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FORMATION OF FOLDED CONSTRUCTIONS BY USING CONTEMPORARY WOODEN TRUSSES

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Folded structures represent three-dimensional constructions, i.e. spatial structures and as such belong to the field of structural systems. For very long time this type of construction has been realized in practice only in reinforced concrete and executed on site, which resulted in the use of a very complicated shutter. Development of prefabricated building led to the improvement of this type of constructions so that folded structures could be derived by assembly of prefabricated elements and their relationship, monolithization, on site. For decades, this type of construction was carried out solely in reinforced concrete and only in the second half of the twentieth century emerged the realization of folded structures using other materials: steel, wood, glass, polyester resin and a combination of different materials.

This paper the analyzes the existing folded structures made of wood as well as their systematization in terms of applied materials and shapes of cross-section of a folded structure, form of the basis and the method of execution. All the factors that affect the acceptance and transfer of load and static stability of spatial structures have also been analyzed. The focus of this paper is to research the possibilities and ways of forming folded constructions by using wooden trusses. A prototype of cylindrical folded constructions, realized in this system, is shown.

The area of application of wooden trusses as elements of the folded structure represents the area that has not been sufficiently explored in the world and our country, in the field of theory and practice. This work and its actual results represent the expansion of knowledge of the area of folded constructions materialized in wood and contribute to modern engineering structures.

Key words: Wood, Wooden constructions, Wooden trusses, Folded constructions, Formation of folded constructions, Cylindrical folded constructions, Calculation of three-dimensional structures - spatial structures.

INTRODUCTION

Wood and steel are the materials of which are mostly formed in-line bearing elements. Those elements, with different options of combination, can form a surface supporting elements, and, by further spatial combination, spatial folded structures. This way leads to the development of prefabricated folded structures with outstanding engineering solutions.

Striving for a more rational and economical construction, and using wood as a building material of exceptional mechanical, physical and aesthetical properties influenced the use of wooden trusses as elements of folded construction.

The term folded construction defines a folded form of construction, including constructions made of elements which from a folded shape by their mutual relationship in space.

Folded structures made of wooden trusses represent the follow-up of a research on development and possibilities of the application of wooden trusses in building practices. Three-dimensional spatial structures obtained in this way, formed by assembly of pre- fabricated wooden trussed elements with unified connections, enable industrial

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production, simple operation and efficient on-site installation, which provides technological, functional and economic advantage of this construction compared to the folded structures of reinforced concrete.

This paper presents the analysis of possibilities of the application of wooden trusses as elements of the folded structure in theory. It has also been realized the prototype of cylindrical folded structure, span 24.0 m, as a test of a computational model of formation of folded construction using wooden trusses in which the node connections have been realized with denticular steel plates - connectors. In this way, there has also been carried out a practical examination of solution of interconnections of trusses, their stiffening by diaphragms formed of trusses, as well as the spatial stability of the structure formed in such way.

FOLDED STRUCTURES

Folded structures - folds represent spatial i.e. three-dimensional structures, in which the size of elements is very small compared to the range of construction [4].

The term folded construction defines the folded form of construction, including constructions made of plates and structures made of sticks which make a folded form by their mutual relationship in space.

Some authors also name a folded structure the origami construction [1].

Folded structures of wood

Due to limitations in terms of the possibility of overcoming large spans, as well as the reduction of world's reserves of wood, other materials (steel, reinforced concrete) prevailed over wood early in the second half of the nineteenth century [3]. Modern technology has enabled good protection of solid wood and its processing into wooden products, creating new possibilities of the application of wood.

Wood represents a renewable material in nature (it fits into the modern trends of sustainable development) and has advantages over other materials: exceptional physical and mechanical properties, the material is environmentally friendly, has low own weight, it is easy to handle - suitable for mechanical processing, has a possibility of using simple structural joints, it is subject to recycling, and it is possible to move the structure made of wood [2].

Forms of folded wooden structures

Folded structures made of wood are easy to transport, manipulation and assembly. This type of prefabricated folds on the basis of the primary supporting structure of the segment of folds can be divided into:

- panel,
- truss constructions.

Panel folded constructions of wood

Folded constructions of wood are usually formed as a panel (Figure 1.). Wooden panel folded constructions by their primary structure can be divided into:

- full-wall panels,
- panels with grid supporting structure,
- panels with framework (Panel) supporting structure,
- panels with arch supporting structure.

Elements of full-wall panel folded construction are made as compact elements of solid timber or of laminated elements - plywood panels and the frame structure panels covered with plywood.

Folded constructions of wooden trusses

Elements of folded structure can be formed of wooden trusses. By combining the trusses it is possible to get different forms of folded structures. Connecting the trusses is done on site. Band members in the deflections and hip of the folded structure, and diagonal bars, are made from solid timber or laminated wood.

