Enhancing the efficiency of using deformable aluminum alloys in composite constructions

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Deformable aluminum alloys have found extensive application in construction, either as standalone bar or sheet structures or as components in composite constructions based on concrete or wood. The latter type is gaining traction due to its ability to counterbalance the negative properties of one material with the positive attributes of another. Combining aluminum and wood enables the creation of structures with high physico-mechanical properties, aesthetic appearance, and good serviceability, including in some chemically aggressive environments or under exposure to low temperatures. This study examines the load-bearing capacity of aluminum-wood floor panels, focusing on the influence of rib cross-sectional shape and the type of deformable aluminum alloy from which they are fabricated. The upper sheathing of the panels under study consists of 12-mm thick plywood sheets. The ribs are directed downward and positioned along the perimeter as well as transversely in the middle, at the junction of the plywood sheets. The types of aluminum profiles used include a rectangular tube measuring 60×120×4 mm, a channel measuring 100×40×3 mm, and an I-beam measuring 116×100×5 mm. The profile materials are chosen from three commonly used aluminum alloys: 6061, 6063, and 7075, all thermally treated to T6 conditions. To select the most effective cross-sectional shape and alloy for the ribs in the composite floor panel, numerical modeling was carried out using the finite element method in the ANSYS software suite. The results yielded stress and vertical displacement isofields. Based on the combined performance and techno-economic indicators (strength utilization factor, stiffness, and cost), the channel profile made from 6061 T6 and 6063 T6 alloys is recommended as the most optimal choice for panel ribs.

Key words: aluminum alloy, aluminum composite panels, computer simulation, strength, deformability

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Introduction

Over the past century, composite materials and structures based on them have gained a prominent position across various industries. It is the combination of different materials within a single product that enables the enhancement of essential physical and mechanical properties or the mitigation of the negative attributes of individual materials [1–3]. For example, wood exhibits a clear trend toward use in combination with steel [4]. In such structures, the core principle mirrors that of reinforced concrete elements: wood (like concrete) is primarily utilized for bearing compressive stresses, while steel (similar to reinforcement) is employed to withstand tensile stresses. The high modulus ratio between steel and wood (approximately 20) facilitates significant stress transfer from wood to the steel element within the same structure. Given that the calculated strength of steel is more than ten times that of wood, this underscores the rational use of these materials in composite structures, as evidenced by numerous domestic and international studies on steel-reinforced wooden structures [5–10].

Aluminum ranks as the second most commonly used metal in construction. Evidence of this includes a substantial body of research in the field. For example, researchers at Liverpool John Moores University conducted an in-depth review of aluminum alloys used as structural materials [11]. They compiled a list of the most commonly applied alloys (5052, 6060, 6061, 6063, 6082, 7108) and the forms of the most common cross-sections (RHS, SHS, CHS, I-section, L-, C-, and regular shapes). Additionally, beam and column cross-sections made of aluminum concrete were reviewed. Special attention was given to a comprehensive examination of the applications and potential of aluminum alloys in structures, as described in Yao San's study [12].

Chinese researchers have developed H-shaped flanges equipped with convex ribs for use in grid-type shell roof structures [13]. A team of scientists from Turkey and the

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United States has demonstrated the advantages of aluminum rods over steel in pinned frame structures [14]. Another study [15] examined the dynamic characteristics and performance of aluminum alloy mesh shell structures under seismic loads. Researchers from China, the United Kingdom, and Italy consolidated recent studies on the mechanical characteristics of structural aluminum alloys under fire exposure and post-fire conditions. They also proposed possible fire protection measures for aluminum [16].

Aluminum is also used in composite materials and combined structural constructions. For instance, Brazilian scientists have developed concrete-like construction composites containing 10–35% aluminum anodizing sludge [17]. The resulting construction material, with high compressive resistance, demonstrates both mechanical and environmental effectiveness of industrial waste application in the construction industry. Indian researchers have investigated the potential of using aluminum metal matrix composites (AMMC) as alternatives to steel reinforcement bars in reinforced concrete structures [18]. They achieved a material with a yield strength of 869 MPa and a Young's modulus exceeding 200 GPa.

