APPLICATION OF VENEER BASED PANELS IN EXOSKELETON ARCHITECTURE

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ABSTRACT

The development of new materials and technologies is one of the greatest initiator of new architectural thought. Development within the long-standing continuous improvement of wood as material was induced by technological development and new market demands. Good mechanical and physical properties of wood and its easy accessibility, initiated further development and improvement of products based on this material. The aims of this improvement are more rational wood application and improvement of its physical and mechanical properties in regard to monolithic wood. In particular significant are wood-based products made from veneer layers, plywood and laminated veneer lumber (LVL). These materials stand out from other wood-based panel materials due to their mechanical and aesthetic performance. Previous application of veneer-based panels as a structural element in architecture has been implied as secondary or tertiary structural elements which transfer the load to supporting structural members, or to stiffen wooden structures. Recognition a good mechanical property of the material and its advantages as a small self-weight encouraged examining the possibilities of using wood-based panel products as the primary structural support element in exoskeleton structures, i.e. using building envelope as object structure. Application plywood and LVL is research study, so in this paper authors will analyze the possibilities of using these products as an exoskeleton supporting element, through case studies of realized experimental structures. Through research realised structures will be analysed, with a focus on shell structures. They will be evaluated through recognition of its advantages and disadvantages, especially those are directly conditioned by the structural characteristics of the material. Analyses of structures will be done according following criteria: structure design, spatial stability, span constraints, possibilities of loads the structure can support and connections between elements. In order to encourage use of veneer-based panels as load-bearing element in the exoskeleton structure, the paper will set guidelines for further research in this area and will recommend possibilities to improve mechanical characteristics of material. Rationalization of the use of wood-based panels in folded structures will highlight in paper. Forming exoskeleton structure from this material contributes rational use of the structure and raw wood materials saving.

KEYWORDS _ *veneer panels, plywood, exoskeleton, structural elements, building envelope as construction*

INTRODUCTION

Wood as a natural material has remained throughout history as one of the most commonly used materials in construction, primarily because of its easy availability, but also due to its excellent physical and mechanical properties. Technological development and new market requirements have led to development of many wood-based products from wood as a basic material, as a result of the main advantages of wood raw materials such as more rational use and better physical and mechanical properties than monolithic wood. In architecture, products based on veneer layers, plywood and laminated veneer lumber (LVL) are of special importance, and they stand out additionally due to their mechanical and aesthetic performance.

Plywood and LVL materials are wood-based products obtained by veneer layers glued together. The way of their formation contributed to the improvement of certain constructive properties in relation to monolithic wood, primally due to the decreasing material limitations as a result of its anisotropy. By distributing the errors through the panel and eliminating them in production, they reduced the variability in material properties, that is, they equalized the mechanical properties of the product in the longitudinal and transverse direction.

The application of veneer-based panels in architecture today is most often in conventional ways, and can be non-constructive - in the form of roof, floor and wall coverings, and constructive - for making diaphragms and shear walls, beam elements or filling elements of complex beam systems. Wood-based panel materials are most often secondary or tertiary structural elements, which serve to accept loads and transfer them to load-bearing structural elements, or to increase the stability of wooden structures.

The weight of element itself and its mechanical properties have encouraged researches in the direction of application of wood-based panel products as a supporting element of the structure- spatial structures. This type of application can be named unconventional method of application, where wood-based panel forms the entire exoskeletal structure, thus becoming the primary supporting element in spatial structures - primarily shell and fold structures. The formation of such structures from wood-based panels contributes to material savings and rational use of construction. For the purpose of this research, in the world, only a few architectural structures have been formed in which veneer and / or LVL panels represent the only structural element and thus form both the structure and the envelope of the building. Due to the dimensional limitations of the panels, the objects formed in the structural system of the shell are made from interconnected smaller flat segments of panels formed of veneer.

Within this research, possible ways of applying veneer - based panels as bearing exoskeletal structures will be defined. The paper will point out the potentials of the application of veneer - based panels in architecture, the analysis of the spatial structures realized so far, but also the problems and limitations of this material. The result of the research is the definition of guidelines and recommendations for the possibility of improving veneer-based panels, with the aim of their wider application in design practice.

