OPTIMAL DESIGN OF WOODEN PAVILION GRIDSHELL STRUCTURES IN THE CONTEXT OF ARCHITECTURAL AND STRUCTURAL COLLABORATION

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Abstract. In the article two interacting aspects of collaborative design are described: shaping of the form and the rational use of materials. Form shaping will be analyzed on the basis of pavilions. The material aspect of this paper is concerned with the use of wood in contemporary construction. The first goal is to analyze the selected technical parameters related to the use of wood in the optimal shaping of gridshell structures in architecture. The second goal is to identify new opportunities for architectural and structural engineering cooperation in the context of generative digital tools. The possibility of creating new plugins for the existing generative modeling programs to improve the quality of collaboration will also be discussed. The paper is concerned with elementary research. I was able to achieve the set goals by means of theoretical analyzes based on the known literature as well as the analysis of the created objects and the accompanying research. The background for the work is a description of the selected trends of using natural wood as load-bearing elements in contemporary architecture and case studies of the selected objects that express the idea of form and material eco-efficiency.

Keywords. Wooden structures; structural detail; bionic models.

1. Introduction

Architecture is the art of building in confrontation with many issues - technical as well as sensational. The overarching goal of architectural design emerges from the antagonism of all of the elements involved in the process of creating the work. The need to express the beauty of the form - its composition, proportions, materials - confronts the author with a reality, which manifests itself, among others, in construction technologies, building law and design standards, etc. The knowledge of the matter and tools of the trade is essential in the process of creating architectural work, but the idea requires sensitivity, reflection and deliberateness. The basis for architectural design is therefore the search for spatial forms whose structural beauty is in symbiosis with the physical forces which affect them. The words of Jordan Woodson (an engineer working at the Arup studio) may be helpful in understanding the issues of the design of structural forms: “To understand how something stands up you have to understand how it might fall down”. The state in which the structure would fail reveals the “uncertainty” of the structure, which

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allows to infer how to safely design a load-bearing structure. Such analysis is particularly valuable for young architects in training.

Due to the contemporary sustainable development trends in architecture, rational design of structural forms is becoming more and more important. The growing interaction between architecture and structural design indicates the logical direction for creative explorations. In the search for effective solutions inspiration can be found in the technologies developed by Nature. Bionic inspirations often take the form of recreating the structure of living organisms. In this context, the use of wood in architecture is a natural choice - due to its material characteristics and anisotropic properties. Optimal design of wooden structures requires an understanding of those properties. Bionic solutions are also visible in the analysis of the flow of physical forces in structures and designing them in such a manner as to reduce unnecessary geometry [P. Charest, A. Potvin, C. Demers, S. Menard, 2019]. This is facilitated by the use of timber as a structural material - which is further supplemented by, among others, the dynamic development of formative construction technologies, e.g. related to the use of CNC machines for the production of load-bearing gridshell elements [A. Menges, B. Sheil, R. Glynn, M. Skavara, 2017].

Modern directions for the developments in architecture are connected with multi-criteria rationalization of technical solutions, aimed at reducing the investment costs as well as the negative impact on the environment. Eco-efficiency became an important part of construction and it finds its expression, among others, in minimizing building material and energy consumption, using materials that can be reused or the production speed of construction elements. At the same time, the search for new artistic quality in architecture is still an unchanging determinant of the design process and the criterion for assessing the work.

