Engineering calculations and numerical modeling of composite adhesive plywood panels

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Abstract. The global construction industry is witnessing a surge in production volumes, particularly in residential construction. To address the growing demand for prefabricated and cost-effective housing, the proposition is to employ glued plywood panels as construction components for building floors and roofs. These panels, comprising a timber frame, plywood skins, and insulation, offer numerous advantages, including low weight and a high strength-to-weight ratio. The objective of this study was to diminish the material consumption of panels by comparing calculations using both the traditional engineering method and the finite element method within a software package. The methodology for calculating and designing glued plywood panels, when employing the engineering method, involves determining the geometric characteristics of the panel sections, accounting for variations in the elastic moduli of wood and plywood. In the numerical calculation, the design method of plate elements of the "ReGridQuad" type was chosen, with the assignment of the required plate thickness. The outcomes of all calculations revealed comparable stress and deflection patterns in structures. The values obtained from both calculations were found to be below the standard ones. Research in this domain underscores the significance of numerical calculation methods in enhancing the quality of glued plywood panels, rendering them more competitive in the building materials market.

1 Introduction

Currently, the construction industry is experiencing a significant expansion of horizons on a global scale, which is confirmed by data from the National Rating Agency, which indicates that in 2022, construction production volumes increased by 26% compared to 2021, and for the period from January to November 2022, the volume of federal infrastructure spending on housing construction increased by 10.5% compared to the results of the same period the previous year. In this regard, the demand for structures that allow the construction of prefabricated, financially attractive and affordable housing that meets modern regulatory requirements has sharply increased [1].

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This article presents one of the approaches to solving the previously mentioned problem – through the introduction of glued plywood panels in construction, acting as load-bearing [2] and enclosing structures of floors [3] and coverings of residential and public buildings [4]. Glue plywood panels consist of a wooden supporting frame and plywood sheathing, connected together with waterproof glue in a box-shaped section, as well as insulation made of fireproof and bioresistant materials, such as polystyrene foam and glass mats.

The feasibility of using adhesive plywood panels in the construction of permanent buildings is determined by a number of advantages, such as: low weight of the finished structure, high load-bearing capacity, environmental friendliness, high industrial readiness and ease of installation [5].

The purpose of this work is to reduce the material consumption of adhesive plywood panels used in modern construction by determining possible safety margins. To do this, the task was set to calculate the model of the glued plywood panel using existing design tools in the Lira 10.12 software package, and to conduct a comparative analysis with the engineering method performed using standard formulas of structural mechanics.

In international scientific publications, this topic is presented by a number of studies that confirm the relevance and feasibility of using the numerical method of calculating glued plywood panels in modern construction.

In article [6] a study was carried out of the influence of the arrangement of layers on the mechanical properties of laminated veneer lumber panels made from poplar and birch veneer. The results showed that the strength [7] and reliability of panels made from birch veneer were higher than those of panels made from poplar. This suggests that proper ply placement can increase the performance value of wood.

Similarly, the possibility of producing veneer for glued veneer panels from ash and red pine [8], hardwood [9], fast-growing poplar and eucalyptus [10], modified poplar veneer [11], and also obtained by combining various wood veneers [12] was studied.

The authors in article [13] studied the effect of various adhesives on the dimensional stability and shear strength of laminated veneer lumber made from pine and Black Sea spruce veneer after exposure to steam. The research results showed that timber made from Black Sea spruce with phenol-formaldehyde glue had the largest increase in mass, and timber from pine with the same adhesive composition had the largest radial swelling. Such studies expand the scope of application of adhesive plywood panels, in which the skins are joined to the ribs through an adhesive layer.

Research was carried out to determine the effect of heat treatment of veneer on the mechanical [14], physical [15] and biological [16] properties of plywood and its behavior under long-term load; the possibility of the influence of wood species [17], types of thermoplastic films and short-term thermomechanical compaction was also investigated [18] on the structure and properties of wood veneers. This study provides an opportunity for a more in-depth study of the application of glued plywood panels in modern construction, taking into account various aggressive environments.

