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STRENGTH AND STABILITY OF BENT AND COMPRESSED BOUNDARY SUPPORTS OF MEMBRANE ROOFS

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Abstract. The design-basis is an idea of presentation of bent and compressed a boundary support unit in the form of a beam on elastic base where a tensile membrane as an elastic base is continuously connected with a boundary support along its full length. Effective building factors of a cross section for a boundary support and a membrane, values of space-stiffness factors are obtained for conditions of Ukraine. Similar numerical research carried out for membrane roof on circular layout together with relative stiffness factors, sag and a lateral load enables to make some aspects of analytical technique of calculation for strength and stability analysis more precise

Keywords: membrane roofs, boundary support, strength, stability.

1. Introduction

Thanks to industrialization and high engineering-and-economical performance of construction, the membrane structures are widely used as roofs, protection *etc.* This introduction is favoured by a specialized production of light metal structures of a complete shipment for industrial buildings which allows decreasing a structure mass, labour-intensity, and cost (Trofimov, Yeremeyev 1990).

Despite a lot of works are devoted to the questions of studying a mode of deformation and to the development of methods of analysis of such structures, some questions such as the behaviour of a roof span (for example, if a thin sheet has toresult the compressive stresses) and the strength and stability of compressed-bent contour still remain ill-defined. The latter aspect is in particular confirmed by variation of a slenderness ratio of membrane roofs used on a square (or close to square) plan which changes from $\lambda = 150$ (Trofimov, Yeremeyev 1990); is typically for the most of roofs is up to $\lambda = 430$ (the plant "Compressor", Moscow) (Braslavsky 1973; Lyudkovsky 1986). At the same time, experimental surveys of a quasi-cylindrical roof on a square plan showed that at a boundary support with slenderness ratio $\lambda = 250$ a loss of stability of boundary support within a membrane plane was observed (Goldenberg and Uchitel 1991). Such an ambiguity in the questions concerning the design of similar objects requires further studies in this direction (Yeremeyev 2008, 2006).

2. Research Experiments

The most long-term approaches studying the problem specified are, to our mind, theoretical and experimental investigations carried out under the guidance of Trofimov and Yeremeyev to calculate strength and work out the methods of designing membrane roofs on the square and circular plans (Trofimov, Yeremeyev 1990; Yeremeyev 2008, 2006), as well as L. I. Goldenberg's works (Goldenberg and Uchitel 1991) in which there were outlined approaches to study stability of compressed-bent boundary support of sagged membrane roofs on the square plan (Fig. 1). Despite of a significance and primary importance of the results obtained, there are some questions which, to our mind, were beyond the investigations. Among them the following are:

- for the roofs on the square and rectangular plans under consideration there is given too wide turndown of the basic design parameters; finally that can result on developing roofs with obviously unpractical parameters;

- there absolutely was not studied the behaviour of compressed-bent boundary supports of sagged membrane roofs on the circular and elliptical plans in which under non-uniformly distributed loads the biaxial compression might form in near boundary supports zones within which a membrane does not have a supporting effect in the form of an elastic basis for a compressed-bent boundary support.

3. Fundamentals of the analytical design of membrane roofs on the square plan

a) strength calculation

The design procedure is based on the theory of zero-moment plates as their stressed state is determined by chain stresses because of rather small membrane beam stiffness. A roof design by the analytical procedure is carried out depending on dimensionless parameters:

$$\bar{n}=\frac{(EI)_k}{Eta^3},\ \bar{n}_b=\frac{(EI)_k}{Et\left(a-a_b\right)^3},\qquad \bar{f}=\frac{qa}{Et}\left(\frac{a}{f_0}\right)^3,\ \bar{k}=\frac{(EA)_k}{Eta}, \tag{1}$$

where $(EI)_k$ and $(EA)_k$ – a boundary support bending and longitudinal rigidity; Et – a modulus of elasticity and a membrane thickness; a – a half of a roof span; q – a uniformly distributed load on a roof; f_0 – an initial sag of a span; a_b – a separator size on a plan.

Maximum value of bending moments in a horizontal plane of a boundary support contour therewith are (Trofimov, Yeremeyev 1990):

- in the middle of a side:

$$M_{1k}=\beta_1\beta_{1f}\beta_{1b}\left(EI\right)_k\sqrt[3]{q^2/\left(E^2t^2a\right)}, \tag{2}$$

where

$$\beta_1=\sqrt{7.3\bar{k}+9.05}-105\bar{n}\bar{k}^{1.42},$$

if $10^{-5}\le\bar{n}\le10^{-3}$;

$$\beta_1=0.108^{10\bar{n}}\cdot0.043^{10\bar{n}\sqrt[3]{1/\bar{k}}}\sqrt{4.8/\bar{k}+11}+0.8\cdot0.93^{1/\bar{n}},$$

if $10^{-3}<\bar{n}\le10^{-1}$;

