Calculation Features of Wooden-Composite Ribbed Plates with Splices in the Cover

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Abstract. Wood-composite plate-ribbed bend structures with plywood and oriented strand board as covers with splices are considered. An overview of studies devoted to the study and increasing of the efficiency of such structures is presented. The theory of calculation of composite rods by A R Rzhantysyn is taken for compiling a mathematical model for calculations of the stress-strain state of these structures, taking into account the splices in the cover and the flexibility of mechanical joints of the covers and ribs. The graphs of the dependence of the maximum tensile stresses in the ribs in the criterion cross section and the maximum vertical displacements from the shear bond stiffness coefficient and the location of the splices in the cover are presented. The values of the coefficients for the engineering calculation of plates, taking into account the decrease in the strength and deformation characteristics of the composite section of panels with splices in the cover, compared to panels without splices in the cover, are proposed. Conclusions and recommendations are formulated based on the results of the research, which can be used in the design of wood-composite plate-ribbed structures.

1. Introduction

Composite panels with wooden frame and cover, made of various sheet materials are widely used in the construction of civil buildings, industrial and agricultural structures. It is the universal enclosing and supporting structures, can be used as covering, floors, wall fencing; and also as the main load-bearing elements in a low-rise building. Coating plates simultaneously perform the functions of beams, flooring, lining, provide thermal protection of the building (panels with the insulation in the structure), and are horizontal stiffness diaphragms. Numerous studies have been devoted to improving the performance of such panels. A new method is proposed in [1] for joining the outer and inner layers of 3-layer panels, which makes it possible to significantly increase the resistance of joints to longitudinal and transverse shear. The bent strength of prefabricated reinforced concrete wall panels with insulation using various connections between the outer bearing reinforced concrete layers is studied in the article [2]. The research for the ultimate compressive load and analysis of the stability of carbon fiber and glass fiber panels with stiffening ribs “Z”-profile and “L”-profile is presented in [3]. The results of studies of shear strength between layers of modular sandwich panels with a sheath made of high density polyethylene depending on the stamping method are presented in article [4].
2. Relevance, scientific significance of the issue with a brief review of the literature

A rigid adhesive joint is generally used at the rid-to-cover boundary for the most effective inclusion of cover in the overall operation in panels with a wooden frame [5, 6, 7]. However, the advisability of taking into account the cover fastened to the ribs using rigid mechanical ties have been demonstrated in a number experimental and theoretical studies [8, 9, 10, 11]. The use of the ties with increased resistance to longitudinal shear [12] allows them to be used as an alternative to adhesive joints [13, 14]. The research [15] presents the results of studies of increasing the strength of panels on a wooden frame, working in conjunction with sheathing made of sheet materials, which are fastened with screws, when the panel bears the shear forces as a vertical diaphragm.

Materials such as structural plywood (FC) and oriented strand board (OSB) are widely used as claddings. Structural timber for ribs is accepted according to [16].

3. Problem statement

Presented in the norms and rules [17] and recommendations [18] method for calculating wooden frame plates (Figure 1), provides for their calculation as a solid cross-section beams without ductility of the ties between rids and cover. This approach introduces a significant error in estimation of the stress-strain state of structures, with the covers fastened to the ribs using mechanical connectors in the form of nails, screws or staples. In the presence of splices in the cover, the design resistance of the cover material is taken with a decreasing coefficient $m_f$, which takes into account the decrease in the design resistance in the joints and the method of joining (gluing butt joints or gluing with plywood linings). However, the position of the joints along the length of the panel is not taken into account in such method, as well as the case of a joints without gluing, which is most convenient in the manufacture of plates with mechanical bonds between the cover and ribs.

![Figure 1. Construction of wood-composite ribbed panel on mechanical ties with cover splices: a - splice in the middle of the span; b - splices in 1/3 span.](image)

4. Theoretical part

For calculating panels according to [17] the actual cross-section is replaced by the reduced (figure 2). The calculated (reduced) width of the cover section is calculated by formula:

$$b_{red} = k_{red} \cdot b_{act}$$

$k_{red}$, the reduction coefficient, taking into account the uneven distribution of normal stresses in the cross section of the cover;

$b_{act}$, the actual (overall) width of the cover.
A length of the plate is split into 3 sections: \( L_1 \) - the section from the left support to the first splice, \( L_2 \) - the distance between the splices. The \( \Sigma L \) dimension is common value of the calculated span of the plate. There are two special cases possible: \( L_2=0 \) – one splice in the middle of plate span; \( L_1 = 0 \rightarrow L_2=\Sigma L \) – failure of splices. The computational model takes into account that there is no tight fit of the cover sheets along the butt faces, therefore bending moments and longitudinal compressive forces are not transmitted through the splices between parts of the cover.