Aluminum is also used in combination with wood and wood-based materials. The elasticity modulus ratio of aluminum to wood ranges from 4.74 to 7 (depending on the type of wood), while the design strength ratio varies from 4 to 10 (depending on the alloy grade), enabling their use in composite construction applications. Notable advantages of using aluminum in wood structures include: high corrosion resistance (allowing aluminum-wood combinations to be used in aggressive and humid environments); the ability to retain strength under extremely low temperatures; relatively low mass (which helps reduce inertial forces caused by seismic impacts); and a more aesthetically pleasing appearance than steel, allowing the creation of architecturally expressive elements in combination with wood's fibrous structure. Additional benefits include ease of disassembly, recyclability, and potential for reuse, with up to 95% of both aluminum and wood materials being recyclable at the end of their lifecycle, thereby facilitating waste management and reducing the carbon footprint.

However, there are also limitations to using aluminum and its alloys in wood-composite structures: the high cost of the metal, differing thermal expansion coefficients between aluminum and wood, aluminum's modulus of elasticity being approximately one-third that of steel, and the tendency of stainless steel to offset the advantages of aluminum over carbon steel (such as durability, high corrosion resistance, and lower energy production costs). Furthermore, aluminum's low fire resistance (losing strength at temperatures above 100 °C) poses a constraint, though it is worth noting that aluminum products do not emit harmful gases when burned. Analyzing the use of wood and aluminum in modern construction materials and products, the primary approach to using aluminum-wood composites can be identified as the combination of aluminum profiles with plywood, LVL (laminated veneer lumber), or lumber, utilizing adhesives and/or mechanical connections (fastening elements).

Dr. Samuel M. Saleh and Nabil A. (Iran) conducted experimental studies on wooden-aluminum composite beams under static loads [19]. The test results demonstrated the effectiveness of the composite structure, which exhibited a high load-bearing capacity relative to its own weight. The same researchers also conducted experimental investigations on similar beams under impact loads [20]. Researchers from the Institute of Construction Engineering at Poznań University of Technology (Poland) performed a preliminary analysis of aluminum-wood composite beams [21]. A beam made of AW-6060 T6 alloy with a span of 2.7 m was composed of an 80 mm thick LVL X plate laid on the upper flange of an aluminum I-beam measuring 140 mm in height and 90 mm in width. The numerical study validated the effectiveness of such beams, with maximum strength achieved when the compressive resistance of the wood was exceeded — at $M = 42.4$ kN·m. Building on this topic, Marcin Chibinski and Lukasz Polyus from Poland conducted experimental investigations on the bending of aluminum-wood composite beams [22, 23]. Researchers from Australian universities carried out experimental studies on an innovative composite impost made from aluminum and wood, which combines the best characteristics of both materials [24]. A group of Chinese researchers from universities in Changzhou, Shanghai, and Nanjing conducted experimental studies on the shear of composite beam samples, consisting of glued laminated timber in the compressed zone and aluminum I-beam profile in the tensioned zone [25].

Despite the considerable body of work aimed at developing aluminum-wood composites, it is important to note the insufficient exploration of issues related to the selection of cross-sectional shape and aluminum alloy for enhancing the load-bearing capacity of composite structures based on aluminum and wood. To address these gaps, it is essential to focus primarily on the numerical modeling of various aluminum-wood composite design options, which allows for the generation of stress and strain isoplots corresponding to the load characteristics of different cross-sectional configurations and aluminum alloys. The selection of the most rational cross-sectional shape and aluminum alloy grade in composite structures will enhance their effectiveness in construction, improving indicators such as stiffness, load-bearing capacity, and economic viability.