PLYWOOD AND LAMINATED VENEER LUMBER (LVL)

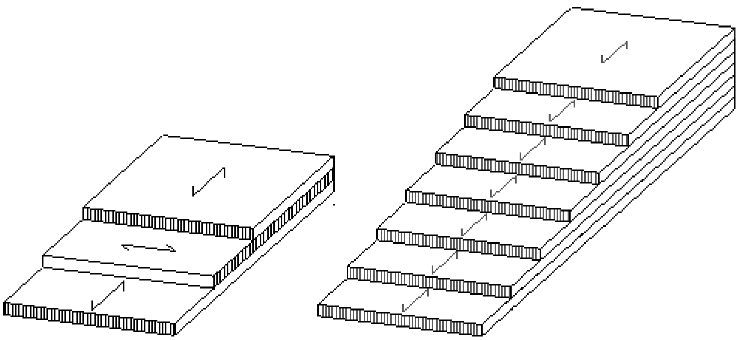
As above-mentioned, veneer-based products that are most often used for construction purposes today are panels formed from layers of veneer - plywood and laminated veneer lumber (LVL). These products are created by gluing layers of veneer together with adhesives. The advantage of products created in this way is the possibility of creating high-strength elements, theoretically without dimensional limitation. The increasing use of these composite products in the construction industry is a consequence of the reduction in the volume of the trunk (logs) and the need to form materials of greater length.

Veneer panels (plywood) are panels made of at least three veneer sheets glued together, whose wood grains are usually placed in a mutual orientation at an angle of 90 degrees (Николић, 2004).

They are formed in standard thicknesses of 6.35–28 mm (Stalnaker, 1997), and for their formation veneers of 2-6 mm thickness are used (Walker, 1993), glued together with adhesive. They can be three-layer boards (triplex), or multi-layer boards (multiplex), with the most common number of layers 5, 7, 9 (Николић, 2004). In order to reduce the anisotropy of the veneer board, the veneers are placed in layers oriented at an angle of 90 ° to the first adjacent layer. This orientation reduces the anisotropy of wood as a material, affects the reduction of swelling, and achieves a more uniform behaviour of the board in two directions due to changes in humidity (Irle & Barbu, 2010). Cross-layering prevents the movement and deformation of individual layers in-plane, the longitudinal orientation of the grains of one sheet of veneer prevents tangential changes to its adjoining sheet. The constant orientation of the veneer layers results in approximately equal stiffness and dimensional stability of the board in both its directions - longitudinal and transverse, and thus the mechanical properties, primarily compressive and tensile strength and stiffness of the board are about the same in both its directions.

Compared to monolithic wood panels, the basic and most important advantage of veneer panels is that the physical and mechanical characteristics of the panel in the longitudinal and transverse direction are quite equal, reducing the possibility of splitting the panel, and enabling the production of larger panels (Youngquist, 2002). In addition to the above-mentioned, the cross-linking of veneer layers in the construction of veneer sheets increases the stability of the board through its layers, i.e., reduces the possibility of splitting veneer sheets, which from the aspect of forming connections between veneer board elements become suitable for mechanical joints - nails, screws, etc. Precisely because of the good mechanical properties in both directions, the application of veneer-based panels can be reflected in constructions with spatial load transfer.

Laminated veneer lumber (LVL) is a wood-based composite product formed of at least three interconnected veneer sheets with a parallel orientation of the grains in the longitudinal direction. Laminated veneer lumber can contain up to 20% of veneer layers whose grains are transversely oriented. Veneers 2.5 mm, 3.2 mm, 3.5 mm thick are used for its production (Šorn, 2006). Laminated veneer, unlike veneer board, is composed of layers of veneer oriented with parallel grains. When forming laminated veneer, as with veneer sheets, the direction of the grains of the outer sheets of veneer (veneer faces) is oriented in the direction of the longer side of the composite product. In this way, its maximum strength in the direction of the span is achieved. The mechanical properties of LVL reinforced with only parallel grains orientation are very often compared with the mechanical properties of monolithic or glued laminated wood, while the mechanical properties of LVL with the existence of strain-oriented grains are compared with the mechanical properties of veneer panels. Laminated veneer is widely used in linear structural elements, where the load is transmitted in one direction, and can also be applied in spatial structures, but taking into account the way the element is loaded in the structure and its position in the entire system.