The choice of dimensions of the cross-section of the wooden truss rod is affected by: the span, load, shape and dimensions of the elements of folds. Structural design accurately determines the dimensions of each rod in the wooden trussed element.

Wooden folded structure of line elements of monolithic timber (planks and billets) can be divided into:

- the system of folds Zahorski,
- the system of folds Kroher,
- folded construction in LKV System,
- folded construction formed from members of glued laminated timber (Figure 2).

Figure 1. The roof of the factory hall constructed as a wooden panel folded construction, span 43.60 m, the architect Josef Lackner, Jenbach, Tyrol, Austria, 1996.

Figure 2. Folded truss structure Hartwald Clinic Pavilion, Bad Zwesten Germany, architect A. Frank, the designer of the construction Natterer,1977.

Folded structure formed of contemporary wooden trusses

Contemporary wooden trusses represent industrialized system for prefabricated building of wooden roof structures of small and medium-span. With this type of girder node connections are achieved by using special metal plate fasteners - connector.

Static analysis of structures of folded constructions formed of contemporary wooden trusses

Nowadays, by using contemporary computational methods, software packages; it is possible to do analysis and structural design of various types of structures, from simple to very complex spatial structures.

In cooperation with the company Radimpex one of the authors of this paper, Nenad Sekularac, PhD, made the algorithm for dimensioning the elements of spatial wooden structures. Based on this algorithm the Module for dimensioning of wooden structures as a part of a software package Tower 3D Model Builder 6 was developed; company Radimpex (Figure 3). With this program, apart from structural design of constructions and dimensioning of members from massive timber, it is possible to calculate design and dimensioning of the elements of glued laminated timber. The software package provides the choice of the standard by which the sizing of elements will be done, according to Yugoslav standards or according to European standards.

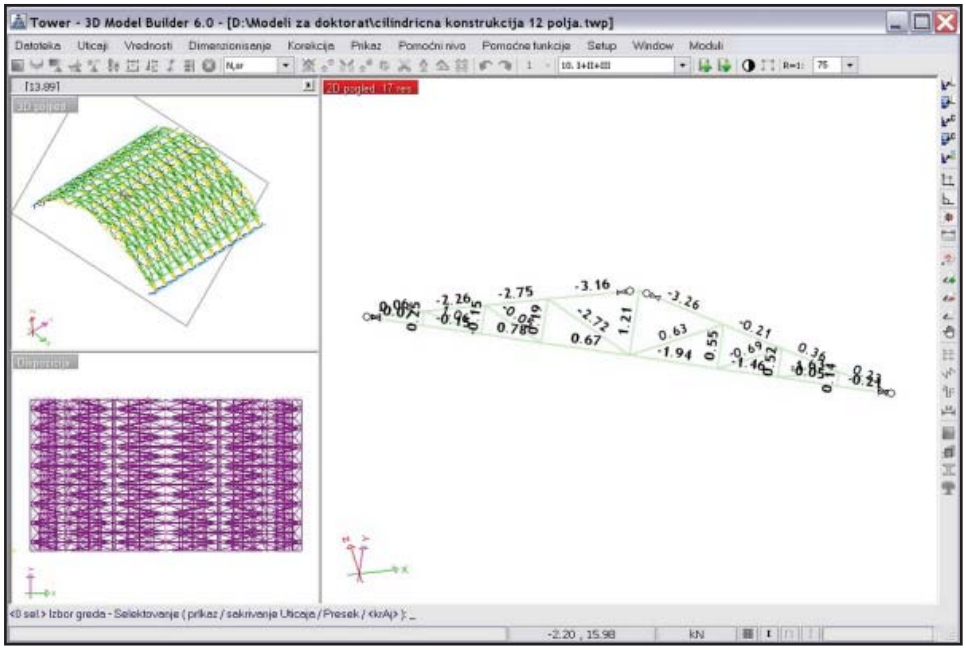

Figure 3. The appearance of Tower 3D Model Builder 6, Programme for static and dynamic analysis of spatial structures, displaying the intensity of normal forces in the member

Correlation between wooden trusses can be formed in several ways, but for this type of cylindrical folded form has been adopted the formation of connections of two lattice elements indirectly through a wooden bar - beam, as an additional element. The connection between the wooden trusses as elements of folds was achieved with screws. Combining the elements of the fold, two wooden trusses, is always carried out in the place of nodes of each element. Since two adjacent wooden trusses of the folded structure do not lie in the same plane, but trusses mutually form an angle of 90 º; thus each truss prevents lateral buckling of the compressed band members in the neighboring wooden truss. Mutual spatial relationship of the elements of folded structure constructed in such way enables that band members of wooden trusses have a very small cross section in regard to the compressive force in them.

