ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
Vol. 7, Issue 12 , December 2020

Some Aspects of the Theoretical Calculation of Energy-Saving Lightweight Roofing Covers

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ABSTRACT: Current scientific issues focus on energy saving research in the world construction practice especially the use of environmentally friendly materials in construction. In this case, great importance is attached to solving environmental and resource-saving problems. For this purpose, the creation and application of energy-efficient lightweight structures in construction is one of the important tasks. It is known that heavy reinforced concrete slabs are used in the construction interspace of buildings and roofing. Their large mass, high thermal conductivity, energy savings, and seismic stability pose problems when viewed. Therefore, it is advisable to use light boards made of wood in roofs and partitions. The article presents the main results of solving these problems, taking into consideration all the operating conditions provided for in the current building codes and regulations in the calculation and design of lightweight roofing sheets, as well as improving the calculation and taking into account various mechanical properties of materials.

KEYWORDS: Light plate, thermal insulation, calculated length, normal stress, shear stress, bending moment, static moment, moment of inertia, suggested geometric characteristics, priority, deformation.

I. INTRODUCTION

Today, the use of lightweight, energy-efficient structures plays an important role in the world construction practice. In particular, the creation of lightweight versions of heavy structures in roofing, the organization of their production remains one of the urgent tasks [1,2,3,6]. Lightweight roofing sheets are flat prefabricated structures that simultaneously perform the functions of beams, cladding, as well as can adequately retain heat in room conditions due to the convenient placement of modern thermal insulation materials (Fig. 1).

Figure 1. An overview of innovative lightweight and energy-efficient panel construction for roofing and interspace covering.

They can range in length from 3 meters to 6 meters and width from 1 to 1.5 meters, which corresponds to the modular system in construction and the dimensions of the slabs. Slabs thickness can be determined by calculating on the base of Russian "Construction norms and rules 23-02-2003-Thermal Protection of Buildings" through thermal technic and solid as well as stiffness and approximately pertains to 1/30 relatively [5].

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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The plates can be fastened directly to the main load-bearing structures (frames, trusses, etc.) and to the second plate by means of mechanical fasteners. Lightweight board coverings can also be made from plywood, wood and metal elements. Slabs have great importance in providing the space stiffness in the structure as the main load-bearing. They can absorb external forces in both vertical and horizontal directions. But in the general case it works to bend and acts as a horizontal connector and ensures the stability of the main support system. Figure 2. below shows a diagram of the state of installation of a light slab in a building:

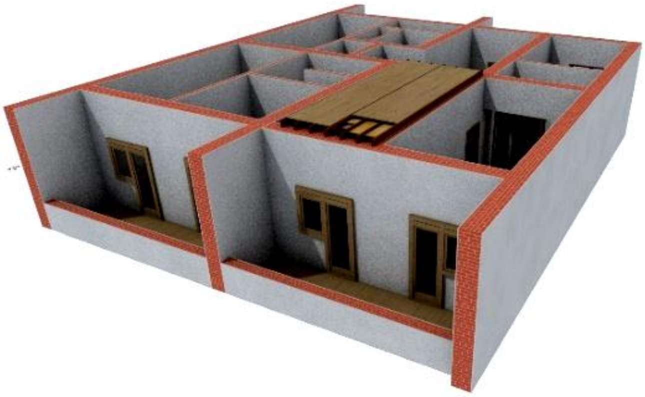

Figure 2. Installation scheme of innovative light energy-saving panel construction in the middle of a low-rise residential building.

II.METHODS

Depending on the temperature of the buildings and the structure of the roof, they can be divided into 2 types [6-12]: 1) slabs with thermal insulation, Figure - 3a.b,g. (for buildings with a positive internal temperature);2) slabs without thermal insulation, Figure- 3b (for buildings with negative internal temperature).