The plate is considered as a two-layer composite element with layers of cover and ribs. The presence of splices in the cover is taken into account by introducing the appropriate boundary conditions. According to [19], the differential equation for describing the distribution of shear forces on the border of a wooden "edge-sheathing" is:

\[
\frac{T''}{\xi} = \gamma T + \Delta
\]  

(2)

\( T \), the distribution function of shear forces;
ξ, linear shear ties stiffness coefficient; 
γ, Δ, coefficient and free term of differential equation (2), determined by formulas (4) and (5), respectively.

The solution to the differential equation (2) has the form:

\[ T(x) = C_1 \sinh(\lambda x) + C_2 \cosh(\lambda x) + \frac{\xi}{\lambda^2} \int_0^\lambda \Delta(t) \sin(\lambda(x-t)) \, dt \]  

(3)

\[ C_1; C_2, \] the integration constants determined from the boundary conditions.

\[ \gamma = \frac{1}{E_c A_c} + \frac{1}{E_r A_r} + \frac{c}{\sum EI} \]  

(4)

\[ E_c, E_r, A_c, A_r, \] the elastic modulus of materials and the cross-sectional area of the cover and rib, respectively;
\[ c, \] the distance between the centers of gravity of the cover and rib sections;
\[ \sum EI \] is the amount of the bending stiffnesses of the cover and the rib.

\[ \Delta(t) = -M_0(t) \cdot c / \sum EI \]  

(5)

\[ M_0(t) \], the distribution function of bending moments only from the external load \( q=\text{const} \) within the lengths of the panel sections. The values of the bending moments in the sections \( L_1 \) and \( L_2 \) can be determined by the formulas:

- for section \( L_1 \):

\[ M_0(t) = \frac{q \sum L \cdot t - q \cdot t^2}{2} \]  

(6)

- for section \( L_2 \):

\[ M_0(t) = \frac{q \sum L}{2} \cdot (t + L_1) - q L_1 \left( \frac{L_1}{2} + t \right) - \frac{q t^2}{2} \]  

(7)

\( t, \) the coordinate measured from the beginning of the section under consideration;
\( q, \) uniformly distributed load on the panel, reduced to linear \( q=\text{g} \cdot b_{\text{act}} \).

A character of the distribution of forces and stresses on the selected panel fragment is shown in figure 4.
Figure 4. Distribution of forces and stresses scheme on the selected section of the panel.

The solutions of the differential equation (2) when substituted into it (5), (6) and (7) can be presented in the form:
- for section $L_1$:

$$T_1(x_1) = A_1 \sinh \lambda x_1 + B_1 \cosh \lambda x_1 + \frac{\xi}{\lambda} \int_0^{x_1} \left( -\frac{(0.5qL \cdot t - 0.5qt^2)}{\sum EI} \right) \sin \left( \lambda [x_1 - t] \right) dt$$

(8)

- for section $L_2$:

$$T_2(x_2) = A_2 \sinh \lambda x_2 + B_2 \cosh \lambda x_2 + \frac{\xi}{\lambda} \int_0^{x_2} \left( -\frac{(q\Sigma L[x_2 - t]) - qL [\frac{L_2}{2} + t] - \frac{qL^2}{2}}{\sum EI} \right) \sin \left( \lambda [x_2 - t] \right) dt$$

(9)

$x_1, x_2$, coordinates measured from the beginning of sections $L_1$ and $L_2$, respectively; $A_i, B_i$, constants of integration, determined from the boundary conditions.