Cylindrical folded structure that is designed and presented in this work consists of triangular trusses. This spatial structure has 12 fields and the span is 24.0 m (Figure 4). Cylindrical form was converted into a polyhedral. Static system of the designed and constructed roof structure can be represented as a two-axle arch construction. The construction is formed of triangular trusses that are rotated by 45 degrees in relation to the cylindrical plane.

One field of this folded structure consists of 10 base and 4 triangular trusses that are ½ of the base truss, spatially combined. In this way is formed a folded structure of cylindrical shape with a small number of various trusses, the maximum length of up to 9.0 m.

Prototype of the cylindrical folded structure

As a logical consequence, after making the software package and computation of one model, appeared the aspiration for its implementation in practice. During the month of September 2005 the prototype of cylindrical folded construction was realized in the Fair of Civil Engineering in Budva, Montenegro.

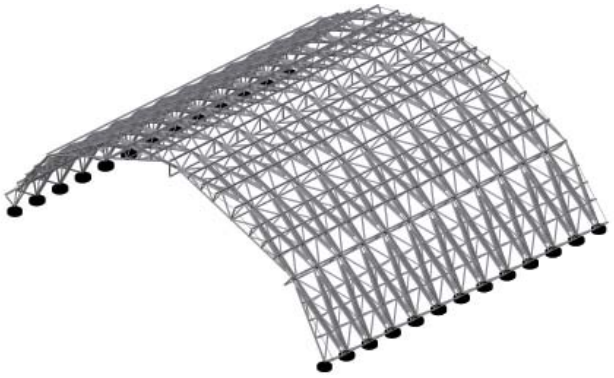

Figure 4. Isometric view of cylindrical folded construction made of wooden trusses

Conceptual and structural design of this construction was made by architect Nenad Šekularac, who used his own authorized programmes. The production of trussed elements was realized in the factory of "Lisina" company from Niksic, and was managed by architect Nebojsa Adzic. The company "Lisina" from Niksic performed the building of this construction, with the instructions of the designer architect. Nenad Šekularac and architect. Nebojša Adžić as the main contractor. During the design and execution of the construction the consultant was the Academician, Professor Vojislav Kujundžić, architect. The prototype of cylindrical folded structure, span 24.0 m, is constructed as a prototype of a hall, which consists of two fields of the folded structure (Figure 5) and represents only one segment of the cylindrical folded structure.

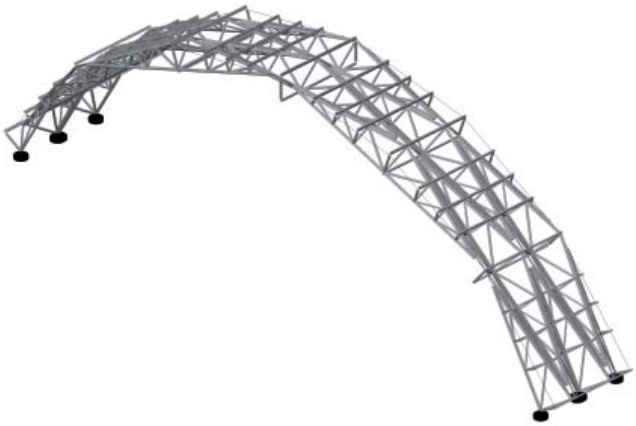

Figure 5. Isometric view of the prototype of folded construction

The prototype of the cylindrical folded structure, consists of 20 basic triangular trusses and 8 which are ½ of the base truss. (Figure 5, Figure 6). Formation of a structure in this way enables to overcome the span of 24.00 m (and more), and successful use of the principle of mutual prevention of lateral buckling of compressed band members of trusses. Such construction is formed with a small number of different trusses, which makes it very rational in production and technological terms. In this way, the production is simplified, enabled transport of relatively small elements (up to 9.0 m long), and assembly and fitting of elements are easily done on site.

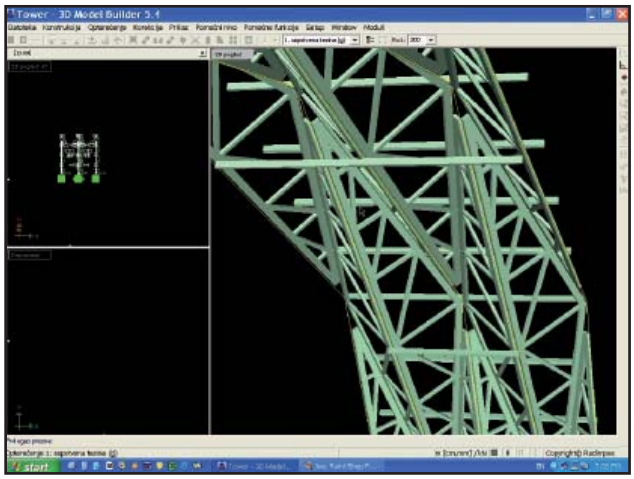

Figure 6. View of the calculation of structures in Tower 3D Model Builder 5.4 programme, from the period when the structure was designed and carried out.