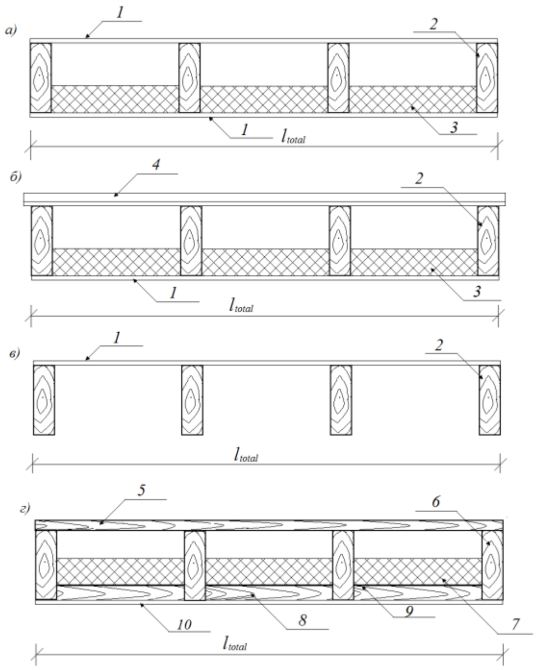

Figure 3. Types of light roofing slabs: a) - cross-section slab with thermal insulation box for roll roofing; b) - a plate for roofing with corrugated sheet metal or asbestos-cement, the lower part of which is covered with plywood; c) - a plate

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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for roofing with a ribbed, without thermal insulation, the upper part of which is plywood roll; g) - industrial board with thermal insulation for roofing with plywood cladding on the upper part, wooden boards on the lower part. 1 - plywood veneer; 2 - longitudinal ribs; 3 - insulation; 4 - roofing with folded cardboard or asbestos cement; 5 - wooden board; 6- longitudinal ribs; 7 - thermal insulation material; 8-transverse ribs; 9-roll metal mesh, 10x10 mm; 10- bottom plywood veneer.

Effective heat-retaining materials can be used as heat preservatives in slabs, including mineral wool slabs, foam plastics and others. Natural ventilation must be provided in buildings where all types of tiles are used. As a vapor barrier bitumen, gluing, painting with moisture-resistant paint, enameling or varnishing the interior and exterior of the underlayment ensures that the roofing element is decorated at the same time.

The cross-section of the roofing slab is calculated as a simple beam in the form of I-beam. In this case, using the calculation methods of construction mechanics, the state of strength and deformation of the slab is determined. Their calculation schemes are shown in Figures 4 and 5 below.

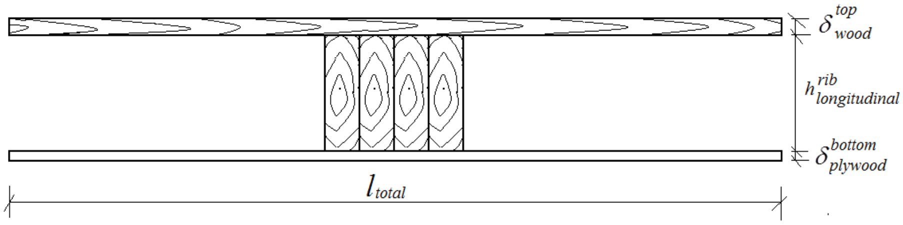

Figure 4. Schematic diagram of a lightweight wooden roofing slab with I-beam.

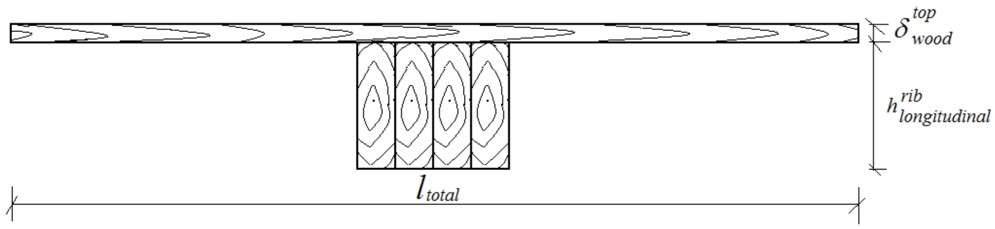

Figure-5. Schematic diagram of a light wooden slab with a I-beam.

III.RESULTS AND DISCUSSIONS

So far, the following formula has been used to calculate this type of slab:

$$l_{calculated} = l_{total} - c$$

It is recommended to determine the calculated spacing of the plate using the following formula (1) based on the law of distribution of the normal stress in the local compression along the length of its supporting surface according to the triangular rule:

$$l_{calculated} = l_{total} - \frac{4}{3}c \quad (1),$$

where: l_{total} is the total length of the slab or pitch of the load-bearing structure;

s ≥ 5.5 cm is the length of the slab resting on the supporting structure [4].

