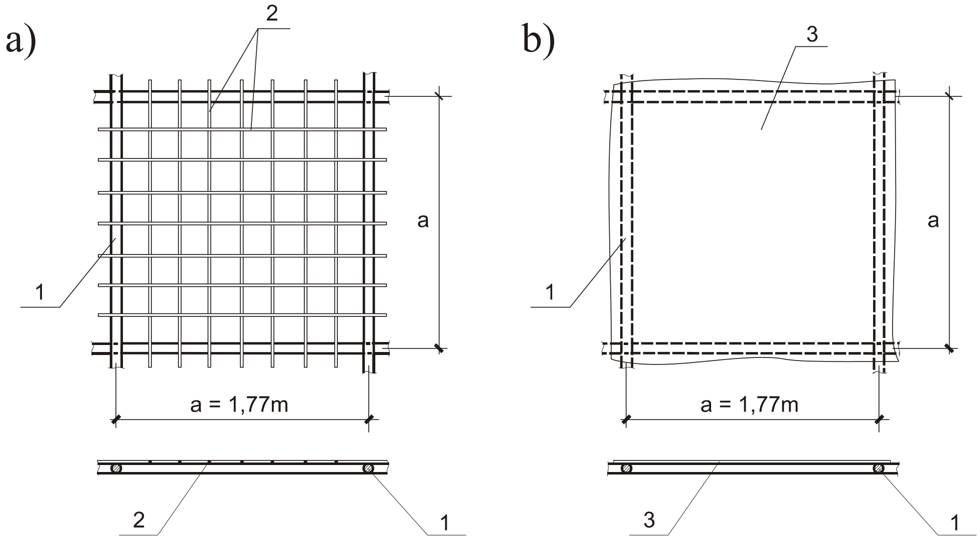

Fig.4. Models of cladding element.
1 – steel cables of the roof (cable net); 2 – cladding element modeled by totality of yarns; 3 – cladding element modeled by membrane.

For the each model was made two calculations with coarse and twice smallest 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. The example of deformed shape for the first model is shown on Fig. 5. The deformed shape of the second model is similar.

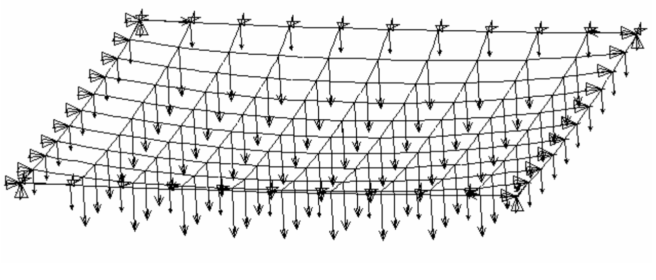

Fig.5. Deformed shape of cladding element.

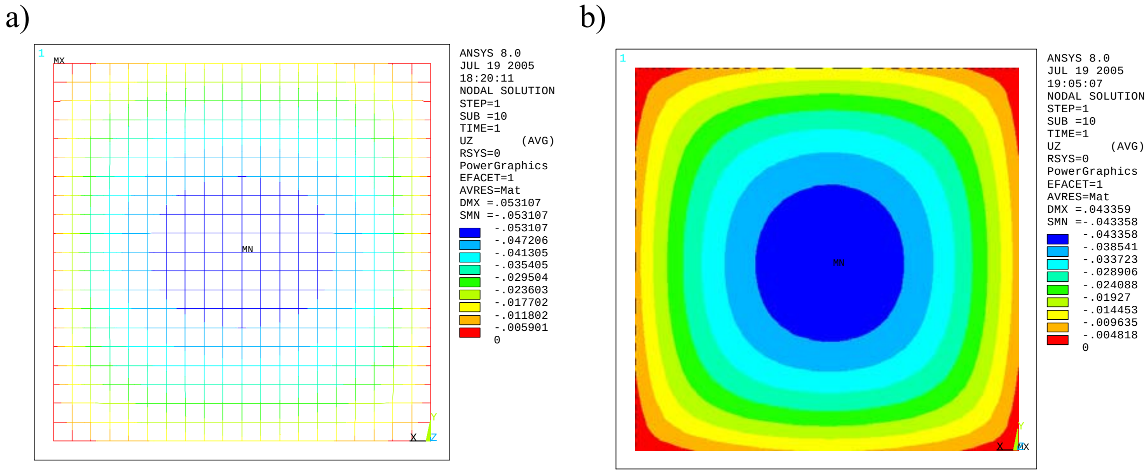

Fig.6. Vertical nodal displacements [m] of cladding element.
a) element modeled by totality of yarns; b) element modeled by membrane.

These two 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 element with shear stiffness for examined case are at 25% smaller then ones without it.
Also 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.