The authors in [19] studied the effect of moisture content on the mechanical properties of laminated veneer lumber. Tests were carried out on samples of laminated veneer lumber with different moisture content and analyzed its effect on the strength and durability of the material. Such studies show how wide the range of applications of adhesive plywood panels is in industrial construction.

In article [20], the authors presented a calculation program capable of performing classical calculations of a glued plywood panel and subsequently analyzing the results obtained.

The author in [21] carried out a comprehensive assessment of the impact of the anisotropy of the elastic characteristics of wood and plywood on the stress-strain state of the elements of the glued plywood ribbed board. The research results showed that the anisotropy of wood properties negatively affects the stress-strain state of structures, which emphasizes the need to take this factor into account in design calculations and scientific research. In addition, it was found that the use of reinforcing stiffeners is an effective design solution for increasing the local stability [22] of compressed plywood slab sheathing and also helps to reduce the material intensity of plywood slab sheathing [23].

Despite all the existing research, it was not possible to fully simulate the calculation using the numerical method and carry out a comparative analysis with the engineering method due to the lack of specialized design tools in all kinds of calculation software packages, therefore, the potential application of this design was not fully revealed and needed further research.

2 Methods

The first stage of the analytical comparison of the two previously mentioned methods for calculating ribbed plywood panels is to consider the engineering method according to the scheme of a single-span simply supported beam for standard and design loads from its own weight and snow. The geometric parameters of the panel in question in plan are 1.48x5.98 meters. The panel design consists of upper and lower skins made of waterproof bakelite plywood, the thickness of which is 8 and 6 mm, respectively, as well as longitudinal ribs made of pine wood with strength class K24, 44 mm high.

The methodology for calculating and designing glued plywood panels, when considering the engineering method, consists in determining the geometric characteristics of the panel sections, determined taking into account the different values of the elastic moduli of wood E_w and plywood E_p. As a result, the given geometric characteristics of the section are determined using the formulas presented in Table 1.

Table 1. Results of the given geometric characteristics of the section

N	Defined parameter	Formulas
1	Reduced (to plywood material) cross-sectional area	$A_{coer} = A_{us} + A_{ls} + \frac{E_w}{E_p} A_e$
2	Reduced static moment of the entire section relative to the axis passing through the lower edge of the lower skin	$S_{coer.x1} = S_{us} + S_{ls} + \frac{E_w}{E_p} S_e$
3	Distance to the neutral axis from the bottom edge of the entire section	$y = \frac{S_{coer.x1}}{A_{coer}}$
4	Reduced moment of inertia about the neutral axis	$I_{coer} = I_p + I_w + \frac{E_w}{E_p}$
5	Moment of resistance of the upper skin	$W^u_{coer} = \frac{I_{coer}}{h-y}$
6	Moment of resistance of the lower skin	$W^l_{coer} = \frac{I_{coer}}{y}$

After determining the cross-section of glued plywood panels, all necessary checks are performed for each element according to the conditions of strength and deformability [24], presented in Table 2.

Table 2. Test results of wooden prototypes and reinforced samples

N	Item name	Name of check	Formulas
1	Lower skin	Test of strength	$\sigma == \frac{M}{W^{l}_{coer}} \le R^{s}_{p} m_{p}$
2	Upper skin	Checking stability for local bending	$\sigma = \frac{M}{\left(\frac{E_w}{E_p} I_w + \varphi_p I_p\right)}(h-y) \le R^{c}_{p}$
3	Upper skin	Checking local bending strength	$\sigma == \frac{6Pa}{8b\delta^2} \le R^{b}_{p} m_{l}$
4	Top edge of the rib	Normal stress strength test	$\sigma = \frac{M}{I_{coer}} = (y-\delta_2)\frac{E_w}{E_p} \le R^{b}_{w}$
5	Lower edge of the rib	Checking strength by shear stress	$\tau = \frac{QS^{e}_{coer}}{I_{coer}\sum b_e} \le R_s$
6	Glue joints	Check for chipping	$\tau = \frac{QS^{ls}_{coer}}{I_{coer}\sum b_e} \le R^{p}_{s}$
7	Panel	Deformability check	$\frac{f}{l} = \frac{5q^{norm}l^3}{384E_w I_{coer}} \le \left[\frac{f}{l}\right], \left[\frac{f}{l}\right] = \frac{1}{200}$

It is important to note that the results obtained during calculations using the engineering method have been used over the past 50 years and have been recognized as reliable and reliable. Based on this, it was decided to model this problem in the Lira 10.12 software package.