The primary objective of this work is to determine the most rational aluminum alloy grade and cross-sectional shape of aluminum ribs in panels based on the results of numerical studies of aluminum-wood composite panels intended for use in building and structure flooring.

Materials and Methods

Floor panels (slabs) serve as load-bearing and enclosing structures in both civil and industrial buildings. They bear vertical loads and transfer these loads to the walls and columns of the structures. Consequently, the load-

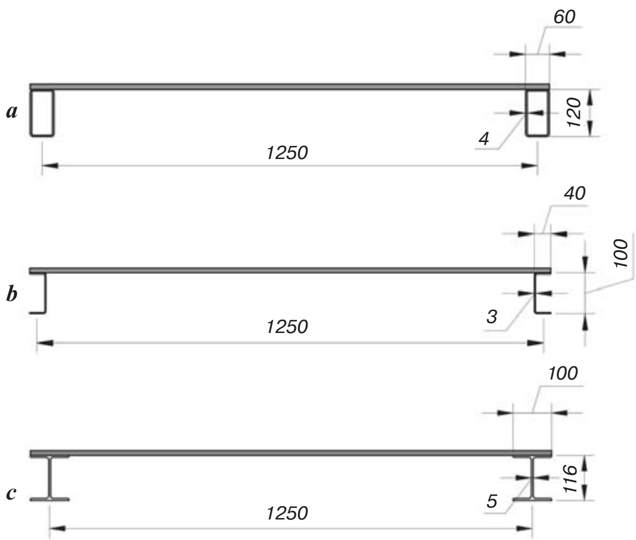

Fig. 1. The cross-section of the investigated aluminum-wood composite floor panels:
a – with ribs made of rectangular tubes, *b* – with ribs made of channels, *c* – with ribs made of I-beams

Table 1
Investigated floor panels

Panel grade	Cross-sectional shape (according to Fig. 1)	Aluminum alloy
P-1		6061 T6
P-2	*a*	6063 T6
P-3		7075 T6
P-4		6061 T6
P-5	*b*	6063 T6
P-6		7075 T6
P-7		6061 T6
P-8	*c*	6063 T6
P-9		7075 T6

bearing capacity of such constructions is crucial for the strength and stiffness of the entire building or structure as a whole. When developing new types of floor slabs, it is essential to conduct a comprehensive investigation, which includes selecting materials that meet all construction requirements (strength, stiffness, durability, fire resistance, etc.); designing the cross-section and calculating geometric characteristics; performing numerical analyses of finite element models; and conducting experimental tests on prototype structures.

This study examines nine variants of aluminum-wood composite floor panels with plan dimensions of 1.25 m (b)× ×3.0 m (l) (see **Fig. 1** and **Table 1**).

The type of panels under investigation consists of ribbed plates with the ribs oriented downward. For the upper sheathing of all panel types, two sheets of FSF construction plywood, each 12 mm thick, are utilized. The plywood sheets are affixed to aluminum profiles installed around the perimeter of the panels and transversely in their midsection. The aluminum profiles are selected based on the most commonly used types in construction: rectangular tube 60×120×4 mm, channel 100×40×3 mm, and I-beam 116×100×5 mm. Three widely used deformable aluminum alloys – 6061 T6, 6063 T6, and 7075 T6 – are chosen as the materials for the profiles.

The primary method employed for the investigation of the stress-strain state of aluminum-wood composite ceiling panels is computer modeling using the ANSYS software. This software suite has established itself as a reliable tool for analyzing the mechanical properties of structural components and products, including those made from aluminum alloys [26–29]. Below is a detailed description of the modeling procedure for the aluminum-wood composite ceiling panel in ANSYS (see **Fig. 2**).