2. Architectural and structural design in the context of material properties

In contemporary wooden architecture, designers strive to design innovative solutions, structurally logical and visually attractive. A technical answer to an aesthetic creation can be found in the structural form, an example of unity between technique and art [Siegel, 1974]. The same applies to structural connections. The joint is a special place for transferring physical forces and the power of visual expression - it combines technology and art in one solution. The essence of design exploration is not to design an architectural form that would cover structural elements. Its purpose is to show the beauty of the structure and achieve synergistic solutions [Gawell, 2018]. This perception of architecture is a modern direction, rooted in bionic thinking. One of the main assumption of this trend is the pursuit of eco-efficiency understood as the rational use of material. This is related to the reduction of material consumption (minimum weight of structural material used). In the case of wood it is particularly due to the effective use of its natural properties. An example of such a design is the roof structure of the Mannheim Pavilion designed in 1975 by Otto Frei (in collaboration with two architects: Carlfried Mutschler and Winfried Langner), see Figure 1 and [I. Liddell, 2015]. The unconventional roof consists of a double-curved four-layer square wooden grid, the shape of which is based on a chain model. The layers of the grid allowed to obtain the appropriate stiffness (important due to the height of the structure) while maintaining the lightness of the form both visually as well as the actual total weight and material consumption. Canadian hemlock wood laths with a cross section of 50x50mm every 0.5 m were used for the construction. Its widest span is 60m (while the longest is 85m) and the height is 20m. The detail of the joints is particularly noteworthy. During the construction of the pavilion, the bolt connecting the four layers of laths allowed for free movement. After determining the target position of all the mesh elements, the bolts were tightened to prevent the sliding of individual layers of wood. Additionally, every sixth node was tied with a steel cable with a 6mm diameter. The logic of the form and the design of the structural detail of this pavilion inspires to search for beauty and engineering quality in simple materials and solutions. However, this requires an understanding of the structure of the material and the forces acting on it.

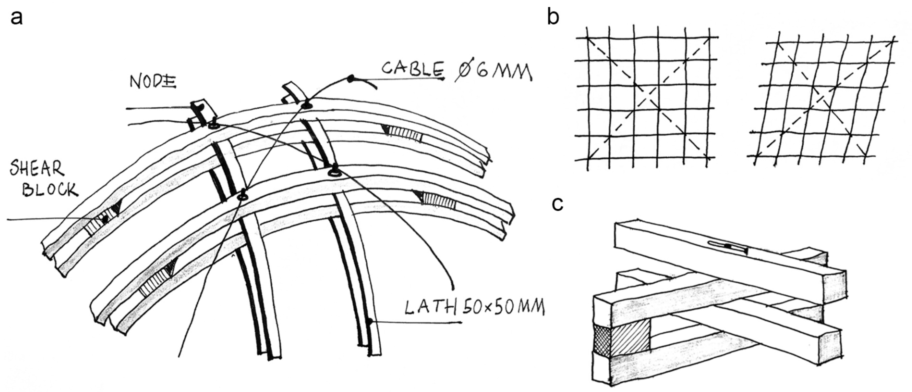

Figure 1. The Mannheim Pavilion – designed by Otto Frei, Germany, 1975; a) sketch of structural detail; b) lattice distortion; c) joint system.

Another example of rational design of a wooden structural form is the Savill Building designed by Glenn Howells Architects, built in 2006 in Windsor Great Park in Great Britain. The distinctive feature of the building is its corrugated barrel vault roof which creates an approximately 90 x 25 m free plan. The gridshell is based on an orthogonal structural mesh made out of larch and oak obtained from the Crown Estate forests. The rational design of the form is continued in its structural connections which benefit from the material properties of wood used for their creation. Just like in the previous example, the laths overlap at nodes and “slide” to allow rotation. This required the use of timber shear blocks fixed between the layers of the orthogonal mesh [D. Naicu, R. Harris, C. Williams, 2014]. This allows the laths to be curved and to obtain the appropriate shape using simple engineering solutions.

