Optimal shaping of wooden structures in the context of contemporary trends in architecture

Abstract

AThe development of modern construction is aimed at minimizing energy consumption. Optimizing construction processes is an obvious activity that accompanies the design process from the very beginning. This is particularly important in the era of digitization of design tools, as well as the use of curvilinear bionic models in architecture. The ability to rationally adjust the material to the structural needs of the building and strive for its effective use is one of the most important conditions for sustainable architecture. Technical solutions in construction ensuring the use of renewable energy are becoming more and more important in view of the need to respect natural resources. In the context of these changes, the use of natural wood in structures is worth paying attention to. Recently, there has been a dynamic development of wood processing technology, as well as tools for modeling and analyzing wooden structures. The article deals with issues related to the optimal shaping of structural forms of wood, with particular emphasis on architectural and construction cooperation. The aim of the work is to review the current trends in the use of construction timber and the known methods of statistic tensile strength analysis for this material.

Key words timber structures
| interdisciplinary design
| wooden gridshell
| pro-environmental building material

1. Introduction

In modern architecture, there is a growing interest in natural construction technologies, especially those with a small carbon footprint. These trends, dictated by the need to reduce carbonization in the construction industry, make wood and its processing technologies one of the most interesting issues in the development of this sector. An additional advantage is the renewable nature of wood, which simultaneously entails the process of intensive absorption of carbon dioxide. In this context, wood provides clearly synergistic solutions for modern construction, in line with the assumptions of the circular economy. On one hand, thanks to, inter alia, gluing technologies, wood can be used as an alternative supporting structure or filling of partitions (with good insulating properties), on the other hand, it actively and passively accumulates atmospheric pollutants. The universal properties of wood and the possibility of its adaptation to the functions performed in construction elements enable its further exploration in modern construction technologies.

Modern woodworking technologies provide new opportunities for shaping rational structural elements. Examples of such activities are: prefabrication of glued timber elements (CLT, LVL, HBE, etc.), which is a clear alternative to other types of structures, and technologies related to gluing and bending wood. They affect areas that are not yet sufficiently developed. The first is shaping curvilinear architecture, the overarching goal of which is more and more often design efficiency, manifested in the reduction of unnecessary geometry[1]. The second relates directly to digital modeling tools based on interdisciplinary collaboration. Both elements are based on an architectural and construction correlation and require the development of specialties, tools and, finally, basic research in the field of optimal shaping of wooden structures.

This situation makes it particularly interesting to use construction timber in objects whose geometry goes beyond the paradigms of Euclidean geometry. This action requires advanced processing technologies, as well as high awareness of the material; its structure and strength properties[2]. The following overview of completed facilities, construction technologies and methods related to modeling and structure analysis refer to examples of bionic architecture, the essence of which is the search for synergy between the aesthetics of form and the logic of structural solutions.

2. Modeling of wooden structures in relation to current standards

Wood is a well-known and commonly used material in building structures, described in numerous manuals and standard documents. Eurocodes (EC) have been introduced for European countries, which provide guidelines for the design of wooden structures. Common design principles are set out in the document: *Eurocode 5. Design of wooden structures. Part 1–1: General. Common rules and rules for buildings*[3]. The standard describes the principles of structural design in terms of the ultimate and serviceability limit states. The regulations contained in this document should be applied by engineers conducting design activities in the European Union countries. In addition, the Eurocodes contain national annexes NA “National Appendix”, which constitute guidelines that take into account, for example, the specificity of the materials used or constitute supplements to general rules, among others, by assigning numerical values into symbols appearing in the standard[4]. Eurocodes also provide information on the applied strength class system. The classification of individual species of wood used in construction and the method of qualifying individual species to the appropriate class is included in the *Eurocode PN-EN 338: 2011. Construction wood. Strength classes*[5]. Physical and strength characteristics of wood from conifers such as pine, larch or spruce and deciduous trees – e.g. beech, oak, ash, maple, linden, alder, poplar, can also be found in technical literature[6].

With the spread of wooden structures in modern construction, the development of material technologies is also taking place. On one hand, there is a growing range of tree species that are used in structural shaping. On the other hand, wood strengthening methods (e.g. gluing, fiberglass or aramid reinforcement tapes, etc.) provide new design possibilities. This development not only stimulates the creativity of designers to look for unusual spatial solutions, but at the same time requires the constant updating of standards, databases and catalogs for digital strength analyses.