In the initial phase, a "static structural" analysis is selected, which allows for the investigation of the behavior of bodies and structures under various mechanical loads over an extended period. Subsequently, geometric

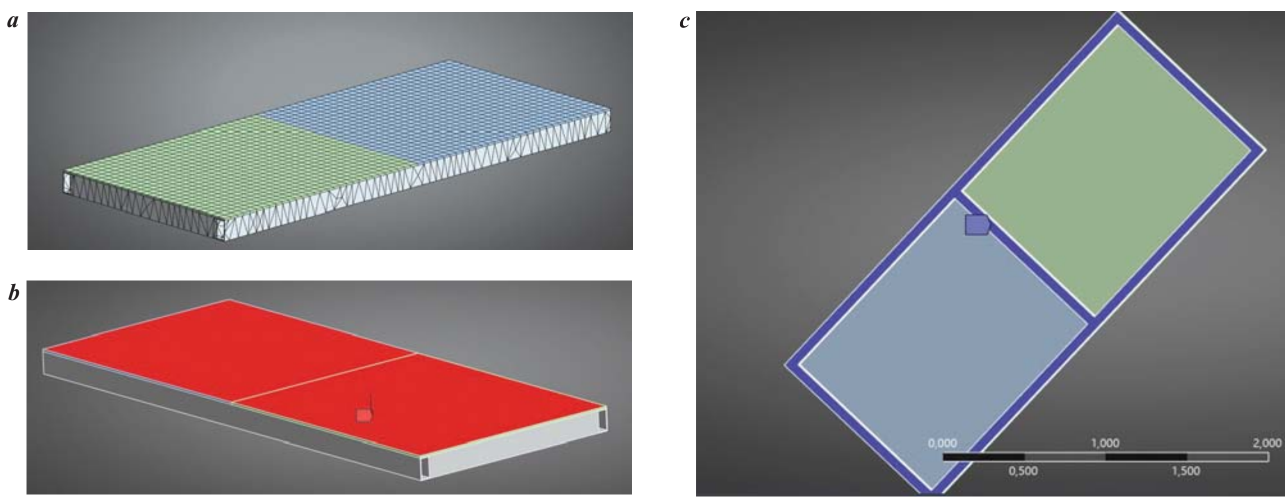

Fig. 2. Modeling of the aluminum-wood composite ceiling panel in ANSYS:
a – model mesh, *b* – application of loads, *c* – boundary conditions

constructions are carried out. ANSYS includes built-in modules for creating 3D models and also supports imported models in "step" and "parasolid" formats. In this study, a solid model in "step" format is imported from SolidWorks.

The next stage involves configuring the model. It is necessary to establish contacts between the bodies or remove them entirely. By default, ANSYS assigns unbreakable "bonded" contacts at the joints of the bodies; in this case, further refinement of the contacts is not required. In the "geometry" section, materials for the constructed bodies must be selected, which can be found in the ANSYS library or created by specifying the required physical and mechanical properties.

The subsequent step involves generating the model mesh. In the settings, one can select the size of the mesh cells and create a mesh from rectangles, triangles, or other more complex shapes. By default, ANSYS automatically determines where to apply each type of mesh. The mesh density and the quality of transitions between elements can also be adjusted. After the mesh is constructed, the primary analysis settings are specified. For this type of analysis, it is essential to set the "number of steps" — the duration of the calculation in seconds (with one step equating to one second in this case) — and to activate the "large deflection" setting to enhance the accuracy of the analysis.

Next, the applied loads on the structure are specified. The current panel includes the self-weight of the structure and a constant load on the plywood sheets (ranging from 0 to 0.08 MPa over 100 steps).

In the final stage, boundary conditions (constraints on the model's movement) are set, and the analysis settings are established. Once the model is fully prepared, calculations for stresses and deformations are performed. In the finite element analysis, ANSYS employs a modified Ludwig von Mises criterion for analyzing failure conditions.

Results and Discussion

The results of the simulation are presented as isostatic stress fields (see **Fig. 3**) and vertical displacements — deflections (see **Fig. 4**) in the aluminum ribs of the floor panels.

Table 2 presents the results of the numerical analysis of the studied aluminum-wood composite floor panels.

Figs. 5, 6 shows the load-stress and load-vertical displacement relationships. The diagrams are constructed only for aluminum ribs of the panels.