The second stage of the analytical comparison of the two previously mentioned methods for calculating ribbed veneer panels is the consideration of the numerical method in the Lira 10.12 software package, based on the typical formulation of the problem being created: a spatial structure (X,Y,Z,UX,UY,UZ) with the application of a load from its own weight and snow.

The initial values of the geometric characteristics of the glued plywood panel and the physical and technical parameters of lumber were taken similarly to the initial data for the engineering calculation method.

The presented problem is solved within the framework of the following assumption: lumber composite adhesive plywood panels operate within the limits of the elastic properties of the materials and do not enter either the elastoplastic or the stage of destruction, i.e. obey Hooke's law.

The first stage of modeling and calculation of the glued plywood panel, during the consideration of the numerical method, is the selection of the design method from plate elements of the “ReGridQuad” type, by assigning the required plate thickness in the z-y plane, the intermediate result is presented in Figure 1.

To complete the previous stage, the final model was triangulated with a step of 5 cm and secured according to the scheme of a single-span simply supported beam with a hinged movable support along the x, z axes and a hinged and fixed support along the x, y, z axes. The final result of constructing an adhesive plywood panel from architectural plates is presented in Figure 2.

The second stage of modeling and calculation of the panel is the assignment of physical and technical characteristics of linear orthotropic materials for the ribs and skin, such as: elastic modulus, shear modulus, Poisson's ratio. Their values are presented in tables 3 and 4.

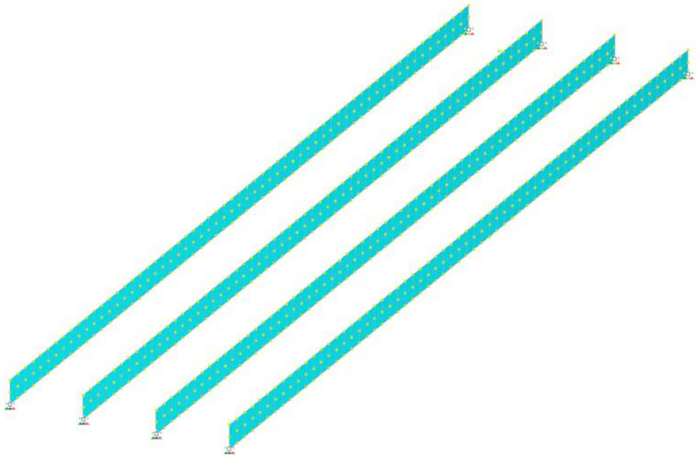

Fig. 1. Construction of the edges of the adhesive panel

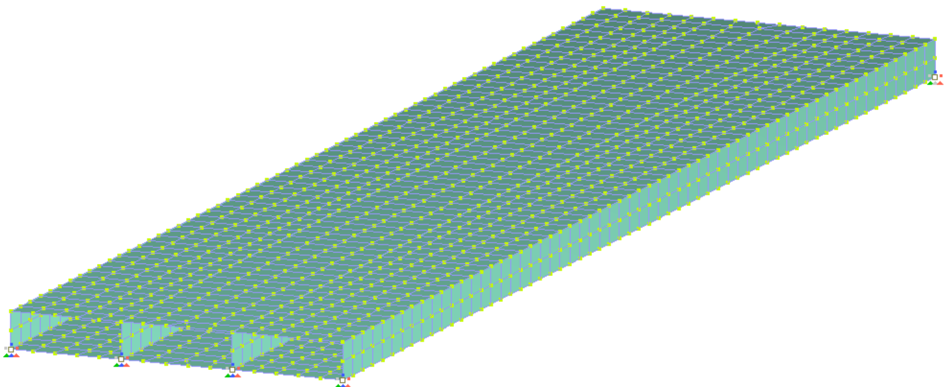

Fig. 2. Construction of the adhesive panel

Table 3. Physical and technical characteristics for the ribs material

Modulus of elasticity, tf/m^2			Shear modulus, tf/m^2		
E1	**E2**	**E3**	**G12**	**G13**	**G23**
44000	110000	44000	12000	4800	4800
Poisson's ratio					
0.5	0.02	0.5	0.02	0.5	0.5