In the design of wooden structures, the basic safety parameters include compressive strength along and across the grain, tensile

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[1] E. Gawell, A. Nowak, W. Rokicki, *Searching for Bionics Structural Forms Optimization*, “IOP Conference Series: Materials Science and Engineering”, 2019, no. 471, p. 1–10.

[2] E. Gawell, *Optimal design of wooden pavilion gridshell structures in the context of architectural and structural collaboration* in: *PROJECTIONS: Proceedings of the 26th International Conference on Computer-Aided Architectural Design Research in Asia (CAADRIA 2021)*, ed. A. Globa, J. van Ameijde, A. Fingrut, Vol. 1, Hong-Kong 2021, p. 473–482.

[3] Eurocode 5. Design of wooden structures. Part 1–1: General. General rules and rules for buildings. P.4 Ultimate limit states; P5. Serviceability limit states; The script is available on the website http://pobierz.intersoft.pl/konkurs/EUROKODY/EUROKODY-Projektowanie-konstrukcji-drewnianych.pdf (access 30.11.2021).

[4] PN-EN 1995-1-1:2010/NA. Design of wooden structures. Part 1–1: General. Common rules and rules for buildings.

[5] PN-EN 338: 2016-06. Construction timber – Strength classes.

[6] J. Kotwica, *Konstrukcje drewniane w budownictwie tradycyjnym*, Warszawa 2011; the author in chapter 3, *Mechaniczne właściwości drewna i materiałów drewnopochodnych*, gives the physical and strength characteristics of the materials.

strength along and across the grain, bending strength and shear strength along and across the grain. The strength parameters are used during the verification of the structure in accordance with the formulas contained in the Eurocode. In typical wooden structures, the effort of a wooden element is determined, apart from the strength characteristics, by the static diagrams of the shaped structure, the system and value of standard interactions, boundary (support) conditions and the physical properties of the material (modulus of elasticity) occurring in constitutive relationships.

Static analysis leads to obtaining internal forces and the state of stresses, and then, taking into account the strength parameters, to verify the weight-bearing capacity. The limit states of the structure are controlled by comparing the obtained stresses with the strength parameters. Ultimate limit states also include the control of the ultimate curvature at which the first crack appears. This type of limit state is relevant for pre-bent structures. The boundary curvature can be determined analytically on the basis of the bending formula which makes the boundary curvature of a bent element dependent on the bending strength given in the Eurocode $\sigma_{cr} = f_m$[7]:

$$\sigma_{cr} = \frac{M \cdot z}{I}, \text{ gdzie } M = \kappa \cdot EI$$

The above information is the basis for the analysis of bionic architectural forms built of wood. Very often, especially in the case of atypical structures, standard material databases are supplemented with experimental tests.

3. Selected methods of modeling wooden structures – static analysis and calculation models

Contemporary trends in architecture are focused on the interdisciplinarity of the design process. This is followed by digital tools for cross-industry cooperation. Depending on the adopted method of shaping the form, the processes of its structural optimization are planned. Analytical methods of designing objects shaped from wood are discussed below.

3.1. Linear analysis

The most commonly used method of static analysis today is the *linear Finite Element Method, FEM*[8]. Computational models prepared by structural engineers assume geometry designed by an architect, which is now created using more and more advanced digital tools. Using the *FEM* method, analyzes can be performed without the so-called second and third order effects characteristic of nonlinear analyses. In a linear analysis, a linear relationship between the stress state of the structure and the state of deformation is assumed. The FEM method, popular among structural engineers, allows for the determination of internal forces in the structure, automated control of the *Limit State Analysis (LSL)* and *Serviceability Limit State (SLS)* in accordance with the rules contained in the *PN-EN 1990:2004. Eurocode – Fundamentals of structural design*[9]. The calculation software that uses *FEM* popular on the European market has built-in modules for the verification of standard strength formulas. These programs include *Autodesk Robot Structural Analysis* by Autodesk, *RFEM6* by Dlubal Software, or the *SCIA Engineer Suite* by Nemetchek. The automatic process of standard verification of individual structural elements comes down to the determination of several initial parameters, such as its length, the lateral and medial buckling model, the influence of knots (imperfections), and, e.g. moisture level under operating conditions.

A more complicated process is the analysis of nodes, where, as a rule, material failure

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[7] E. Adiels et al., *Design, fabrication and assembly of a geodesic gridshell in a student workshop*, "Proceedings of the IASS Symposium 2018", ed. C. Mueller, S. Adriaenssens, Boston 2018, p. 2–3, 5.