It should be noted that the material of the ribs in the ceiling panel structures does not reach yield strength values, which is why the deformed aluminum alloys 6061 T1 and 6063 T6 exhibit similar dependencies on the graphs. Analyzing all the results from the modeling of the stress-strain state of aluminum-wood panels leads to the clear conclusion that the structural failure occurs due to the loss of load-bearing capacity of the plywood sheathing. The destructive load for panels P-1 to P-3 averaged 55.53 kN/m^2,

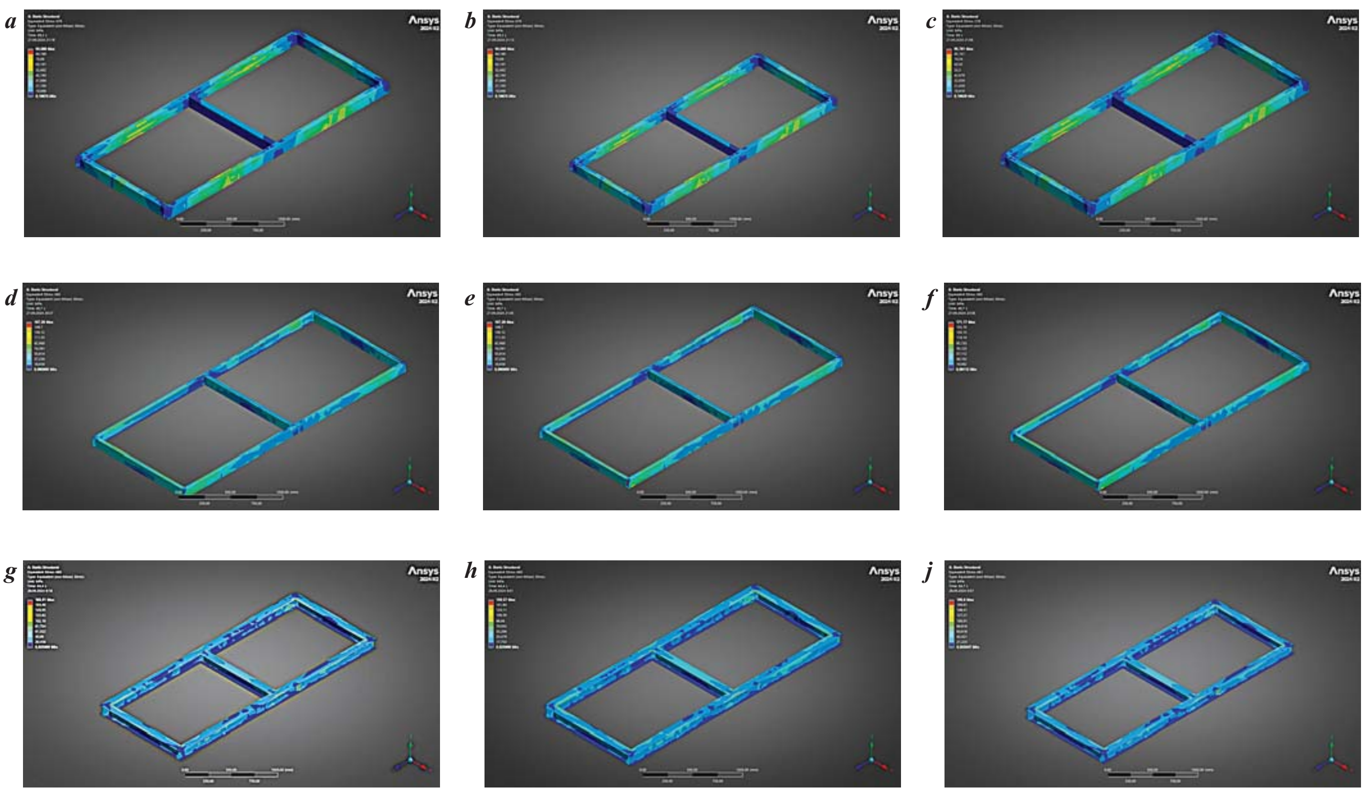

Fig. 3. Stress isofields in the aluminum ribs of the floor panels, Pa:
a – P-1; *b* – P-2; *c* – P-3; *d* – P-4; *e* – P-5; *f* – P-6; *g* – P-7; *h* – P-8; *j* – P-9