- in the place of joining to a separator (in a roof corner):

$$M_{1k}=\beta_2\beta_{2f}\beta_{2b}\left(EI\right)_k\sqrt[3]{q^2/\left(E^2t^2a\right)}, \tag{3}$$

where

$$\beta_2=128\cdot0.92^{1/\bar{k}}\Big/\left(10^5\bar{n}\right)^{\left(0.26-0.24/\bar{k}\right)},$$

if $10^{-5}\le\bar{n}\le2\cdot10^{-4}$;

$$\beta_2=0.54\Big/\bar{n}^{-0.55}+6.16\cdot0.933^{1/\bar{n}},$$

if $2\cdot10^{-4}<\bar{n}\le10^{-1}$.

Compression force in a boundary support contour:

- in the middle of a side:

$$N_{1k}=\beta_3\beta_{3f}(EA)_k\sqrt[3]{\left(qa/Et\right)^2}, \tag{4}$$

where

$$\beta_3=1.4\cdot0.225^{\bar{k}}-2.3\cdot0.2^{(\bar{k}^{-2.5})}\bar{n}^{-0.35}+0.81\cdot0.19^{(\bar{k}^{-3.5})}0.5^{(0.1/\bar{n})},$$

if $0.2\le\bar{k}\le1$;

$$\beta_3=0.29/\bar{k}^{-0.78}-0.0215\cdot20^{\sqrt{1/\bar{k}}}\bar{n}^{-0.35}+0.02\cdot7.6^{1/\bar{k}}0.5^{0.1/\bar{n}},$$

if $1<\bar{k}\le20$;

$$\beta_{3f}=\bar{f}^{-0.645}\Big/(0.088+0.976\bar{f}^{-0.645});$$

- in the place of joining to a separator (in a roof corner):

$$N_{2k}=\beta_{4b}N_{1k}, \tag{5}$$

where

$$\beta_{4b}=0.92(\bar{n}_b)^{0.05}.$$

A shear in a boundary support in the place of joining to a separator:

$$Q_{kb}=\beta_{7b}at\sqrt[3]{q^2a^2E/t^2}, \tag{6}$$

where

$$\beta_{7b}=0.65(\bar{n}_b)^{0.645}\Big/\left(0.0175+3.65\bar{n}_b^{0.645}\right).$$

Maximum value of displacement of a boundary support center in the horizontal plane:

$$U_k=\alpha_3\alpha_{3f}\alpha_{3b}a\sqrt[3]{\left(qa/Et\right)^2}, \tag{7}$$

where

$$\alpha_3=1.9(1.5)^{\sqrt{1/\bar{k}}}-32(1.8)^{\sqrt{1/\bar{k}}}\bar{n}^{-0.6},$$

if $10^{-5}\le\bar{n}\le10^{-3}$;

$$\alpha_3=\left(0.32+0.09/\bar{k}^{-0.65}\right)\sqrt[4]{1/\bar{n}}-0.36,$$

if $10^{-3}<\bar{n}\le10^{-1}$;

$$\alpha_{3f}=0.96+0.104\bar{f}^{(-0.38)}.$$

One should know the distance between a separator in a boundary support corner and the place where a bending moment curve changes the sing to determine the sizes of boundary suport elements fasteners:

$$a_{0b}=\alpha_2\alpha_{2b}a, \tag{8}$$

where

$$\alpha_2 = n^{-0.18} - 1.33 n^{-0.79}.$$

Proceeding from the above and within the performed finite-elements analysis the authors considered the behaviour of a span and a compressed-bent boundary support of a membrane roof on the square plan, namely:

- to determine optimal parameters of a membrane roof on the square plan for climatic conditions of Ukraine;
- to develop a model of numerical computation of a membrane roof on the square plan;
- to define the analytical design procedure for different spans, loads (in accordance with Ukraine zoning) and rigidity characteristics of a boundary support of a membrane roof on the square plan.

For the regions of Ukraine there were determined loads on a roof and dimensionless parameters obtained in accordance with the membrane roof optimal parameters. Ranges of dimensionless parameter distribution by values of optimal parameters according to the engineering strategy are shown in Figs 2…8, including roof angular zones (Fig. 5). Ranges of dimensionless parameter distribution by calculated values of optimal parameters (profile parameters are taken in accordance with the range of metal-roll) according to the engineering methods are shown in Figs 6 and 7. Changes of a membrane thickness depending on a span and load are shown in Fig. 8.