[8] A.M. Bauer et al., *Software Approaches for the Design and Simulation of Bending Active Systems,* "Proceedings of the IASS Symposium 2018", ed. C. Mueller, S. Adriaenssens, Boston 2018, p. 1–2.

[9] Terms derived from the English version of the Eurocode 5.

occurs in timber structures. Popular structural design packages have relatively little node analysis capability, limited to the typical nodes commonly used in timber structures. Joinery (structural nodes) is modeled individually, very often in applications other than the program in which the analysis of the entire structural system was performed. However, designers also use the *FEM* method when analyzing nodes. Shell or solid models of structural nodes constructed for this purpose provide the designer with information on the state of stresses present in individual elements making up a structural node.

Despite ignoring second- or third-order effects, the *FEM* method can be used for very sophisticated structures. *FEM* analyses are used for structures, which due to the negligible influence of deformation on internal forces, do not require nonlinear analyses. An example of a timber structure analyzed with the help of *FEM* is the Treet building in Bergen (Norway) (Fig. 1). The building was built in 2015 as a result of cooperation between the Artec architectural office and SWECO, with the support of a research team from the Norwegian University of Science and Technology (NTNU in Trondheim)[10]. The framework of the 14-storey building with a structure height of 52.8 m is made up of prefabricated panels made in the CLT technology. The structure analysis was carried out on Robot Structural Analysis Professional 2013. Thanks to the detailed model and optimized logistics, the assembly of individual prefabricated modules of the building was extremely efficient and, which deserves special recognition, also very accurate. It is worth mentioning that the maximum deviation of the assembled structure for this tall building was only 3 mm.

3.2. Geometric nonlinear analysis

Linear FEM analysis methods do not always give a correct picture of the behavior of the structure. During the analysis of structures – both core and shell – more advanced methods are often required, taking into account the non-linearity of the processes occurring during the structure's operation. The non-linearities occur when the structure is characterized by large deformations, resulting in the appearance of *second-order effects* or *third-order effects*. The methods used in nonlinear analyses include the *P-Delta method* and the *Large Displacements Analysis* method. The *P-Delta* (second-order effects) analysis takes into account the change in the stiffness of the bar element depending on the longitudinal forces, while the *Large Displacements Analysis* method takes into account the third-order effects, i.e. the appearance of additional forces depending on the deformation of the structure[11]. Nonlinear methods will be applicable wherever there are significant deformations in the structure that cannot be ignored in the static analysis. This type of analysis will be necessary in the case of structural systems which include membrane, tension or cable elements. Such elements often complement timber structures and function as bracing or prestressing tendons.

3.3. Form Finding

The *Form Finding* method has been known by this name since the beginning of the 20th century, but in practice it has been known and used for a long time before that, for example by Antoni Gaudi. The chain models supporting the way Gaudi's extraordinary buildings are shaped show the beauty of the logic of structural forms. Nevertheless, building spatial physical models is a difficult and laborious task. An example of an early analog application of the *Form Finding* method is the Multihalle construction, designed by Otto Frei, in Manheim, Germany in 1975 (Fig. 2a, 2b, 2c). The object was shaped by analogy to strength tests carried out on a physical model made on a 1:100 scale. The static analysis was

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[10] R. Abrahamsen, K. Malo, M. Bjertnæs, *Some structural design issues of the 14-storey timber framed building "Treet" in Norway,* "European Journal of Wood and Wood Products", Vol. 74, 01/05/2016, p. 407–423.

[11] *Autodesk Robot Structural Analysis Professional 2021*, https://help.autodesk.com/view/RSAPRO/2021/PLK/?guid=GUID-FB3C86D3-0E30-43A6-82D6-6C50F429FA0D (access 30.11.2021).

carried out in the 1970s on the basis of one of the methods of *Form Finding*, based on the *Nonlinear Force Density Method NFDM*. The final form of the object was designed by Klaus Linkwitz and his colleagues, who used stereographic analysis to optimize the shape.

The model of the covering made by the designers was used not only for static analysis, but was also useful for removing singularities (smoothing) from the surface of the outer shell of the entire structure[12]. The roofing characterized above is an example of an effective structure that inspires designers who use *Form Finding* today with the use of digital computational models. On one hand, the very process of modeling and shaping the structure in this example is interesting, on the other hand, we have the admirable use of slender wooden slats to build a load-bearing shell. This solution is in line with the most current and important trends in sustainable architecture. The Multihalle has a roof span of over 60 m with a low covering weight – about 14 kg/m² [13].