Table 4. Physical and technical characteristics for sheathing material

Modulus of elasticity, tf/m^2			Shear modulus, tf/m^2		
E1	**E2**	**E3**	**G12**	**G13**	**G23**
9000000	611830	9000000	76478	76478	76478
Poisson's ratio					
0.065	0.085	0.065	0.085	0.065	0.065

The third stage of modeling and calculation of the panel is to assign the type of loading of the structural elements and select the most unfavorable combination of loads, such as a

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uniformly distributed force on the top plate and an interactive load - its own weight, which falls on the entire frame. A graphical representation of the most unfavorable combination is shown in Figure 3.

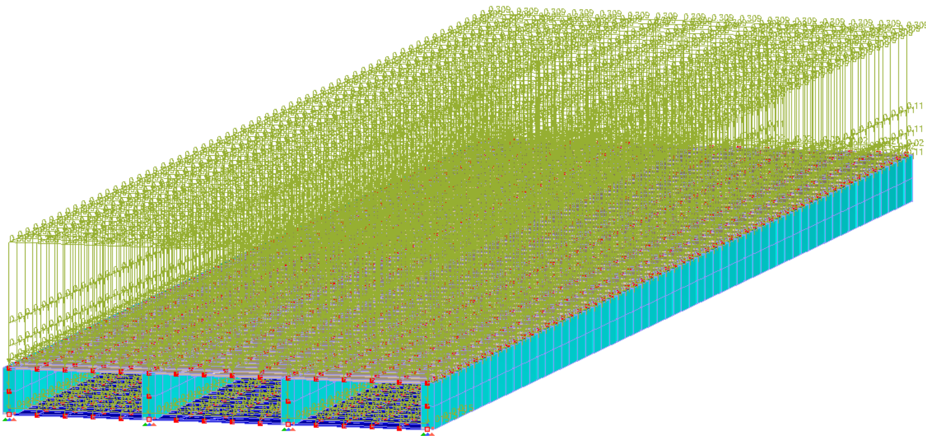

Fig. 3. Graphical representation of the most unfavorable combination of loads

The fourth stage of modeling and calculation of the panel is the analysis of the obtained results of the forces arising in the glued plywood panel (Nx, My, Qx) presented in Figures 4,5,6, respectively, and the determination of displacements (Fz), which was carried out by analyzing the obtained isofields and mosaics movements along the Z axis, presented in Figure 7. The final results for strength and deformability for each element were checked in a similar way to the engineering calculation method.