_ Figure 1. Construction of three-layer veneer sheet and construction of laminated veneer lumber. Author's illustration.

EXOSKELETON STRUCTURES IN ARCHITECTURE

It is mentioned that elements made of veneer-based materials can have a constructive role, as elements that accept and transmit loads in the structure, which are the most common diaphragms, shear walls, beams or part of beams of complex cross section, but also non-constructive, in the form of roof, floor or wall coverings. All of the above can be considered conventional ways of applying veneer-based panels. There are other ways of applying veneer-based panels, which we can freely say are unconventional ways of application, and that is primarily in the form of the supporting outer membrane of spatial structures - exoskeletons. The exoskeleton (Greek: ἐξω - éxō - outside, beyond) is the name for the outer, supporting structure outside the body, and within which the organism is located and which actually forms its supporting structure. The term exoskeleton enters the processes of biomimicry of nature in many sciences and disciplines such as medicine, but also in the branches of technology, especially in robotics and architecture. An exoskeleton in architecture can be defined as an external structure that also becomes the supporting structure of an object, and its role is not only the role of a static and constructive element, but it becomes a structural envelope that can solve complex sets of problems by integrating different building systems (Scuderi, 2015). The exoskeleton is actually the envelope of an object whose role is constructive, it is a membrane that can divide the outer and inner space of an object, it becomes a thermal envelope, controls its energy performance, but also aesthetic values forming the geometry of the object, its shape and expression. The exoskeleton in its primary meaning, using only the external structure of the object, without integration with the internal structure - the endoskeleton is used in only a few structural systems, and these are primarily systems of spatial surface structures - shells and folds. The shell is characterized by the optimal ratio of the mechanical strength of the material since it was formed and its own weight. This is of crucial importance and can provide a significant advantage in the choice of wood-based materials for the formation of exoskeletal architectural structures.
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SHELL STRUCTURES AS EXOSKELETON

Shells are spatial thin-walled curved structures with three-dimensional load transfer, usually large spans, surface-loaded, which are in the membrane state of stress. In wooden spatial structures, shells are formed as polygonal spatial structures composed of panels, interconnected. For their realization, wood-based materials are used - veneer-based panels (veneer and LVL panels) or CLT. Polygonal shells are constructions whose shaping follows the shape of a shell, single or double-curved, positive and / or negative Gaussian curves, but it is composed of flat segments interconnected in a system that forms a single spatial structure. This type of shell provides great opportunities for geometric experimentation and free-form design.

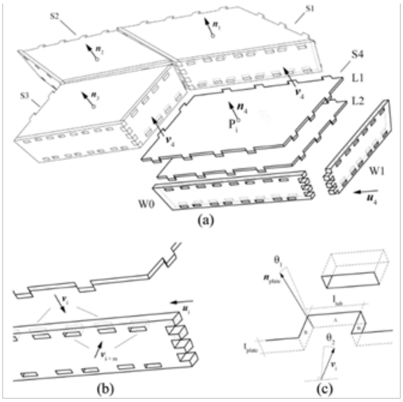
_ Figure 2: ICD/ITKE Research Pavilion 2011. Taken from ttps://visuall.net/2012/05/22/icditke-research-pavilion-2011/, accessed 25.09.2020.