The first timber gridshell in Britain - The Weald & Downland Open Air Museum, in Downland (1996-2002) is another example of effective use of materials. The building was created as a result of the cooperation between the architect Edward Cullinam and engineers from Buro Happold and the carpenters from Green Oak Carpentry. The corrugated vaulted roof creates an unsupported space that is 48m long and 11-16m wide. It was made of green oak harvested locally (Normandy region - northern France) [D. Naicu, R. Harris, C. Williams, 2014]. Initially, the orthogonal 1,0x1,0m mesh (in places densified to 0,5x0,5m) was assembled flat from 50x35mm laths . The grid was then bent to the final shape of the gridshell using the elasticity of the freshly cut raw material. The Weald & Downland Open Air Museum is a remarkable example of sustainable architecture - as it minimizes material and energy consumption. The examples mentioned above show the synergy of solutions that arise from multi-disciplinary cooperation - the exchange of knowledge and experience in working with building materials.

2.1 From form to material

Form dominates architectural design - other elements such as function, ergonomics and technical solutions affect its shape, but as a rule, conceptual analyses begin with the form. Cooperation between architectural and structural design begins at the stage of preliminary technical verifications. Issues related to structural shaping of the form (span of the load-bearing elements, types of connections, etc.) and the selection of material solutions are the basic background for inter-branch cooperation. Nowadays, the cooperation is more and more often facilitated through the use of BIM. It is based on the refinement of building information on a single model (for many related disciplines). Nevertheless, the order of tasks remains the same - structural engineers analyze the spatial form designed by the architects. The usage of BIM enables the improvement of tools - it accelerates the exchange of information, detects collisions, etc. However, it does not change the way of thinking in the search for the new quality of this cooperation. Algorithmization of the architect's digital work tools provides more and more interesting parametric modeling opportunities - it allows architects to shape complex systems of urban and environmental connections, or to create complex geometries [G. T. N. Brígitte, R. C. Ruschel, 2018]. This in turn forces the current dynamic development of numerical programs to be able to verify the construction of such solutions. Referring to Patric MacLeamy's research - "MacLeamy Curve" (inspired by Boyd Paulson's work), an architectural design becomes more difficult to change the more it develops. The concept of early optimization - Integrated Project Delivery (IPD) aims to reduce the costs related to the optimization of the structure [S. Talebi, 2014]. The awareness of this dependency means that the cooperation of architects and structural engineers begins at an increasingly earlier stage of the project.

A contemporary example of cooperation between architecture and structure using digital design tools is the research done for the Modular Timber Structure - a roofing designed by Bastien Thorel, see Figure 2 and [Nabei, Weinand & Baverel, 2011]. The designer created a form of structural arches connected in a parallel system, and as a result, four types of simple flat modular interlocking elements were used. The concept was that flat elements would overlap and stiffen each other - this assumption required numerous structural analyses. As a result of simulations, it was found that the distribution of stress concentrates at the place where the flat elements are joined. Further design (changes resulting from the need to strengthen the connections) was made in cooperation between the architect and the civil engineer. This object is an interesting example of optimal shaping of the form and structural detail. Nevertheless, the form dominates the material - the structure of this roof could as well be made of a different material. This is also evident from structural analyses that focus on general issues and do not take into account, for example, the anisotropic features of wood. From an engineering point of view this kind of structure, made from simple elements, creates a very complex stress pattern which may trigger fracture, crushing, surface interaction, and other types of nonlinear material and geometrical effects. Probably, none of the currently available computational models for wooden materials can handle this properly, neither with respect to deformation nor safety. To utilize the potential for creativity and good design of timber structures, more effort should be put into numerical modeling of wooden materials as numerical modeling is the design tool of the future.

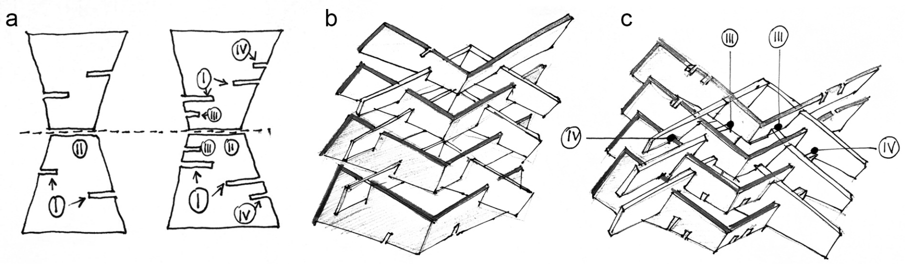

Figure 2. Modular Timber Structure – designed by B. Thorel, Germany, 2008-2009; Two geometrical configurations of structural detail; a) connection variants - plans; b) basic variant – perspective sketch; c) optimization variant – perspective sketch.