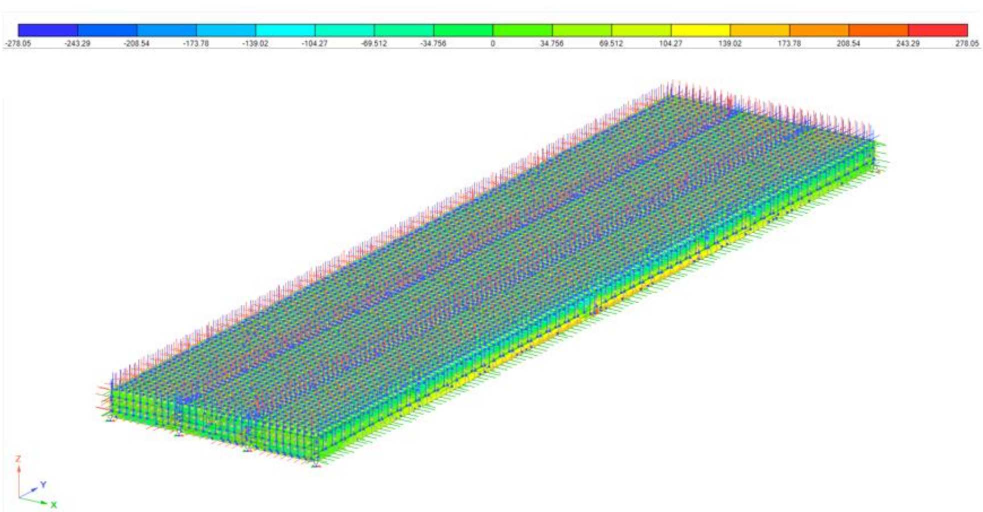

Fig. 4. Tensions N_x, tf/m^2

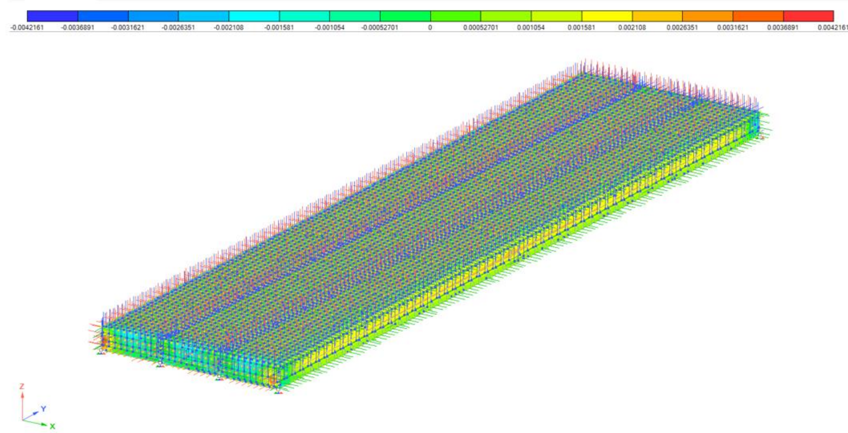

Fig. 5. Forces M_y, tf*m

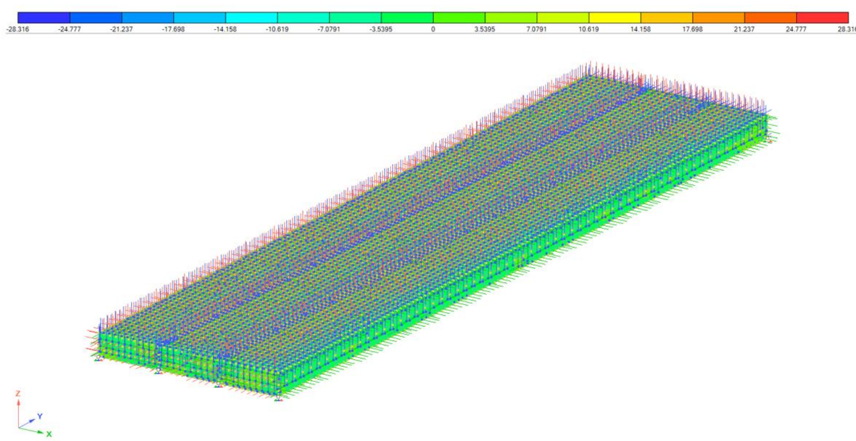

Fig. 6. Forces Q_x, tf.

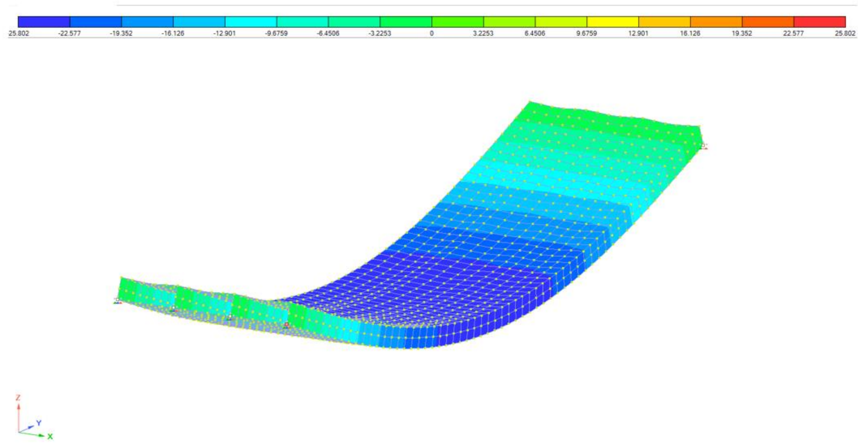

Fig. 7. Deflections F_z, mm

3 Results and Discussion

An analytical comparison of the results of the two calculation methods of the Lira 10.12 numerical simulation and the engineering method presented in Table 5 showed that both of these methods produce comparable results regarding the performance of the structure. The final results obtained using both methods were also less than the calculated values specified in the design standards for wooden structures. This suggests that the structure has sufficient strength and the presented calculations are acceptable when developing adhesive plywood panels for real construction.