On the base of the analysis performed in dependence on loads and spans for membrane structures, on the square plan there the optimal values of the parameters t, $\overline{n}$, $\overline{k}$ for the loads typical for Ukraine were obtained. After updating the values in such a way with the regard of the gradation of the range of metal-roll, actual limits of variation of these parameters were:

$$3.2 \cdot 10^{-4} \le \overline{n} \le 5.1 \cdot 10^{-4},$$

$$7.6 \cdot 10^{-1} \le \overline{k} \le 9 \cdot 10^{-1}.$$

Let us consider the results of numerical investigations of a membrane roof on the square plan with given sag (see Fig. 1).

A spatial design of a membrane roof is carried out using the software *Windows SCAD office: 7.31R5.* A rectilinear arrangement of bed elements in the plan and a squared shape of panels were adopted in the design.

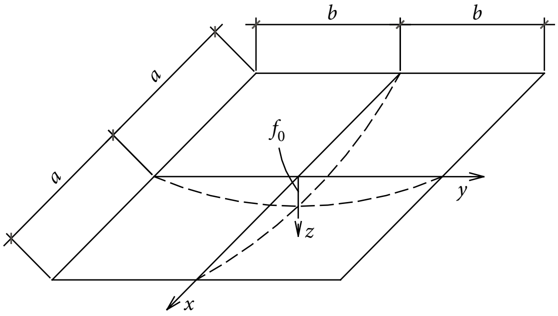

Fig. 1. Geometry of a shell structure surface

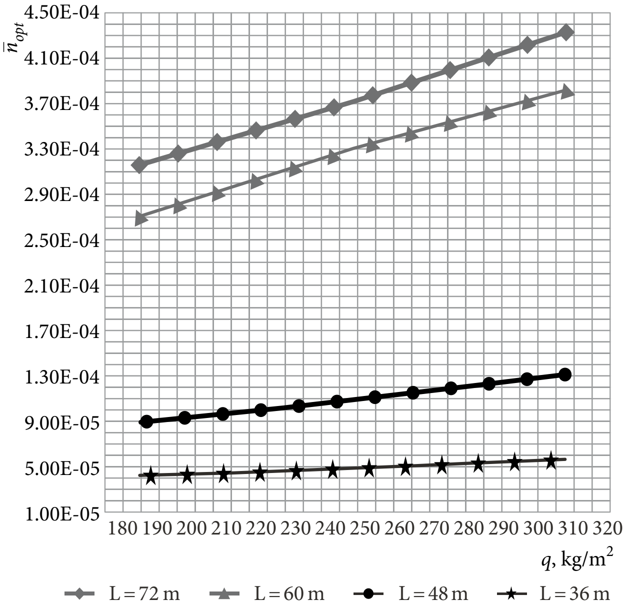

Fig. 2. Optimal values of the parameter $\overline{n}$

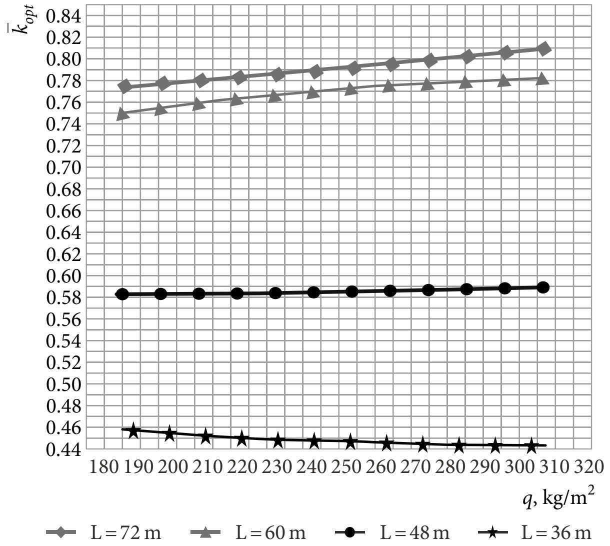

Fig. 3. Optimal values of the parameter $\overline{k}$