2.2 From material to form

Eco-efficient structural and material solutions are not a tendency, but a challenge facing us today. Contemporary generative modeling programs enable form shaping in line with the idea of 'form follow forces', which aims at the reduction of unnecessary structural geometry. An example of which is form finding. It uses the methods of transient stiffness, force density and dynamic relaxation [W. J. Lewis, 2008]. One of the computational tools for the modeling of gridshell structures using the dynamic relaxation method is the Kangaroo Live Physics program developed by Daniel Piker. This type modeling leads to construction based on digital fabrication, where the materials with a homogeneous structure, such as concrete, steel etc. are most often used. In this context, wood as a building material is reduced to repeatable boards, strengthened beams, or it is processed to such an extent that it can be printed (laywood). The material is modified, simplified in terms of structural structure, to allow for the creation of complex forms. Contemporary digital tools do not provide one effective form-finding program in which one could analyze a material with a heterogeneous structure. Carrying out analyses in terms of the strength of wood, including the determination of limit states due to damage, requires a separate design study. The individual analyses have to be performed in stages, using several different digital programs. However, the constantly developing technologies also lead to greater respect for the known, simple technologies. Moreover, advanced technologies are more often used to increase the effectiveness of natural materials and solutions.

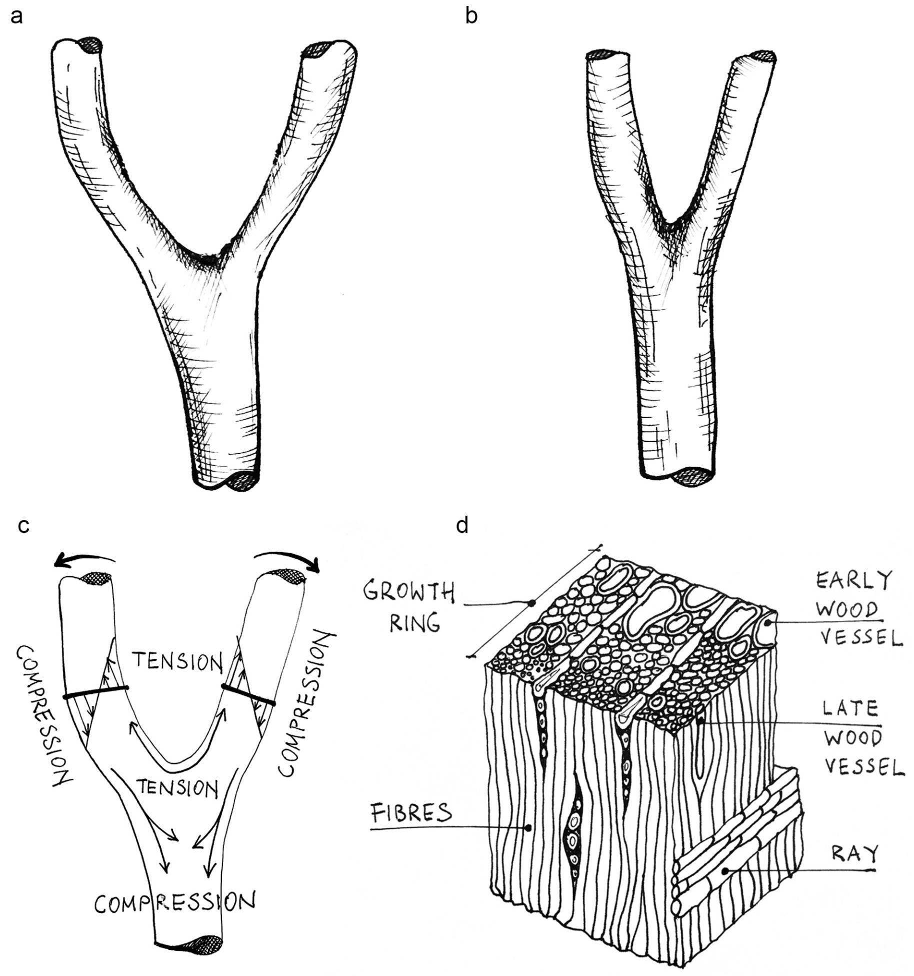

Figure 3. Type of branches used in the Robotically Fabricated Wood Chip Barn – designed by AA School of Architecture, 2015-2016: a) tension fork; b) compression fork; c) stress diagram in tension fork; d) structure of wood.

For instance, there is a concept of scanning natural tree branches to build architectural objects from those elements [M. Self, E. Vercruysse, 2017]. Natural knots (tree branches) are not the most effective structural solution for architectural buildings - this is due to the difference in the load model (Figure 3). Different forces act on the branches in the tree's natural environment and in a structural form. Nevertheless, the activities outlined below are an interesting example of structured exploration and cross-industry cooperation. The Design + Make program at the Architectural Association