So far, this type shells have been realized only as experimental research facilities, and the pioneers of their development are the research teams of the University of Stuttgart. The objects of polygonal shells that were realized within the research are:

_ Table 1: Realized objects of polygonal shells based on veneer

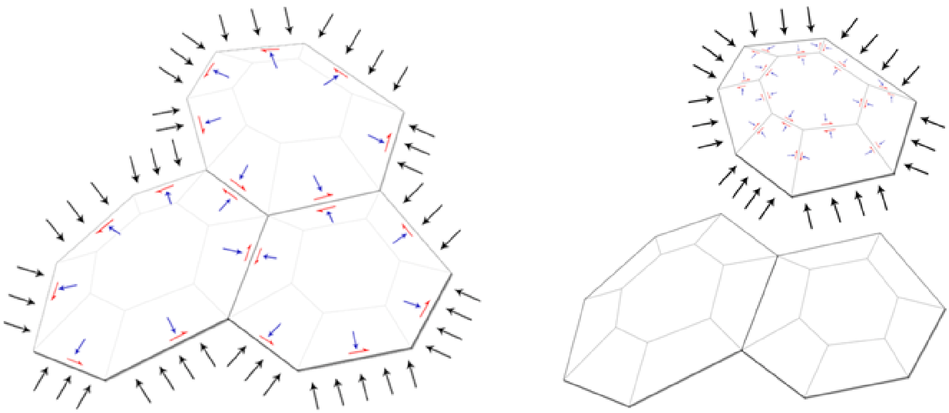
Year	Location	Project Name	Team	Material	Structure Span
2011	Stuttgart, Germany	ICD | ITKE Research Pavilion 2011	University of Stuttgart - ICD/ITKE	Veneer based panels – birch (6.5mm)	
2014	Schwäbisch Gmünd, Germany	Landesgartenschau Exhibition Hall	University of Stuttgart - ICD/ITKE/IIGS	Veneer based panels – beech (50mm)	10m
2019	Heilbronn, Germany	BUGA WOOD PAVILION	University of Stuttgart - ICD/ITKE	Veneer based panels	25x35m
2019	Sidney, Australia	HexBox Canopy	University of Sydney - „Code to Production“ and DTC group	LVL	~4.5m

In the exoskeleton structures of the above - mentioned objects, formed as polygonal shells, common constructive principles based on the principles of trivalent polyhedral segments are observed (Krieg, et al., 2015; La Magna, Waimer, & Knippers, 2016; Bechert, Groenewolt, Krieg, Menges, & Knippers, 2018). This constructive principle implies a topological rule of shaping and forming a polygonal shell by always joining three surface elements in one point (Fig. 3). The structure is formed so that the three plates always meet at one point, stabilizing each other and forming a spatially stable system.



_ Figure 3. Cell hierarchy and load distribution between elements in a trivalent-polyhedral system. La Magna, Riccardo, Frédéric Waimer, and Jan Knippers. „Nature-inspired generation scheme for shell structures." Proceedings of the International Symposium of the IASS-APCS Symposium 2012: From Spatial Structures to Space Structures. (Seoul: IASS, 2012.).

The design and construction of polygonal shell segments is possible in two ways. The first method involves the formation of a shell of segments (cells) composed of several parts forming a segment of box or variant cross- section (Fig. 4). Another way is to form a shell from segments of monolithic cross-section, where one element is a solid veneer-based panel, without substructure elements.
Polygonal shells are usually composed of segments (cells) - consisting of a plate (surface plane layer) and a substructure positioned along the edges of the plate (Fig. 4). The most common are segments of hexagonal shape, which also belongs to the group of trivalent polyhedral networks, in which the other two plates meet at one point of the polygonal plate (Fig. 3). The hexagonal matrix has the possibility of adjustment and shaping in parts of the shell with positive or negative Gaussian curves (Li & Knippers, 2015).



_ Figure 4. Structural system of a single segment of a shell composed of several parts, forming a segment of box cross-section. Robeller, Christopher, Mina Konaković, Mira Dedijer, Mark Pauly, and Yves Weinand. „Double-layered timber plate shell", International Journal of Space Structures 32 (3-4), (2017): 160–175.