An example of a more recent project using *Form Finding* is the Center Pompidou facility built in Metz, France in 2010. The authors of the architectural design are Shigeru Ban and Jean de Gastines (Fig. 3a, 3b, 3c). The design of the structure was created in the Ove Arup office with the participation of Herman Blumer. Noteworthy in this example are the double-curved elements of glued laminated timber used to shape the roof covering with an area of approx. 8,500 m² with construction supports spanning up to 40 m[14]. The methods supporting the digital process of *Form Finding* include the above-mentioned *Geometric Stiffness* method (of the *FDM* variety – *the Nonlinear Force Density* method) and a method from the *Dynamic Equilibrium*[15] family, called the *Dynamic Relaxation (DR)*[16] method. Computer-driven algorithms are a modern tool for searching for a form in which there is a balance of forces for a deformed structural system. Thanks to such analyses, it is possible to determine the initial configuration of structural elements (before applying the effects occurring during the operation of the object), as well as to perform an analysis of the deformed structure after applying loads. *Form Finding* analyses are of particular importance when studying flaccid elements like structural timber. Pre-bent structural elements of glued laminated timber slats or coatings take shapes suitable for their purpose. At a relatively low Young's modulus, wood is a deformable material and thus easily preforms with a relatively low amount of energy required to impart the desired curvature.

An example of such application (where the Dynamic Relaxation method was used) is The Downland Gridshell at the Weald and Downland Open Air Museum, designed by Edward Cullinan and engineers from Buro Happold, commissioned in 2002 in Sussex, Great Britain. The structure made of oak slats creates triangular panels formed by slats running diagonally in two opposite directions and slats running in the longitudinal direction. The longitudinal slats constitute a substructure for the outer fabric cover and at the same time constitute the structural concentration, creating triangular divisions of the structural mesh. The Downland Gridshell structure does

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[12] J.M. Songel, *Sustainability lessons from vernacular architecture in Frei Otto's work: tents and gridshells,* "The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences", Vol. XLIV-M-1-2020, p. 239.

[13] D. Wendland, *Model-based form finding processes: Free forms in structural and architectural design,* in: *E. Torroja: from the philosophy of structures to the art and science of building: international Seminar, Politecnico di Torino*, ed. F. Levi, M.A. Chiorino, C.B. Cesari, Milano 2003.

[14] T. Schwinn, *Tobias Schwinn in conversation with Holzbau Amann and Müllerblaustein*, in: *Advancing Wood Architecture. A computational approach*, ed. A. Menges, T. Schwinn, O.D. Krieg, New York 2016, p. 187–189.

[15] D. Veenendaal, P. Block, *An overview and comparison of structural form finding methods for general networks*, "International Journal of Solids and Structures" , Vol. 49, 2012, Issue 26, p. 3741–3753.

[16] D'Amico B et al., *Timber gridshells: Numerical simulation, design and construction of a full scale structure,* "Structures", Vol. 3, 2015, p. 5.

not cover such impressive spans as the Multihalle in Manheim, because here the beam span has reached 15.2 m, but it is an interesting example of the use of structural timber as a lightweight structural frame, pre-tensioned by giving the elements appropriate curves[17].

4. Production automation

For modern wooden structures, an important aspect is the automation process – both for architectural and structural modeling and the production process itself. The use of robots in subtractive or additive manufacturing is becoming more and more common[18]. Subtractive methods are characterized by the fact that during the manufacturing process, material is subtracted that does not participate in the work of the structure or participates in an ineffective manner. Reduction of unnecessary material can be carried out by properly programmed machines (machine tools), which cut out redundant material rejected by the designer in the process of design optimization. The additive method has become very popular in the era of 3D printers, which add the desired material by enlarging its cross-section or adding entire elements. With regard to wooden structures, the additive method also consists in adding whole segments of the structure in the form of prefabricated elements prepared in advance.

An example of the use of digitized fabrication can be the 2016 implementation of The Sequential Roof, covering the new building of the Institute of Technology in Architecture of the ETH University in Zurich. The creation of the cover structure was preceded by analyses of the parameterized geometry of the structure. The parameterization of the roof geometry was helpful in optimizing the shape of the structure in order to obtain material savings in the selection of the cross-section of the slats, simplify and maximize the uniformity of the patterns of nodes (joinery), as well as in terms of adjusting the shape of the roof to the configuration of the lighting and fire protection systems used. Fully automated production methods were used to prefabricate all elements of the structure consisting of 168 girders with a span of 14.70 m. In this way, an area of 2,308 m² was covered with one roof[19]. The manufacturing and assembly process is shown in Fig. 4a, 4b, and 4c.