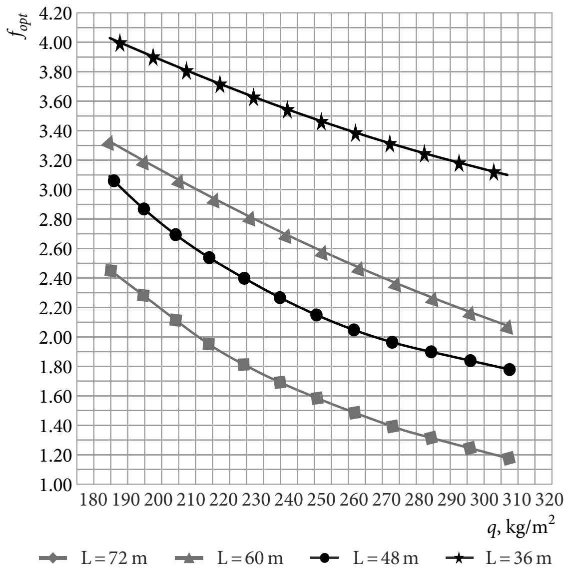

Fig. 4. Optimal values of the sag f

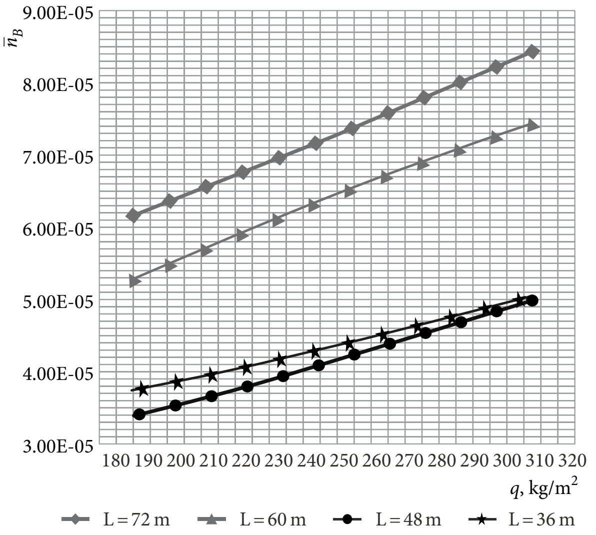

Fig. 5. Optimal values of the parameter $\overline{n}_B$ for the roof angular zone

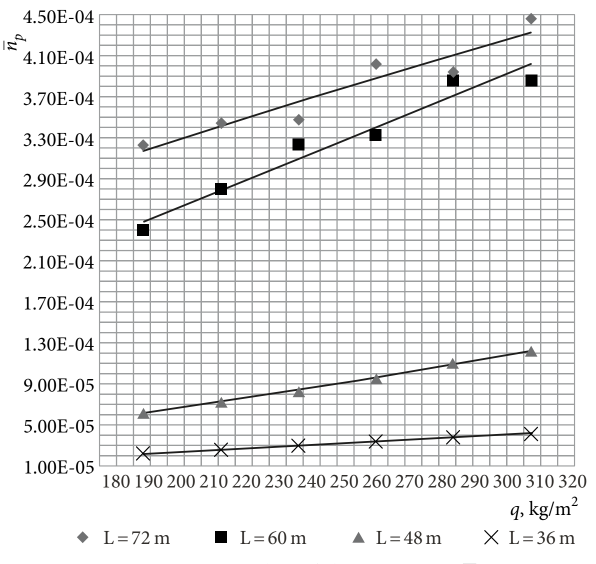

Fig. 6. Design value of the parameter $\overline{n}_p$

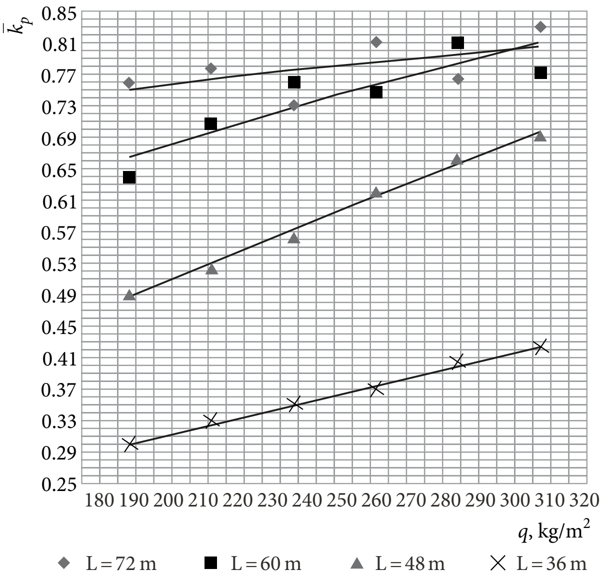

Fig. 7. Design value of the parameter $\overline{k}_p$

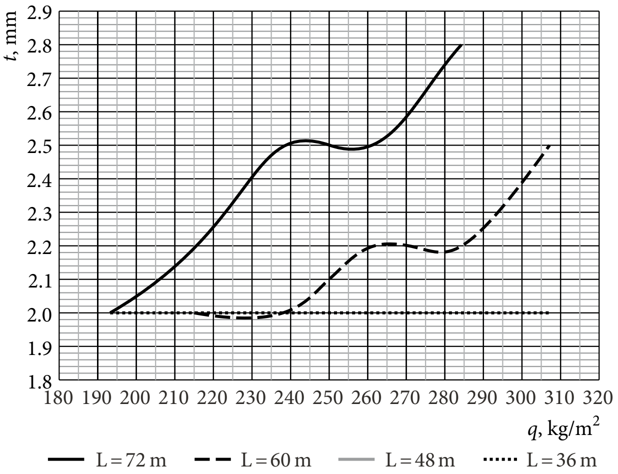

Fig. 8. Changes of the membrane roof thickness t calculated by the design values of the parameters $\overline{n}_p$ and $\overline{k}_p$

An initial shape of a roof surface for developing design model was calculated by the formula:

$$z = f_0\left(1-\frac{x^n}{a^n}\right)\left(1-\frac{y^n}{b^n}\right), \qquad (9)$$

where a, b – halves of the sides of a roof rectangular plan; f_0 – an initial erecting sag in the center of a roof; x, y – running coordinates, n = 2…4 (2 – at the overhead erection, 4 – at the erection of an initial plane membrane on scaffolds or on the ground level). A beam separator (haunch) size in the plan is accepted as 1/10 of a structure span.