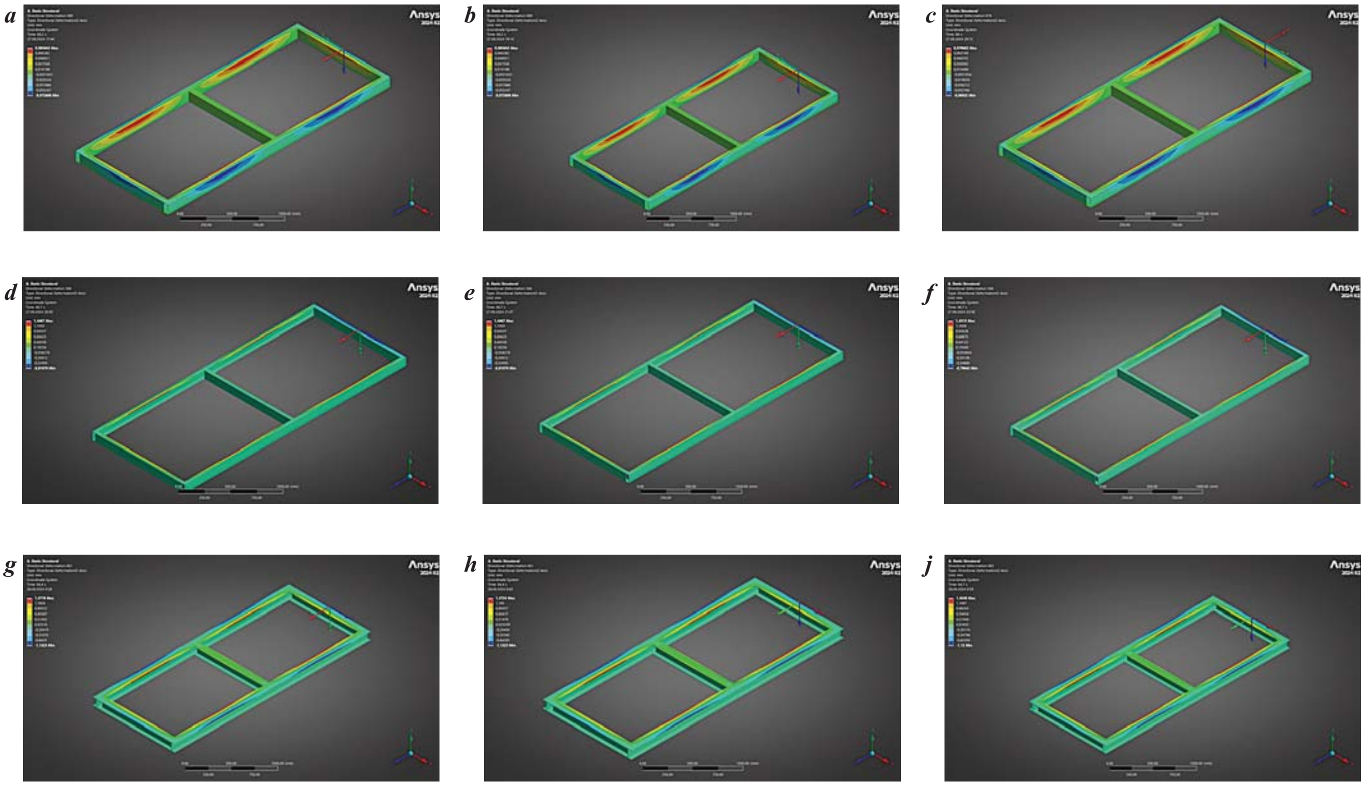

Fig. 4. Deflection isofields in the aluminum ribs of the floor panels, mm:
a – P-1; *b* – P-2; *c* – P-3; *d* – P-4; *e* – P-5; *f* – P-6; *g* – P-7; *h* – P-8; *j* – P-9