We determine the calculated firmness of a slab with a cross-sectional I-beam or beam cross-section by the longitudinal rib step and the length of the slab by the following formula (2):

$$L_{total} \geq l_{calculated} + \frac{4}{3}c \geq 6a, \text{ in this } b_{calculated} = 0{,}9 \cdot b_{topcovering} \quad (2),$$

where:a - spacing of longitudinal ribs (along the axes); $b_{topcovering}$ is the constructive width of the top cover (or that of the bottom cover, if there is no top cover).

We determine the calculated width of the longitudinal rib of the light plate using the formula - $b_{longitudinal\ rib}$(3):

$$b^{calculated}_{longitudinal\ rib} = n_{ribs\ number} \cdot b_{longitudinal\ rib} \quad (3),$$

where: $n_{ribs\ number}$ – longitudinal ribs; $b_{longitudinal\ rib}$– longitudinal rib width.

If themechanical properties of lightweight slab is made of two different materials (for example, plywood and wood), then these slabs are calculated using the following geometric characteristics (4) formulas for the elements with the greatest stress:

$$A_{set} = A_{plywood} + A_{wood} \cdot \frac{E_{wood}}{E_{plywood}};$$
$$S_{set} = S_{plywood} + S_{wood} \cdot \frac{E_{wood}}{E_{plywood}}; \quad (4),$$
$$I_{set} = I_{plywood} + I_{wood} \cdot \frac{E_{wood}}{E_{plywood}}.$$

where:$A_{plywood}, S_{plywood}, I_{plywood}$- cross-sectional area, static moment and moment of inertia, given by the calculated dimensions of plywood elements;

$A_{wood}, S_{wood}, I_{wood}$ - cross-sectional area, static moment and moment of inertia (longitudinal ribs) given by the calculated dimensions of wooden elements;

$n_{set} = \frac{E_{wood}}{E_{plywood}} = \frac{1 \cdot 10^{10}}{0{,}9 \cdot 10^{10}} = 1{,}11$-к reduction coefficient;

Wood and E_{wood} and $E_{plywood}$ are modulus of elasticity of plywood and wood. (5)

In simple practical calculations, it is easier to calculate the width of the longitudinal rib given in the determination of geometric characteristics, and it is equal to (5):

$$b_{calculated\ set} = n_{number\ of\ ribs} \cdot b_{lonitudinal\ rib\ width} \cdot n_{set} \quad (5)$$

In these cases, the geometric characteristics of the slab cross-section are determined by the calculated dimensions of the coatings and the calculated width of the longitudinal ribs. In this case, the actual values of the covering thickness and rib height are taken into account in the calculations. Slabs are considered normal components of permanent and temporary loads in the slab plane.

Temporary snow load is not taken into account in attic roofs. The reason is that these tiles are used in the interspace covering and the top floor roofing (except when the slab is placed on top of the rafters).

However, in the calculations, the specific gravity of the plate is also taken into account. The load on the plate is calculated using the following formula (6) [1]:

$$q_{private\ weight} = \frac{1}{b_{real} \cdot l_{real}} \cdot V \cdot \rho \cdot g \quad (6),$$

or $q = \rho_s \cdot g$; or $q_{privateweight} = \delta_{plywood} \cdot \rho \cdot g$

where: b_{real} width of the plate; l_{real}length of the plate; V-is the sum of the volumes of elements of the same type; ρ is the density quantity of the same type of the element; g = 9.81 m / sec^2 - acceleration of free fall; ρ_s –is the surface density of the material;

$\delta_{plywood}$- plywood coating thickness.