The design was carried out by the step-by-step and iterative technique in a non-linear sequence. A roof design model with a roof partition mesh 0.5×0.5 m: a number of elements – 42168; a number of joints – 21081; a number iterations – 15; a number of steps – 10. Thickness of the roof elements were taken in accordance with the design, but not less than 2 mm. A boundary support was assigned in the form of bar elements, the length being equal to the size of the partition cell of a membrane. A haunch is also assigned in the form of a bar element, its profile being equal to the boundary support profile.

As can be seen from the Table 1 there are some imprecision in the results of some designs carried out by the analytical technology and with the help of MCE. The largest imprecision in efforts were fixed for roof angular zones (22…33%) while for the boundary support center these imprecisions are low and average 0.1–8.4%.

The investigations carried out made it possible to specify the procedure of determining efforts in the angular zone of a boundary support. To estimate the influence of dimensionless parameters $\overline{n}$, $\overline{k}$ there were used numerical and analytical methods to design a 72 m span with a full load q = 193 kg/m^2. The following values of the parameters were considered:

$$\overline{k} = 0.76; 0.83; 0.9; 0.00032 \le \overline{n} \le 0.00051 .$$

On the base of the fixed differences in the results of the numerical and analytical designs for the roof angular zone there can be recommended the following values of the falling coefficients of correction which are used as multipliers when determining efforts with the help of the analytical procedure:

- for bending moment:
  $k_M = 0.76...0.79$;
- for longitudinal force:
  $k_N = 0.8...0.82$;
- for cross-axis force:
  $k_Q = 0.76...0.78$.

b) stability calculation

As the basis for the design model put forward by L. I. Goldenberg (Goldenberg and Uchitel 1991) there was suggested an idea of presentation of a compressed-bent rectilinear bar (an element of the boundary support) in the form of beam on the elastic foundation in the form of a tension membrane continuously connected with the boundary support contour along its length. As a criterion of taking a sheet membrane off the work is the formation of a biaxial compression zone on the membrane local part, in its turn that makes it impossible to perform supporting functions of the elastic foundation.

In its turn the length of the membrane part taken off the work determines a free length of the part of the compressed-bent element of the boundary support which might suffer of collapse.

As can be seen from Figs 9 and 10, a middle part of the boundary support rid at the length of about 0.5 *l*

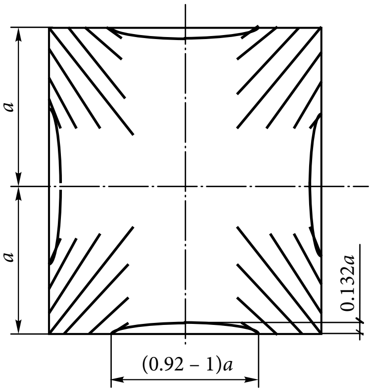

Fig. 9. Mode of stress-strain state in the near-contour zone

Table 1. Substantiation of the partition mesh of elements

Analytical design	A step of the finite-element net (m)					
	0.5×0.5	%	1.0×1.0	%	2.0×2.0	%
$M_y^{mid} = 47162774$ kg cm	47 240 000	0.16	42 220 000	−10.48	35 250 000	−25.2
$M_y^{corn} = 322632145$ kg cm	236 400 000	−26.7	225 700 000	−30	116 400 000	−62
$N^{mid} = 1515399$ kg	1 586 700	4.7	1 578 704	4.17	1 540 616	1.66
$N^{mid} = 972026$ kg	783 788	−19.36	782 491	−19.49	780 071	−19.7
$Q_z^{mid} = 783293$ kg	546 154	−30.3	523 018	−33.2	459 818	−41.3
$U_y^{mid} = 26.3$ cm	19.96	−24.1	18.39	−30	16.66	−36.6
$W_0^{cent} = 131.9$ cm	146.8	11.2	134.8	2.13	127.4	−3.47