Table 5. Analytical comparison of the results of two calculation methods

N	Item name	Engineering calculation	Numerical modeling Lira 10.12	Discrepancy, %
1	Lower skin, tf/m^2	670.97	617.25	-8.7
2	Upper skin, tf/m^2	$\frac{976.88}{624.062}$	496.1	$\frac{-97}{-25.8}$
3	Bending of the upper skin, tf/m^2	687.29	167.0	-311.55
4	Top edge of the rib, tf/m^2	767.85	546.5	-40.5
5	Lower edge of the rib, tf/m^2	693.41	406.9	-70.41
6	Oblique bend of the rib, tf/m^2	28.86	61.15	+111.89
7	Glue seam, tf/m^2	24.37	70.19	+188.02
8	Deflection, mm	20.2	25.8	+27

Note: in line 2, the number of fractions indicates the value of stresses taking into account the buckling coefficient, in the denominator - without taking it into account.

The stresses in the lower casing obtained as a result of both calculations have minimal discrepancies and, therefore, are reliable. Also, a small difference indicates that the computer model of the glue-plywood board design was chosen correctly. The discrepancy between the stress values in the upper skin for stability was -97 %. This discrepancy in stability is due to the fact that in PC Lira the buckling coefficient φ is not taken into account. The increased discrepancy between the stress values in the adhesive joint is a consequence of the fact that the stress data in the Lira PC are taken along the upper edge of the rib, because a separate layer of the adhesive joint was not specified at the initial stage of modeling. Most likely, in its presence, the voltages will be more comparable, which we will definitely take into account in further studies. The differences in the bending strength stresses of the ribs range from -311.55 to +111.89 %, which is a large value and requires additional verification. The deflections of the entire structure obtained as a result of analysis of comparisons of two calculation methods have a discrepancy of +27%. This discrepancy goes into the safety margin and generally confirms the correctness of the choice of the orthotropic wood model in PC Lira.

In addition to the above, to identify the actual stress values in the structure of glued plywood panels, full-scale tests using strain gauge methods are required. This method will allow us to determine the accuracy of both calculation methods.

4 Conclusions

Analyzing the results of two calculation methods - numerical modeling of Lira 10.12 and the engineering method, the following conclusions can be drawn:

1. Simulation of calculations using the numerical method has been and remains a relevant topic for future research. Many scientists from all over the world are directing their efforts to obtain developments in these areas, since their relevance is expressed in many factors, such as: obtaining more accurate results, reducing time and resources, eliminating research in dangerous and extreme conditions, improving design and optimization. Overall, numerical simulation has relevance in a variety of fields and plays a key role in improving our technologies, developing new products, and predicting the behavior of complex systems.
2. Numerical modeling was carried out in Lira 10.12, in which comparable results were obtained with the engineered calculation method for the nature of the structure's operation, and the values obtained as a result of both calculations are less than the standard ones. As a result of the numerical calculation, final values were obtained that differed from the engineering calculation, but most of them go into the safety margin. Based on the resulting difference in values, we can conclude that the engineering calculation method involves many assumptions and, as a result, increased stress indicators, due to the fact that the Lira 10.12 software package does not take into account design for volumetric and plate elements. To confirm the accuracy of the results of engineering or numerical calculations, field tests are required. It should be noted that it will be enough to carry out tests in the elastic stage of the materials, and not to bring the structure to destruction. This "gentle" testing regime will allow to preserve the glued plywood panel for further use. These studies will reveal the real values of stress and deformability of the adhesive plywood panel structure. After they are determined, it will be possible to enter correction factors into the engineering calculation method or make refinement design settings in PC Lira.

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