Integrating of the right part of the solutions (8), (9) produce the expressions:

$$T_1(x_1) = A_1 \sinh \lambda x_1 + B_1 \cosh \lambda x_1 - \frac{\xi}{\lambda} \left( \frac{cq \left[ \lambda^2 x_1^2 + \Sigma L \sinh \lambda x_1 - 2 \cosh \lambda x_1 - \Sigma L^2 x_1^2 + 2 \right]}{2 \sum EI \lambda^2} \right)$$

(10)

$$T_2(x_2) = A_2 \sinh \lambda x_2 + B_2 \cosh \lambda x_2 - \frac{\xi}{2 \sum EI \lambda^2} \left( \frac{2 - 2 \cosh \lambda x_2 + L_1^2 \lambda^2 + \lambda^2 x_2^2 - L_1^2 \cosh \lambda x_2 - \Sigma L \sinh \lambda x_2 - \Sigma L^2 \cosh \lambda x_2}{2 - 2 \cosh \lambda x_2 + L_1^2 \lambda^2 + \lambda^2 x_2^2 - L_1^2 \cosh \lambda x_2 - \Sigma L \sinh \lambda x_2 - \Sigma L^2 \cosh \lambda x_2} \right)$$

(11)

The boundary conditions have the form: $T_1(0)=T_1(L_1)=T_2(L_2)=0 \rightarrow B_1=B_2=0$. Respectively:

$$A_i = \frac{\xi \cdot cq \left( \lambda^2 L_1^2 - 2 \cosh \lambda L_1 + \Sigma L \cosh \lambda L_1 - \Sigma L^2 + 2 \right)}{2 \sum EI \lambda^2 \sinh (\lambda L_1)}$$

(12)
\[
A_2 = \frac{\xi_{cg}}{2\sum EI\lambda^2 shL_2} \left( L_2^2 \lambda^2 - 2ch(L_2\lambda) + L_2^2 \lambda^2 - L_2^2 \lambda^2 chL_2 \lambda + \Sigma L \lambda shL_2 \lambda - 2L_2 \lambda shL_2 \lambda - \Sigma LL_2 \lambda^2 - \Sigma LL_2 \lambda^2 + 2L_2 L \lambda^2 + \Sigma LL_2 \lambda^2 chL_2 \lambda + 2 \right)
\]  
(13)

\[
\lambda, \text{ the characteristic number determined by the formula:}
\]

\[
\lambda = \sqrt{\xi \cdot \gamma}
\]  
(14)

\[\xi, \text{ linear shear ties stiffness coefficient;}
\]

\[\gamma, \text{ the coefficient of the differential equation (2), determined by the formula (4).}
\]

The bending moments and normal stresses in the cover and rib in composite structure are determined by the formulas:

\[
M_{ob} = (M_o - T \cdot c) \frac{E I}{\Sigma EI} \quad M_p = (M_o - T_i (x_i) \cdot c) \frac{E I}{\Sigma EI}
\]  
(15)

\[
\sigma_{ob} = -T \frac{M_{ob} \cdot h_{ob}}{2I_{ob}} \quad \sigma_p = T \frac{M_p \cdot h_p}{2I_p}
\]  
(16)

In some cases for a panel with two splices most dangerous section position can locate out of the middle of the span. Equation (17) respect to \(x_2\) allows to determine the section with the maximal tensile stresses in the rib:

\[
d \left( \frac{T_2 (x_2) \pm \left( M_o (x_2) - T (x_2) \cdot c \right) h_p}{2I_p} \right) dx_2 = 0
\]  
(17)

To determine the vertical displacements panel the equation (17) for the curved axis of the bending element is used:

\[
y(x) = \int \int \frac{M(x)}{\Sigma EI} dxdx = \frac{1}{\Sigma EI} \int \int M(x) dxdx
\]  
(18)

The function \(y(x)\) has fractures at the splices in the skin, therefore, expression (18) should be applied for \(L_1\) and \(L_2\) parts of the span, and the equality of deflections at the boundary of parts should be related by boundary conditions:

\[
y_1 (x_1) = \frac{1}{\Sigma EI} \int \int M_1 (x_1) dxdx = \frac{1}{\Sigma EI} \int \int \left( \frac{q \Sigma L x_1 - q x_1^2}{2} - T_1 (x_1) \cdot c \right) dxdx
\]  
(19)

\[
y_2 (x_2) = \frac{1}{\Sigma EI} \int \int M_2 (x_2) dxdx = \frac{1}{\Sigma EI} \int \int \left( \frac{q \Sigma L (L_1 + x_2) - q x_2^2}{2} - q \Sigma L \left( \frac{L_1}{2} + x_2 \right) - T_1 (x_2) \cdot c \right) dxdx
\]  
(20)