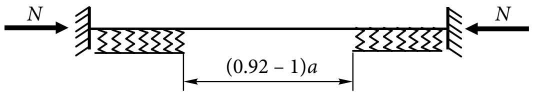

Fig 10. A design model of the support contour element in the form of a beam on the elastic foundation

contacts with that part of the membrane which lost its stability because of compressive stresses. Therefore, authors suggest for determining an axial critical load the following formulas:

$$N_{cr} = \left(-\frac{0.0283 w^2}{f_c} + \frac{0.0126 Ca}{f_c} + \frac{0.00924 \Delta a}{f_c} \right) E_0 t + \frac{\pi^2 E_c I}{a^2}, \tag{10}$$

where

$$f_c = 2.2 \times 10^{-4} \frac{w^2}{a_b} - \frac{2.5 N_{corn} b \left(0.6a\right)^2}{\pi^2 E_c I_c};$$

$$\Delta = \left(2.4 + 97.2\overline{k}\right) \frac{w^2}{a\left(5.3 + 12.1\overline{n} + 157\overline{k} + 212\overline{k}\overline{n}\right)};$$

$$E_0 = \frac{E}{1 - \nu^2},$$

$$C = 0.142 \frac{w^2}{a} + \left(0.61 + 1.65\overline{n} + 10.8\overline{k}\right) \times \frac{w^2}{a\left(5.3 + 12.1\overline{n} + 157\overline{k} + 212\overline{k}\overline{n}\right)}.$$

In what follows the authors suggest testing the boundary support stability in the horizontal plane in accordance with the design norms SNiP II-23-81* for an eccentrically loaded bar with eccentricity $e = M_0 / N_0$ and with the design length factor $\mu = 0,5\left(\pi/a\right)\left(E_c I / N_{cr}\right)^{0.5}$.

4. Investigation of strength and stability for sagged membrane roofs on the circular plan

a) strength calculation

By analogy with the previous chapter, the analytical procedure of an approximate analysis of roofs on the circular plan is based on the membrane theory of depressed shells and is put into effect depending on the dimensionless parameter $\overline{S} = 0,125 qR / Et$, relative longitudinal rigidity of the boundary support $\overline{k} = \left(EA\right)_k / EtR$ and coefficient β, which specifies the surface form (Trofimov, Yeremeyev 1990). It should be noticed that the authors have obtained a more complex system of the analogous dimensionless parameters which are used for the approximate analysis of membrane depressed shells on the circular (elliptical) plan with a large cutout (Gorokhov *et al.* 2008):

$$\overline{D}_1 = \frac{EI_z^{ext} a b_1^4 + EI_z a_1 b^4}{Et^* b^4 b_1^4}, \quad \overline{D}_2 = \frac{a^2}{b^2} + \frac{a_1^2}{b_1^2},$$

$$\overline{D}_3 = \frac{\overline{w} a_1^2 f}{(t^*)^2}, \quad \overline{D}_4 = \frac{EI_y b}{E(t^*)^3 R_2^2},$$

$$\overline{D}_5 = \frac{EI_y b}{E(t^*)^3 a^2}, \tag{11}$$

$$\overline{D}_6 = \frac{a^2}{b^2}, \quad \overline{F}_1 = \frac{EFab_1^2 + EF_{\text{int}} a_1 b^2}{Etb^2 b_1^2},$$

$$\overline{F}_2 = \frac{EFba_1^2 + EF_{\text{int}} b_1 a^2}{Eta^2 a_1^2},$$

where

a_1 and b_1 – lengths of the elliptical cutout semi-axes.

b) stability calculation

It should be noticed that the above system of dimensionless parameters are implemented when calculating strength for the case of loading of a uniformly distributed load on a roof when both in a supporting structure and in a span maximal forces occur. A compressed boundary support along its whole length is therewith additionally supported with a stretched membrane and following recommendations specifying its inflexibility characteristics there are no, as a rule, questions of guaranteeing stability. But when loading a membrane roof on the circular plan with a non-symmetrical temporary (for example, snow) load, in a membrane on the square plan in the near-boundary support zone of a sheet membrane dibasic compression zones occur, within these zones the membrane can not have a supporting effect on the eccentric-compressed boundary support, and in the result the latter suffer of a lack of stability.

To specify the zones mentioned, lets us consider the membrane roof of 100 m in diameter, membrane thickness – t = 3 mm, sag – *f*/*D* = 1/20 = 5 m and a relation between dead and live loads – *g*/*s* = 0.5/2 = 0.25. For the structure under consideration the load parameter was $\overline{S} = 2,53 \times 10^{-5}$, the parameter of bending rigidity of a boundary support varied within $1 \times 10^{-5} \ldots 3 \times 10^{-5}$. Calculations performed with the help of the software *Windows SCAD office:7.31R5* made it possible to estimate the length of "free lengths" of a compressed-bent boundary support parts which are not strengthened by an adjacent membrane stretched in 2 directions within which a loss of stability can occur.

The results of the investigations carried out are given in Table 2. Some illustrations of the picture of the mode of deformation for variant 1 of Table 2 are given in Figs 11…14.