Table 2
Results of the numerical analysis of the studied floor panels

Panel grade	Calculated load, kN/m^2	Destruction load, kN/m^2	Stresses in the element, MPa		Vertical displacements of the element, mm	
			Aluminum ribs	Plywood cladding	Aluminum ribs	Plywood cladding
P-1	30.222	55.111	56.248 / 94.688	38.105 / 56.144	0.251 / 0.418	29.032 / 36.733
P-2						
P-3	30.465	55.949	57.489 / 95.781	38.234 / 56.165	0.243 / 0.399	29.036 / 36.569
P-4	18.747	32.081	114.0 / 167.28	38.244 / 56.304	0.88 / 1.447	31.854 / 41.062
P-5						
P-6			116.03 / 171.17	38.141 / 56.147	0.875 / 1.43	31.764 / 40.935
P-7	30.06	51.232	111.08 / 183.91	38.127 / 56.223	0.89 / 1.472	32.473 / 41.5
P-8						
P-9	30.22	51.475	115.35 / 190,8	38.176 / 56.255	0.883 / 1.455	32.444 / 41.429

Note: Stresses and vertical displacements are specified in the numerator when the normative resistance of the plywood material is reached from the design load on the structure, in the denominator – when the structure sheathing fails.

while for P-4 to P-5 it was 32.08 kN/m^2, and for P-7 to P-9 it was 51.35 kN/m^2.

The maximum stresses at the moment of failure of the plywood sheathing in the aluminum ribs of panels P-1 to P-3 did not exceed 95.78 MPa, while for P-4 to P-5 it reached 171.17 MPa, and for P-7 to P-9 it was 190.8 MPa. Considering that the yield strengths for alloys 6061 T6, 6063 T6, and 7075 T6 are 276 MPa, 214 MPa, and 503 MPa respectively, it can be concluded that the maximum utilization ratios for the aluminum ribs are 0.34, 0.44, 0.19, 0.606, 0.78, 0.34, 0.67, 0.86, and 0.38 for panels P-1 to P-9, respectively. The utilization ratio of the load-bearing capacity of the ribs based on the first group of limit states under the design load is 0.2, 0.26, 0.114, 0.41, 0.53,