satellite campus out in Hooke Park, Dorset aims to educate students in structural design by experiencing wood as a natural material in its ”growing” phase. In this case, the study of wood means the haptic experience of the forest - the environment in which this material is formed. The assumption of the Design + Make program is the digital analysis of the anisotropic structure of wood and the use of natural properties of the material in architecture. This approach to wooden construction sets new directions in design, but also in cooperation between architecture and structural engineering. The result of this approach and the students' work is a robotic barn, the structure of which was made of local trees. An arched vierendeel truss structure that supports the roof consists of 25 forked beech branches. Elements were selected on the base of the preliminary criteria, harvested and scanned into a 3D model. Then the students, in collaboration with the engineers from ARUP, used an optimization script to set the final ”forks”. Milling robots drilled holes along the ”structural branches” into which steel fasteners were inserted.

3. Wood properties in the context of structural analysis

Wood is an attractive structural material, easily available and easily shaped, a highly sustainable material storing large amount of greenhouse gases. As an organic material, wood is produced by Nature - through a growth process whose rate depends on climatic conditions, as well as water and sunlight availability. The anatomy of wood is close to being cylindrical in the cross section of the stem due to the growth taking place only at the exterior (Figure 3). The internal structure of wood can be simply described as formed by [clusters of tubes] [aligned channels?] (straws) glued together and arranged in the form of rings. Annual rings are varied and depend on the growth rate - this has an impact on the properties of the material. Wood is a naturally grown composite structure, strong and stiff in the direction of the tubes but distinctly weaker in the other directions [M. Self, 2017]. The weakest properties of wood are its tensile strength (towards the grain) and shear stress resistance between the annual rings. As a rule, the cracks that form as a result of these stresses occur along the direction of the fibers where the strength is the lowest. The vulnerability to cracking is one of the biggest challenges for the use of wood in construction. Furthermore, strong anisotropy is problematic in the context of using parametric modeling tools.