5. Conclusions

1. For membrane roofs on the square plan with a side length from 36 to 72 m:
   - for the territory of Ukraine there have been determined optimal parameters of a boundary support cross-section and membrane. A boundary support cross-section varies from 230×640 mm to 680×2000 mm and a membrane thickness varies from 2 mm to 2.8 mm, respectively, as span increases;
   - for roofs with optimal values of relative dimensionless parameters $\bar{n}=(EI)_c/(Eta^3)$ and $\bar{k}=(EA)_k/(Eta)$ have a rather narrow turndown $0.00032 \le \bar{n} \le 0.00051$ *u* $0.76 \le \bar{k} \le 0.9$;
   - for real turndowns $\bar{n}, \bar{k}$ there are suggested correcting coefficients which make more accurate the value of efforts in the angular zone of a membrane roof on the square plan and the constituents, $k_M = 0.78$, $k_N = 0.81$.

Table 2. On the mode of deformation of a compressed-bent boundary support

NN	$\bar{S}=0{,}125\dfrac{qR}{Et}$	$\bar{k}$	$\bar{n}$	$\bar{N}=\dfrac{NR}{(EA)_c t}$	$\bar{M}=\dfrac{MR^2}{(EI)_c t}$	$\bar{\sigma}_x=\dfrac{\sigma_x}{E}\left(\dfrac{R}{t}\right)^2$	$\bar{\sigma}_y=\dfrac{\sigma_y}{E}\left(\dfrac{R}{t}\right)^2$	$\dfrac{l}{R}$
1	$2{,}53\times10^{-5}$	0.25	1×10^{-5}	8.30	63.9	–(45000…97000)	–24300…95700	0.85
2			1.5×10^{-5}	8.29	43.1	–(49700…106400)	–24000…81500	0.82
3			2×10^{-5}	8.28	32.9	–(52300…116000)	–23700…61000	0.79
4			2.5×10^{-5}	8.27	27.0	–(58900…125400)	–23300…50000	0.77
5			3×10^{-5}	8.26	23.0	–(63500…135300)	–22900…40500	0.75