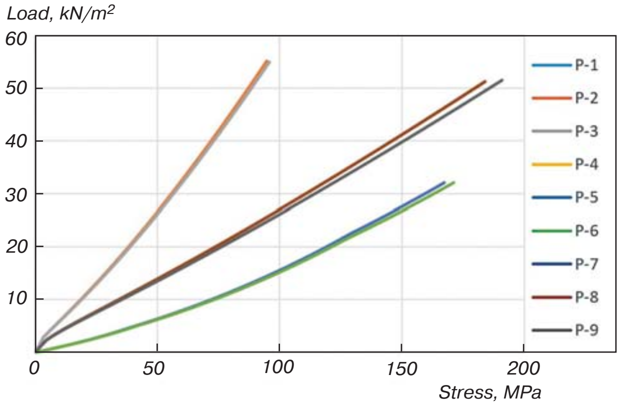

Fig. 5. Load-stress diagram for aluminum ribs

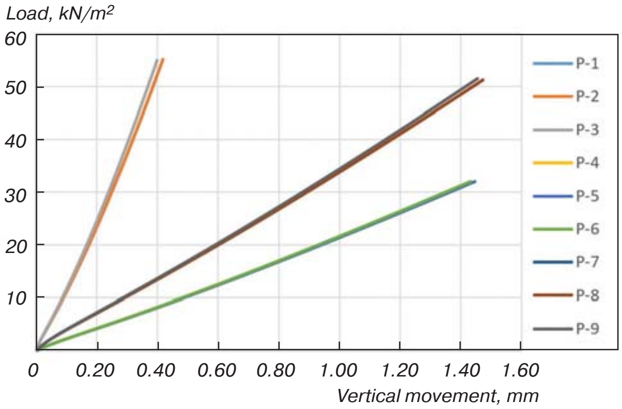

Fig. 6. Load – vertical displacement diagram for aluminum ribs

0.231, 0.4, 0.51, and 0.3 for panels P-1 to P-9, respectively. Given these ratios, it can be concluded that the more favorable alloy for the ribs of the studied panels is 6063 T6. The most rational cross-sectional shape is considered to be the channel and I-beam, with rib element loads exceeding 50%.

The deformability of the ceiling panels should not exceed 1/150 of the calculated span. For the designs with hinged support, the maximum allowable deflection is 20 mm. The vertical displacements of the tested ribs under the design load ranged from 0.24 to 0.89 mm for all types of panels; thus, the load-bearing capacity for the second group of limit states is ensured with a reserve of 95%. In the analysis of the deflections of aluminum-wood panels, the choice of alloy did not significantly affect the deformability of the structure. However, the ribs made from rectangular profiles exhibited the highest stiffness, being 3.5 times greater than that of other profile types, while the deformability of the channel and I-beam profiles coincided within 98%.

The final load-bearing capacity of the tested aluminum-wood ceiling panels is determined based on the design load at which the stresses in the plywood sheathing reach the normative resistance. For panel grades P-1 to P-3 and P-7 to P-9, this capacity does not exceed 30 kN/m^2, whereas for panels P-4 and P-5, it is 18.75 kN/m^2. Given the nature of the structural failure, the influence of the chosen deformed alloy on the overall load-bearing capacity of the ceiling panel structure is practically negligible. However, the shape of the aluminum profile, with a similar construction height of the panel, does affect the load-bearing capacity. The use of rectangular profiles and I-beams as ribs for the panels provides an advantage of 1.6 times over the ribs made from channels.

To select the most economically efficient rib for the panel, cost calculations for the materials were conducted. The weight per running meter of the rib made from rectangular profiles is 3.73 kg, from channels is 1.864 kg, and from I-beams is 4.66 kg. The total length of the profile used in the panel fabrication is 9.75 m. With the average price of aluminum per ton in October 2024 being $2,650 for alloys 6061 T6/6063 T6 and $2,800 for alloy 7075 T6, the total costs for the ribs of the aluminum-wood panels will be $96.37 for panels P-1/P-2, $101.83 for P-3, $48.16 for P-4/P-5, $50.88 for P-6, $120.40 for P-7/P-8, and $127.22 for P-9.

Conclusions

1. The potential for utilizing aluminum ribs in the form of rectangular profiles, channels, and I-beams within composite panels in conjunction with plywood sheathing has been demonstrated.
2. The maximum stresses in the aluminum ribs do not reach the yield strength during the operation and failure of the aluminum-wood panels. The most effective cross-sections identified are channels and I-beams, with a strength utilization factor exceeding 0.5.
3. The deformation of the aluminum ribs did not exceed 0.89 mm. The rectangular profile exhibits the highest rigidity. The load-bearing capacity of the investigated panels ranges from 18.75 to 30 kN/m^2.
4. From an economic standpoint, the most advantageous ribs are those made from channels constructed of alloys 6061 T6 and 6063 T6, which, in conjunction with their strength and stiffness properties, render them the most preferred option for use in the developed aluminum-wood panels.
5. For further optimization of the structural solution and the selection of the optimal combination of cross-sectional shape and alloy, it is recommended to conduct a similar study with panels measuring 4.5 and 6.0 meters in length. Additionally, it is necessary to consider I-beams and angles, as well as two types of aluminum alloys — 5083 H111 and 2024 T3.

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