An interesting example in the field of fabrication with the use of structural timber is also the latest construction of the Pavilion livMatS in the Botanical Garden in Freiburg in 2021, designed by Achim Mensges (ICD, University of Stuttgart) and Jan Knippers (ITKE, University of Stuttgart), with the support of the Deutsche Bundesstiftung Umwelt, ExolonGroup[20]. The structure of the pavilion was inspired by the structure of the saguaro cactus and the fig opuntia, by using an analogy to the shell structure of plants, reinforced with layered fibers. As a building material, the authors of the project used flax fibers, which were robotically woven onto steel frames. After removing from the frames, repeatable structural modules were obtained in the form of membranes formed from woven flax fiber rods. The design of the structure required basic research in the field of strength of unusual materials. Prior to implementation, the tests were performed on prefabricated modules of the structure. Despite the fact that the facility is relatively small (approximately 48 m²), the designers showed a great knowledge of interdisciplinary design and used advanced numerical techniques. The process of building the facility was preceded by thorough studies, including experimental tests of the material

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[17] *Downland Gridshell,* https://www.wealddown.co.uk/buildings/downland-gridshell/ (access 30.11.2021).

[18] E. Gawell, A. Stefańska, *Idea fabrykacji elementów strukturalnych w kształtowaniu współczesnych pawilonów*, „Zeszyty Naukowe Uczelni Vistula", 2018, no. 61(4), p. 82–92.

[19] J. Willmann, F. Gramazio, M. Kohler, *New paradigms of the automatic: robotic timber construction in architecture*, in: *Advancing Wood Architecture*, ed. A. Menges, T. Schwinn, O.D. Krieg, New York 2017, p. 24–26.

[20] *livMatS Pavilion*, https://www.icd.uni-stuttgart.de/projects/livMatS-Pavilion/ (access 30.11.2021).

used in terms of its strength parameters. The directions of fiber arrangement, fiber density and quantity in individual layers were strictly adjusted to the numerically determined directions and values of internal forces. The construction design of the pavilion was adapted to the requirements of German design standards, taking into account the climatic code interactions, and completed with fully robotized prefabrication of the construction modules, implementing the additive fabrication method (Fig. 5 a, b, c, d).

4. Discussion

Architectural design is more and more often a complex process of making forms emerge as a result of digital processing related to modeling, analysis and production. It is, among others, the result of dynamic technical and technological development, as well as the digitization of design and research tools. Further progress in this area will simultaneously provide new opportunities and challenges in construction and building.

The interdisciplinary nature of building structures is nothing new and surprising. However, due to the implementation possibilities provided by formative technologies, this process can take place without human participation (self-steering machines). The fabrication of structural elements or entire objects enables the production of irregular and complex forms, but at the same time requires the execution of in-depth structural simulations preceding the implementation stage. The answer to such developing trends in contemporary architecture is the idea of "from file to factory", referring to the smooth connection of the design process with production. A characteristic feature of the spatial forms that result from such activities is the use of digital design and manufacturing strategies based on computational concepts. This makes engineering sciences an essential element of creative design searches. In relation to the discussed topic of the use of structural timber in architecture, several important issues should be additionally taken into account. One of them is the nature of the material, which on one hand is an undeniable advantage, and on the other, an engineering challenge in the field of structural analysis. The problem is that the raw material is sensitive to growth factors, the structure of each element is different, and the digital databases for calculations (with approximate strength parameters) are not always complete. In this context, cooperation between designers, technologists, material scientists, etc. must be sustained, developed and supported at the level of basic research and implementation.

5. Summary

Improving the tools for modeling structural forms of wood is an indispensable activity in shaping optimal solutions in contemporary architecture. On one hand, following the trend of pro-environmental ideas, designers are more and more often inspired by construction technologies characterized by low-emission material processing processes. On the other hand, it is important to minimize the energy losses built into the facility, also resulting from the process of its operation. This forces the development and improvement of the known tools for the optimal shaping of structures and building elements. Following this, progress can be observed in the construction sector. Digitization as well as robotization of implementation processes inspire to shape not only increasingly interesting forms, but also drive innovative material technologies that effectively use the natural properties of wood.

The above-mentioned changes, dynamically taking place in modern construction, make cooperation at the meeting point of various disciplines involved in the process of creating architecture more and more important. It is not just about the design process that initially combines elements of engineering and humanities. Particular attention should also be paid to the sphere of science and the implementation of innovative solutions for construction, preceded by the development of basic research.

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