The stretching of slab bottom cover is estimated in the following formula (7)

$$\sigma = \frac{M}{W} = \frac{M_{calculated}}{W^{bottom}_{x(set)}} \leq R_{p.e.} \cdot m_{plywood} \quad (7),$$

where: $$M_{calculated} = \frac{q \cdot l^2_{calculated}}{8} = \frac{q(l_{total} - \frac{4}{3}c)^2}{8}$$

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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q - is the normal component of the total load on the slab, H / m; $W_{x.set}^{bottom} = \frac{I_{set}}{y_0}$-the moment of the cross section of the slab for the lower coating; y_0 is the distance from the center of gravity of the slab cross section to the lower plane of the slab;
$R_{plywood-elongation}$is the calculated resistance of plywood to elongation; $m_{plywood} = 0{,}6$- the coefficient of working conditions, taking into account the weakening of the joints of plywood, in addition, the calculated resistance of plywood is multiplied by the coefficients of all working conditions [4];
$l_{calculated}$ – is the accounting length of the slab.

The roofing slab works to bending. In this case the upper part is in a state of compression from the neutral axis, and the lower part is in a state of elongation. Among the geometric characteristics in compression and elongation, the cut surface is one of the main indicators. In torsion, bending, as well as in the calculation of priority, more complex geometric characteristics, including the static moment of the cross section, the moment of inertia, the moment of resistance, etc. are the main indicators.

Moreover, the simplification and reduction of the cost of roofing constructions play an important role in designing it in the most optimal shape and size. The following formula (8) is appropriate for calculating a surface with a known shape:

$$A = \int_A dA \qquad (8)$$

If in the calculation scheme the cross-sectional surface has a complex surface consisting of several shapes, they are divided into finite surfaces in the calculations. In this case, formula (9) takes the following form:

$$A = \sum_{i=1}^{n} A_i \qquad (9)$$

Calculations of the reduced static moment with respect to the x and y axes are performed using the following formula (10). In this case, the cross-sectional area is the simplest geometric characteristic, which does not relate to the choice ofy coordinate system.

$$S_x = \int_A ydA, \qquad S_y = \int_A xdA;$$
$$S_x = \iint_A ydxdy, \qquad S_y = \iint_A xdxdy; \qquad (10),$$
$$S_x = Ay_c, \qquad S_y = Ax_c$$

where: y_c is the distance from the center of gravity to the x-axis; x_c is the distance from the center of gravity to the y-axis.

The moment of a complex section with respect to one axis is equal to the quantity of the static moments of all parts with respect to that axis:

$$S_x = A_1y_1 + A_2y_2 + \ldots + A_ny_n = \sum_{i=1}^{n} A_iy_i;$$
$$S_y = A_1x_1 + A_2x_2 + \ldots + A_nx_n = \sum_{i=1}^{n} A_ix_i \qquad (11)$$

The above formula (11) includes definitions such as $A_1, A_2, A_3, \ldots A_n$ - surfaces of simple elements; $x_1, y_1, x_2, y_2, x_3, y_3, \ldots x_n, y_n$, - are the coordinates of the centers of gravity that make up the simple cutting surfaces relative to the obtained xand y axes. The coordinates of the center of gravity in the case of a single cross-sectional area are calculated using the following formula (12):

$$x_c = \frac{S_y}{A}; \qquad y_c = \frac{S_x}{A}. \qquad (12)$$

Also, the coordinates of the center of gravity of a complex cross-sectional surface of several shapes are determined using the following formula (13):

$$x_c = \frac{S_y}{A} = \frac{A_1x_1 + A_2x_2 + \cdots + A_nx_n}{A_1 + A_2 + \cdots + A_n};$$
$$y_c = \frac{S_x}{A} = \frac{A_1y_1 + A_2y_2 + \cdots + A_ny_n}{A_1 + A_2 + \cdots + A_n} \qquad (13)$$

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The usage plywood cladding for compressing of the cross-sectional surface is checked for priority using the following formulas (14,15,16):

$$\sigma = \frac{M_{calculated}}{\varphi_{plywood} \cdot W_{x(set)}^{top}} \leq R_{plywood-compression} \quad (14),$$

where: $W_{x(set)}^{top} = \frac{I_{set}}{h_{clabthickness} - y_0}$ - the moment of resistance of the cross-section for the slab top coating; $h_{clabthickness}$- slab thickness; $R_{plywood-compression}$ - the calculated compressive strength of plywood multiplied by the coefficients of all operating conditions [4]; $\varphi_{plywood}$. - the priority factor of compression plywood coating, $\frac{a'}{\delta_{plywood-top}}$ is determined by the ratio; a' is the open distance between the slab ribs; $\delta_{plywood-top}$ – top-coating thickness.