\(y_1(x_1); y_2(x_2), \text{ the functions of vertical deflections in sections } L_1 \text{ and } L_2, \text{ respectively.}

The integration of expressions (19) and (20) with the dependences of the distribution of shear forces (10) and (11) is a rather difficult problem, therefore, for simplicity of solution, integrands functions are replaced by quadratic approximating polynomials:
\[ M_1(x_1) = a_1x_1^2 + b_1x_1 + d_1 \quad M_2(x_2) = a_2x_2^2 + b_2x_2 + d_2 \] (21)

\( a_1; b_1; d_1 \) are the coefficients and free terms of polynomials determined by the least squares method. Taking into account \( M_1(0) = 0 \), the free term \( d_1 = 0 \).

It is necessary to substitute expression (21) into expression (18). We integrate the resulting expression and get the result:

\[ y_1(x_1) = \frac{1}{\Sigma EI} \left( \frac{a_1x_1^4 + 2b_1x_1^3}{12} + C_1x_1 + D_1 \right) \] (22)

\[ y_2(x_2) = \frac{1}{\Sigma EI} \left( \frac{a_2x_2^4 + 2b_2x_2^3 + 6d_2x_2^2}{12} + C_2x_2 + D_2 \right) \] (23)

\( C_1 \) and \( D_1 \) are the constants of integration determined from the boundary conditions.

From the condition of equality of the vertical displacements to 0 on the supports, as well as the equality of deflections and angles of the cross-section rotations at the boundaries of the parts \( L_1 \) and \( L_2 \) border conditions: \( y_1(0) = 0; y_1(L_1) = y_2(0) = y_2(L_2); y_1(L_1) = y_2(L_1) = y_2(L_2) \) - can be obtained, which leads to the system of equations (24) for determining arbitrary constants (25), (26):

\[
\begin{align*}
\frac{a_1L_1^3}{12} + \frac{b_1L_1^2}{12} + C_1L_1 + D_1 &= 0 \\
\frac{a_2L_2^3}{12} + \frac{b_2L_2^2}{12} + C_2L_2 + D_2 &= 0
\end{align*}
\] (24)

\[ C_1 = -\frac{a_1L_1^3}{3} - \frac{b_1L_1^2}{2} - \frac{a_2L_2^3}{3} + \frac{2b_2L_2^2}{2} + 6d_2L_2 \]

\[ C_2 = -\frac{a_2L_2^3}{3} - \frac{b_2L_2^2}{2} - \frac{a_1L_1^3}{3} + \frac{2b_1L_1^2}{2} + 6d_1L_1 \] (25)

\[ D_1 = 0 \quad D_2 = -\frac{a_1L_1^3}{4} - \frac{b_1L_1^2}{3} - \frac{a_2L_2^3}{4} - \frac{b_2L_2^2}{3} + \frac{6d_1L_1}{12} + \frac{6d_2L_2}{12} \] (26)

5. Practical significance, proposals and results of implementations, results of experimental studies

Consider a wood-composite panel with a common span of \( \Sigma L = 6 \) m with three longitudinal ribs and a plywood/OSB cover 18 mm thick. The ribs are made of pine/spruce structural timber of strength class C22 [16] with a dimension of cross-section 50 × 200 mm. Flat load, reduced to linear \( q = 1 \) kN/m. The design width of the cover is taken according to [17]: \( b_{red} = 1,125 \) m.

The covers are made with splices with a distance of 1, 2 and 3 m from the supports, the results are comparable to the plate without splices of the cover. The stiffness of the flexible shear bonds is taken according to research [20] and is considered in the range \( \xi = 2000 \ldots 10000 \) kN/m² (for each rib). Normal stresses \( \sigma_p \) in the stretched fibers of the rib are taken as the strength criterion, since according to the chosen scheme it is the strength criterion of the entire structure. The dependence of stresses \( \sigma_p \) on the coefficient of stiffness of the bonds \( \xi \) are shown on graphs in figure 5a. The value \( \xi = \infty \) corresponds to a rigid glued joint of the cover and ribs.
Figure 5. Graphs of the dependence: of the maximum tensile stresses $\sigma_x$ in the tensile fibres of the rib (a) and maximum vertical displacements (b) on the shear stiffness coefficient of ties $\xi$. 