Conclusions

By analysis of existent types of tensioned fabric claddings suitable for covering of cable roofs and membrane structures is considered that a special attention should be given to liquid crystal polymer yarns based on regularly oriented aromatic polyester molecules along the longitudinal direction of fibers (LCP) covered by PTFE. Practical absence of creep allows to consider that this material is very applicable as component of tensioned fabric 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 on the assumption that the properties of cladding are mainly determined by the properties of the base fabric. Using these 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 above-mentioned approach was determined the tensile stress of several existent types of coated fabric and compared with experimental testing data. Comparisons show that the maximum differences not exceed 13%.
Based on two developed calculation models was evaluate the stress and deformation state of cladding element by applying 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 element with shear stiffness for examined case are at 25% smaller then ones without it. In the future experiments these models

must be developed and compared with experimental testing results to obtain more accurate displacements and reliable stress, which allows to find rational steps of load bearing and stressing cables of main structure depending on the constructive conditions lest rain bags should develop, 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 more exact model with method of substructuring allows to estimate how the displacements of the whole structures affect the cladding stress-strain condition, that in one's turn can get chance to reduce the safety factor and accordingly reduce the material consumption of long span coverings.

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Pakrastiņš L., Rocēns K. Serdjuks D. Norobežojoša stiepta kompozīta elementa darbības novērtēšana vanšu pārsegumiem.

Analizēta iespēja pielietot šķidro kristālu (LCP) polimērmateriāla audumus, kas izveidoti no šķiedrām uz poliestera molekulu bāzes ar regulāri orientēto struktūru, ka vanšu pārsegumu norobežojošo konstrukciju. Šī auduma šķiedru minimāla šļūdes tieksme ļauj viņu novērtēt kā labi piemērojamo komponentu uzspriegtiem audumiem iepriekš saspriegtām vanšu konstrukcijām. Lai novērtētu galvenās mehāniskās īpašības norobežojošam elementam no groza pinuma austam LCP šķiedrām, veikts elementa elastības moduļa un stiepes stiprības aprēķins ieaudu un pamatnes virzienos, balstoties uz pieņēmutu, kā norobežojošā elementa īpašības ir galvenokārt atkarīgas no auduma īpašībām. Šīs metodes precizitātes novērtēšanai, tika veikts analoģiskais aprēķins un rezultātu salīdzinājums līdzīgiem materiāliem ar iepriekš zināmām īpašībām. Pamatojoties uz darbā izstrādātiem diviem aprēķina modeļiem veikta elementa deformētā spriegumstāvokļa novērtēšana vertikālās slodzēs gadījumam, ka visneizdevīgākām. Aprēķina rezultāti rāda, kā ievērojot pārklājuma bīdes stingumu, maksimālie pārvietojumi ir par 25% zemāki nekā gadījumā, kad šo stingumu neievērtē.

Pakrastinsh L., Rocens K., Serdjuks D. Evaluation of the Behavior of Tensioned Composite Cladding Element for Cable Roofs.

The possibility of cable roofs covering by woven fabric based on liquid crystal polymer fibers with regularly oriented aromatic polyester molecules (LCP) was analyzed. Practical absence of creep allows to consider that this material is very applicable as component of tensioned fabric 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 on the assumption that the properties of cladding are mainly determined by the properties of the base fabric. To estimate the precision of above-mentioned approach was determined the tensile stress of several existent types of coated fabric and compared with experimental testing data. Based on two developed calculation models was evaluate the stress and deformation state of cladding element by applying vertical loading as most unfavorable. The calculation results show that with taking into account shear stiffness the maximal displacements are at 25% less in comparison with the model without it.

Пакрастиньш Л., Роценс К., Сердюк Д. Оценка поведения растянутого комозитного ограждающего элемента вантового покрытия.

Анализируется возможность использования полотна из волокон жидкокристаллического полимера (LCP) на основе регулярно ориентированных молекул полиэстера в качестве кровельного материала для вантовых покрытий. Практически полное отсутствие ползучести позволяет считать этот материал наиболее перспективным компонентом тканых натяжных материалов для предварительно напряженных вантовых конструкций. Для того чтобы оценить основные механические свойства элемента покрытия, выполненного из тканого полотняным переплетением LCP материала, был произведен расчет максимального разрывного усилия и модуля упругости элемента в направлениях основы и утка. Расчет производился на основе предположения о том, что свойства элемента покрытия в основном определяются свойствами тканевой основы. Для оценки точности вышеупомянутого подхода был произведен аналогичный расчет для существующих подобных материалов с известными характеристиками со сравнением полученных результатов. На основании двух разработанных расчетных моделей была произведена оценка напряженно-деформированного состояния элемента покрытия для случая вертикального нагружения, как наиболее невыгодного. По результатам расчета, в случае учета сдвиговой жесткости, максимальные перемещения на 25% меньше, чем без ее учета.