The construction and behaviour of individual segments - slabs in the structures of polygonal shells can be compared with the behaviour of a diaphragm or slab in the construction of folds. Common to all the mentioned elements is that axial forces in-plane appear as the dominant load in the construction. Each plate in the construction must work according to the principle of the diaphragm, i.e., accept the forces acting in-plane, i.e., the slabs must not be constructed in such a way as to accept torsion or moments in order to achieve the stability of the structure. The connections between the plates are formed as linear joint connections, through which the transmission of exclusively axial and shear forces is enabled.

The slab in the structure accepts the load acting outside the plane of the slab, the forces are further distributed by forces in the plane of the slab, and by shear are transmitted to the substructure or to the adjacent slab if the shell is formed of slabs in one layer, without substructure. The plate accepts external forces over its entire surface, but their distribution occurs along the edges of the plate, not only through axial forces but also by shear forces in the plane of the plate. The distribution of forces can occur in any direction, depending on the geometry of the shell and the way the connections between the elements are formed.

Precisely due to the distribution of forces in several directions and directions, the most suitable for such constructions is the use of materials that have similar mechanical properties in all directions, and the most commonly used material is veneer panel. Due to its low self-weight and good mechanical characteristics in two directions, the veneer panel is suitable for the formation of exoskeletal structures according to the principle of polygonal shells. Also, its advantage is low self-weight in relation to other wood-based materials, which enables the formation of light structures, low self-weight, where the weight of the material itself does not represent a large constant load on the structure. The small static height (thickness) of the veneer panel can lead to the appearance of protrusions in the plane of the panel when exposed to axial pressure forces. Also, the small thickness of the veneer panel causes small spans of the shell construction, the impossibility of forming a connection. To avoid this, the shell is formed polygonally, in segments, where each segment has its own substructure that reduces the span of the panel itself. Another way to form a shell is in the form of full panels of great thickness, as a massive section of greater static height. The system of receiving and transferring loads on the entire structure does not differ in these two cases.

Pavilions with the segments formed only from veneer-based panels, without substructure, require a large thickness of the panel, i.e., the static height of the element is achieved by increasing the thickness of the panel, which is much larger than usual. The large thickness of the panel in this case is necessary due to the formation of connections between the elements, because in panels with substructure connections between elements are formed at the level of the substructure, while in this case connections are formed directly between two panels. Also, the large thickness of the panels is conditioned by the lateral bending of the panel in-plane at large spans of one element, when the panel is loaded with axial forces. The advantage of such constructions is the possibility of forming a connection between the panels in-plane. The disadvantage of the construction is its more difficult assembly due to the way the elements are connected and their more difficult access. The biggest drawback is the high consumption of materials, and thus the increase in the self weight of the structure, which leads to a large load on the structure under its self weight, which results in a reduction in the span of the exoskeletal structure. Also, the problem in certain elements and positions of these constructions occurs with elements loaded with large shear stresses or large axial forces, which very often the veneer panel cannot support.

Panels based on laminated veneer lumber are not often present in the spatial structures of shells, precisely because of their good mechanical properties expressed in one direction. Since the shells are spatial structures with three-dimensional load transfer, LVL boards are not a good solution in this case, especially for double-curved shells. One realized example of shells using LVL is the construction of a single curved shell, where the load transfer is dominant in only one direction.

CONCLUSION

Veneer panels have proven to be an extremely good material in the design and implementation of exoskeleton spatial structures. In addition to good geometry in such structures, a good choice of materials for their realization is also important. Veneer panels are a natural, environmentally friendly wood-based material with exceptional mechanical properties. Also, their production reduces the consumption of wood raw materials compared to solid wood panels. Different spatial structures can be formed by their application. Their behavior in spatial structures is very good, especially important is their low self-weight. However, there are material limitations in the field of span and load capacity. In order to make their application more widespread in the realization of exoskeleton spatial structures, further research is proposed in order to improve certain mechanical characteristics of veneer panels. Reinforcement of the material would enable the retention of the principle of forming the structure with panels of small thickness, which would enable the achievement of even larger spanes of the structure, by retaining light constructions, with low self weight. The advantage of reinforced wood-based panels is the possibility of using soft wood, with poorer mechanical characteristics for their production. This would contribute to the saving of wood resources and nature conservation.

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