The presence of splices in the cover significantly affect the behavior of the entire structure. With a $L_2/L_1$ ratio decrease, the efficiency of the cover as part of the entire structure decreases. The share of decrease in panel strength during bending can be 9.8 ... 47.5% (8.9 ... 43.1%) for a panel with a sheathing of SP (OSB) was shown. When the splices are located at a distance of 1/3 from the panel supports (at $L_2/L_1 \leq 1$), the most dangerous cross-section of rib locate on the cover splices. The flexural strength of the panel is determined only by the strength of the ribs if the splice is located in the middle of the common plate span ($L_2=0$).

There are similar situation arises according to vertical displacements design. If the splices of the cover are removed from the supporting cross-sections, the displacements of the structure increase (by 40 ... 100% for panels with SP cover; by 37 ... 90% - with OSB cover). However, the case $L_2/L_1=1$ in this case more unfavorable than $L_2=0$, therefore, if there is necessary to locate cover splices at a distance of more than $1/3\Sigma L$ from the supports, it is recommended to take into account which factor will be decisive for selecting a cross-section dimensions - strength or vertical displacements.

There can be used coefficients $k_{sp,w}$ and $k_{sp,f}$ taking into account the negative effect of joints in the skin on the strength and rigidity of the entire panel structure in the engineering calculation of ribbed wood-composite bent plates. These coefficients are multiplied by the obtained values of normal stresses and deflections calculated for a panel without splices in the cover. The method for calculating such panels is presented in [21]. The coefficient of stiffness of the ties $\xi$ depends both on the type of used joints (staples, nails, screws) and on the increment between ties, vary over a fairly wide range of values. Figure 5.a and 5.b, presents the graphs run almost parallel and in order to simplify the calculations, the values of the coefficients $k_{sp,w}$ and $k_{sp,f}$ assigned without taking into account the stiffness of the fasteners at the “rib-to-cover” boundary.

The values of the coefficients $k_{sp,w}$ and $k_{sp,f}$ are determined by the formula:
\[ k_{sp,w} = \frac{\sigma_p^*}{\sigma_p^r}; \quad k_{sp,f} = \frac{f'}{f} \]  \hspace{1cm} (27)

\( \sigma_p^*; (\sigma_p^r) \) are the values of the maximum tensile stresses in the bottom fibers of the ribs for plate without splices in the cover and with splices, respectively; 
\( f'; f \) - the same, maximum vertical displacements.

The values of the coefficients \( k_{sp,w} \) and \( k_{sp,f} \), depending on the \( L_2/L_1 \) ratio, are presented in Table 1.

For intermediate ratios \( L_2/L_1 \) the coefficient values can be determined by linear interpolation.

| Coefficient | \( L_2/L_1 \) ratio | \( L_2=0 \) |
|-------------|---------------------|------------|
| \( k_{sp,w} \) | 4                   | 1.1        | 1.47 |
|             | 2                   | 1.21       | 1.23 | 1.47 |
| \( k_{sp,f} \) | 1.4                 | 1.7        | 2.0  | 1.78 |
|             | 1.37                | 1.65       | 1.9  | 1.72 |

\(^a\) The numerator shows the values for panels with SP covers, and the values with OSB covers - in the denominator.

6. Conclusions

- A mathematical model for the stress-strain state of wooden-composite ribbed bent plates with flexible ties and splices in the cover determination was developed.
- The splices in the cover negatively affect the stress-strain state of the wood-composite structure, increasing the normal tensile stresses in the rib by 10 ... 50\%, the maximum vertical displacements by 40 ... 100\% compared to a panel without splices in the skin.
- If it is necessary to arrange splices in the skin, it is recommended to move them outside the middle 1/3 of the common plate span. If it is impossible to fulfill this condition, it should be taken into account which of the criteria: strength or deflection - is the main one when assigning the dimensions of the cross-section of the main bearing ribs.
- The values of the coefficients \( k_{sp,w} \) and \( k_{sp,f} \) are proposed for the engineering design of ribbed plates, taking into account the decrease in the strength and deformation characteristics of the composite section of the panel with splices in the cover. The values of these coefficients are recommended to be determined according to table 1.

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