In order to stiffen the folded structure, the diaphragms have beenformed in places of the change of the inclination of the roof planes of the folded structure, and the axis of the longest vertical rod of the truss core element from which the folded structure is formed. Diaphragm, apart from spatial stiffening of the structure, also has the role to receive the load of the roofing, snow and wind. (Figure 8). Rafters placed on the roof plane, in the area of truss nodes, are also designed so that in addition to accepting the load of the roofing, snow and wind, have a role to stiffen the cylindrical folded structure (Figure 8).

All workshop documentation and estimate of the connections by connectors have been made using a programme for calculation and design of modern wooden trusses (autor of software Nenad Šekularac, PhD, engineer of architecture).

The estimate foresees for the use of wood of class II quality, conifers, adequately protected by coatings. Metal connectors LKV-C are made of steel, C-0146 quality, 1.50 mm thick, previously protected from corrosion by zinc. Hardware has been protected by paint and painted with finishes.

Figure 7. Comparative view of 3D model of the calculated and performed cylindrical folded structure - prototype

Figure 8. Diaphragm connection detail and rafters of cylindrical folded structure

Installation of a prototype of cylindrical folded structure

When installed the designed system proved good results. The first step in the assembly was to form a package of four triangular elements of folded structure, connected to diaphragms which also represent the rafters that support the roofing with all the layers of insulation. Formed packages of trusses are interconnected into a folded construction on the ground (Figure 9). The structure was put on the projected position by lifting - rotation with a car crane (Figure 10). In this way the use of large scaffold was avoided, and only handy elevators were used, since the packages of 3:56 m height were moved. Almost all work was done on the ground, allowing easy and quick installation of the complete structure (Figure 11).

Figure 9. Installation of cylindrical folded construction on the ground

Figure 10. Lifting the prototype of construction with a car crane

Figure 11. Mounted prototype of cylindrical folded structure at the Fair in Budva

Consumption of material in making a prototype of cylindrical folded structure

For the prototype of a 24.00 m span, which consists of two folded fields, the total width of 3.56 m, and covering the surface of 91.35 m2 and 110.00 m2 of developed area of the roof, was spent a total of 4:47 m³ of wooden elements, 175.33 kg of melal plate fasteners and 295.66 kg of metal bond elements - along with the shackle and bolts. The total consumption of material to build a prototype of cylindrical folded construction is given in Table 1, Consumption of material needed for the performance of a prototype of cylindrical folded structure[5]. It is necessary to emphasize that the total amount of timber includes elements which prevent lateral buckling of the structure-diaphragm and the rafter, as well as elements for mutual connection of adjacent sticks of top and bottom trusses.

Table 1. Consumption of material needed for the performance of a prototype of cylindrical folded structure

Recapitulation	By m² of horizontal projection	By m² of developed roof surface
Wooden elements	0.049 m³/m²	0.041 m³/m²
Metal plate fasteners	1.919 kg/m²	1.594 kg/m²
Hardware and metal bond elements	3.237 kg/m²	2.688 kg/m²
Total weight	~ 30.156 kg/m²	~ 25.282 kg/m²

CONCLUSION

Folded roofs, as well as three-dimensional roof structures, are formed by the assembly of prefabricated elements - wooden trusses, with unified joints, and thus enable industrial production of wooden trusses as elements of folded structures. The aspiration for more economical and rational construction resulted in the selection of wood as a building material with excellent physical, mechanical and aesthetic properties. With the application of the principles of unification and systematization of wooden trusses as basic elements of the structural system, with a small number of different elements, we get a flexible

system of building of folded structures in terms of technology and facilitate the process of production, transport and installation of folded structures.

The research presented in this work confirmed that the formation of folded structures by the use of wooden trusses represents a modern technical and technological solution. Folded structures formed by using wooden trusses can meet high aesthetic requirements. From an economic point of view this type of folded structure has an extremely low consumption of cut timber and a possibility of rational utilization of material, since the constructions with a big span can be obtained from members of a relatively small dimension.

In terms of a formal and visual effect with formation of folded structures by using wooden trusses we can get shapes and design solutions that make the structure obtained in this way different and special compared to this type of structures realized in a different material.

This paper should contribute to the reaffirmation of wood as a material and trusses as technologically improved elements that enable the fulfillment of modern architectural requirements for design and construction of spatial structures.

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