$$\text{If} \frac{a'}{\delta_{plywood-top}} \geq 50 \quad \text{itis, } \varphi_{plywood} = \frac{1250}{\left(\frac{a'}{\delta_{plywood-top}}\right)^2}; \quad (15)$$

$$\text{or} \quad \frac{a'}{\delta_{plywood-top}} < 50 \quad \text{itwere} \varphi_{plywood} = 1 - \frac{\left(\frac{a'}{\delta_{plywood-top}}\right)^2}{5000}; \quad (16)$$

The top cladding of the lightweight roofing slab is also tested with an reliability coefficient p = 1,2 (in the range of longitudinal ribs) for an additional local bending P_{normal}= 1000 N accumulated-directed (point-loaded) load.

In this case, the calculated width $b'_{plywood-top} = 1{,}0$ м value is assumed. The test is performed using the following formula (17):

$$\sigma = \frac{M}{W} = \frac{M_1}{W'_{plywood-top}} \leq R_{plywood-bending} \quad (17),$$

$$\text{where: } M_1 = \frac{P \cdot a}{8}$$

$$P = P_{normal} \cdot n$$

$W'_{plywood-top} = \frac{b'_{ply-wood} \cdot \delta^2_{plywood-top}}{6}$ is the moment of resistance of the upper coating with a width of 1 meter for calculation of local load. Longitudinal ribs on the neutral layer, adhesive joints between the ribs and plywood cladding are checked for cracking in bending using the following formula (18):

$$\tau = \frac{Q \cdot S_{x\,(set)}}{I_{set} \cdot b_{cal..rib}} \leq R_{cracking} \quad (18),$$

where: $Q = \frac{q \cdot l_{calculated}}{2}$ -calculated transverse force:

$S_{x(set)} = S_{plywood-top} + b_{rib-set.} \cdot \frac{(h_{total} - y_0 - \delta_{plywood-top})^2}{2}$ -the static moment of the sliding part of the cross section of the plate relative to the neutral axis; $R_{cracking}$–calculated resistance of wood or plywood to bending cracking with all operating coefficients. [4]. Considering the deformation of slab contraction joints, it should be checked for bending. [4]. The value of the transverse bending is determined using the following formulas (19,20):

$$f = \frac{f_0}{k} \cdot \left[1 + c \cdot \left(\frac{h_{total}}{l_{total}}\right)^2\right] \quad (19),$$

where:

$$f_0 = \frac{5}{384} \cdot \frac{q^{normal} \cdot l_{cal.}^4}{0{,}7 \cdot E_{plywood} \cdot I_{set}} \quad (20)$$

Q^{normal} - component of the normative total loading on the plate; k- is the coefficient taking into account the variability of the cutting height of the bending element, when the height is constant k=1,0; $c = (45{,}3 - 6{,}9 \div \beta) \cdot \gamma$ - coefficient which is considered the effect of tensile stresses on the bending value; β is the coefficient of accounted in the variability of the slab cross-sectional height, β = 1.0 when the height is constant; $\gamma = \frac{b_{cal.}(\delta_{plywood-top} + \delta_{plywood-bottom})}{b_{rib-set} \cdot h_{rib}}$; the k, c, β, γ-coefficients are determined on the basis of a table for a hinged base and double-section(ib.) with a linearly distributed load and a constant height [4].

The relative deflection of the slab is determined as follows [4] - $f/l, \left[\frac{f}{l}\right] = \frac{1}{250}$. In cases where it is less than the allowable value, the stiffness requirement is considered fulfilled.

ISSN: 2350-0328
International Journal of Advanced Research in Science, Engineering and Technology
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IV. CONCLUSION

1. In the calculations, a decrease in the value of the calculated length of the slab reduces the bending moment and leads to the selection of the cross-sectionalsurface of the slab in the most optimal option. For this purpose, it is recommended to use the formula $l_{calculated} = l_{total} - \frac{4}{3}c$ developed by the authors of the article, instead of the formula $l_{calculated} = l_{total} - c$which has been used so far in finding the calculated length.
2. In determining the calculated length of lightweight roofing slabs, it is expedient to take into consideration the distribution of the local compression curve formed by the slab resting on the foundation not by the quadratic law but by the triangular law.

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