Carrying out detailed computer analyses for wood requires a digital database of strength properties. The creation of such a catalog for various species of conifers (mainly those used in load-bearing structures) is an essential element in the development of digital tools for the work of structural engineers. Currently, the available programs are insufficient for detailed wood analysis [Y. Weinand, 2017]. Programs such as Revit or Robot Structural Analysis use standards and catalogs of wooden profiles available in them (or imported by users). However, it is a simplification consisting of averaged strength parameters, as for a material with a homogeneous structure. Analysis of the connections allows to explore the issues related to the diverse structure of wood. Nevertheless, these constitute the scope of a very narrow structural specialization based on original research and optimization processes. Architectural and structural cooperation usually takes place at the stage of form conceptualization. In the case of conventional modeling tools, the architectural model is usually simulated from loads and modified based on the suggestions of the civil engineer (Figure 4).Using generative modeling tools, it is possible to initially automatically verify the variants generated by an algorithm. However, this requires individual modifications: creating an original script and introducing matrices relating to the properties of a given material [G. Stellmacher 2017]. Another direction of possible research is the creation of an accurate database for each specific material. The material then becomes the starting point for further work - such as form shaping. This design path is, however, closely related to fabrication technologies. The adoption of precise research tools at the start of the design process usually indicates unconventional material solutions. An alternative to the modification of natural wood is a deeper understanding of the strength characteristics of wood depending on the species of the trees, their growth conditions, or the phenomenon of the so-called wood programming [J. Burry, B. Sheil, R. Glynn, M. Skavara, 2020]. An example of such thinking is the Urban Tower, designed and constructed by engineers from the University of Stuttgart (ICD + ITKE). The form is the result of a non-energy-intensive process of predicting how the wood will shrink as it dries out. This design contains clear elements of a scientific experiment. The solution proposed by the designers for the "processing" of CLT panels (allowing them to deform under the influence of moisture) seems to contradict the logic of the material itself. The main goal of the cross-laminated wood technology is to eliminate these deformations [R. Brandner, 2013]. On the other hand, minimizing the energy built into material processing, which controls this process, as well as the method of shaping of the form, are an interesting example of cooperation between architecture and structure. Such designs also show possibilities in the development of material and manufacturing technologies.

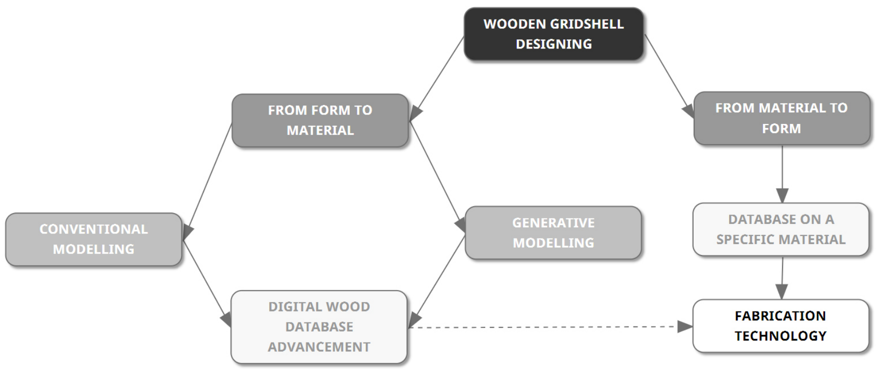

Figure 4. Diagram of stages for the design of contemporary wooden structures .

4. Summary

The collaboration of architects and structural designers is an interesting field in the development of digital modeling tools. In the era of widespread digitization, an indispensable element of building design is the creation of both a model of the architectural form and a structural model (loads, supports, material, etc.). Regardless of the chosen method of search, invariably it is about the flow of information, as well as the method of its recording. In the case of wood, which is a material with a heterogeneous structure, a key element in the development of computer programs is the creation of a digital database for different types of wood. This issue applies both to structural analysis programs as well as programs for the optimization of joints.

An interesting trend is the return to the simple material processing technologies, the aim of which is to conserve energy. Using the natural properties and form of modernized wood or carpentry connections are just some of the inspirations that architects reach out for. An important role in increasing the quality of eco-efficient solutions is the use of broadly understood fabrication technologies that support the entire process of the formation of architecture (material analysis, design, construction). The search for synergistic structural solutions will indicate new directions for the development in material technologies. This requires the continuous broadening of knowledge and skills from all of the involved disciplines, which can be achieved through practical cooperation between the designers.

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