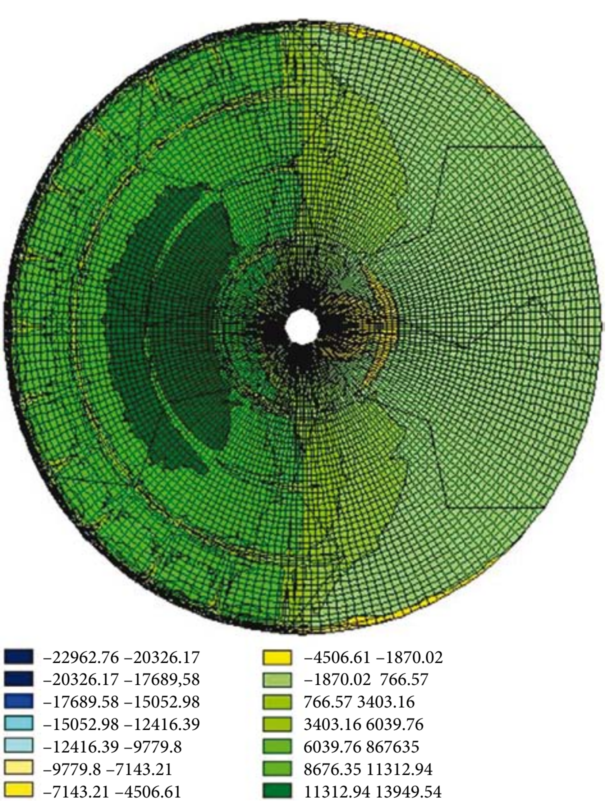

Fig. 11. A stress field σ_x under snow load

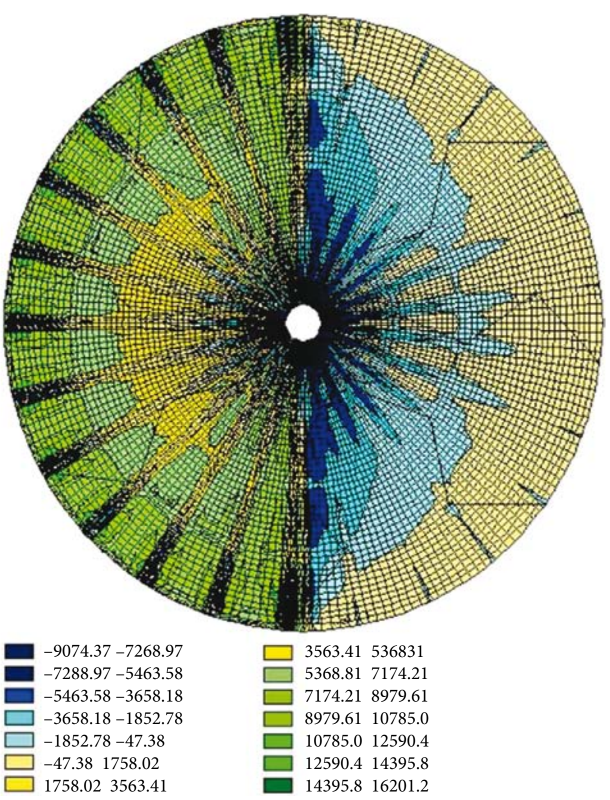

Fig. 12. A stress field σ_y under snow load

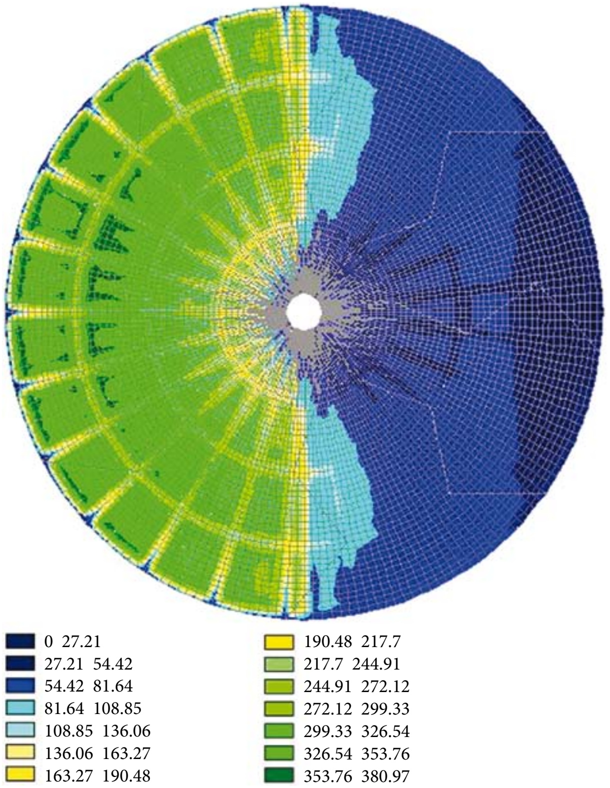

Fig. 13. A displacement field *w* under snow load

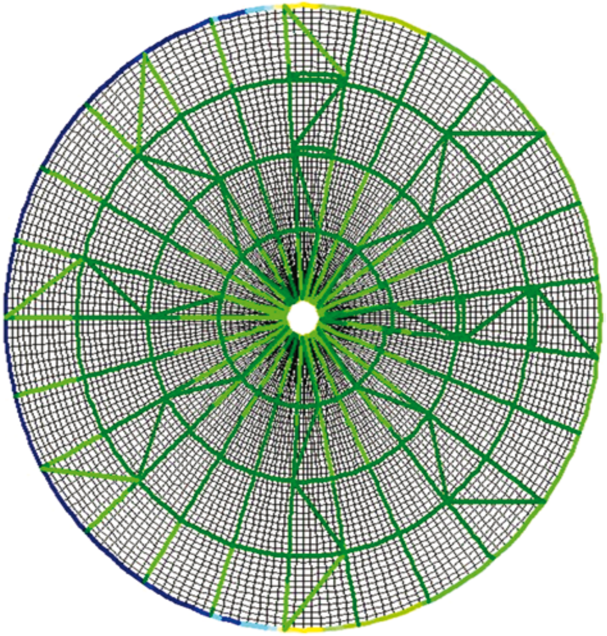

Fig. 14. Distribution of a longitudinal force N in support contours under snow load

2. For membrane roofs on the circular plan the parts of "free lengths" of a compressed-bent boundary support which are not strengthened by a stretched membrane at a half loading of the roof with a live load were up to 0.75…0.85 l/R.

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MEMBRANINIŲ STOGŲ LENKIAMO IR GNIUŽDOMO ATRAMINIO KONTŪRO STIPRUMAS IR PASTOVUMAS

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Santrauka. Straipsnyje nagrinėjamas lenkiamas ir gniuždomas membraninių stogų atraminis kontūras. Jis nagrinėjamas kaip sija ant tampriojo pagrindo, visu kontūru sujungtas su tempiamąja membrana. Membrana ir atraminio kontūro skerspjūvis apskaičiuoti Ukrainos sąlygoms. Panašūs skaitiniai eksperimentai atlikti ir su sukimo kevalu, imant panašias charakteristikas (elementų standumus, išlinkius, šonines apkrovas), siekiant atlikti tikslesnę stiprumo ir standumo skaičiavimo metodų analizę.

Reikšminiai žodžiai: membraniniai stogai, atraminis kontūras, stiprumas, pastovumas.

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