The current situation with the issue of modeling of flat and spatial structures based on wood

T L Dmitrieva¹, K A Podshivalova¹ and I P Pinaykin¹

¹Irkutsk National Research Technical University, 83 Lermontov str., Irkutsk, 664074, Russia
E-mail: dmitrievat@list.ru, 1295536@mail.ru, pinaykin@bk.ru

Abstract. The analysis of the current state of issues related to the construction of design and optimization models of flat and spatial core structures based on wood under static and seismic impacts is presented. The need to develop methods for finding the best projects for such structures, which would allow for rational technical solutions, taking into account the set criterion of optimality and all the requirements for their tense-deformed state. Particular attention is paid to the construction of adequate calculation models taking into account the anisotropic structure of wood.

1. Introduction
The key priority of the building industry is to reduce the cost of production and reduce the time of commissioning. This goal is achieved by reducing the material intensity and complexity of the manufacturing and installation of structures in buildings and structures.

One way to meet these requirements is to develop methods for the optimal design of buildings and structures. Among the most important areas of optimization theory is the justification of methodological principles for the formulation, existence and adequacy of solutions to optimality problems of typical and individual constructive solutions.

Tasks of this type are multifactorial, they include the assessment of natural and climatic conditions, taking into account the laws of stress distribution, the nature of the action of loads, the relationship of the ratio of forces with the spatial forms of elements, buildings and structures. On the other hand, these tasks should take into account economic laws governing the measure of consumption and the ratio of resources needed to implement structural solutions (cost of materials, services, operating costs, economic consequences of structural failures, reconstruction costs).

For wood-based structures, the analysis of factors affecting their dressed-deformed state is complicated by the fact that the tree as a structural material, due to its natural origin, has a large spread of mechanical characteristics, significantly larger compared to materials such as steel and concrete. Features of influence on mechanical characteristics of wood of various conditions of the work of a structural element are considered by special coefficients [1]. The calculated mechanical characteristics of wood, as well as for other structural materials, are determined by statistical methods using distribution functions.

2. Examples of optimization of individual structural elements in structures based on wood
We note some examples of the optimal design of individual elements and compounds from wood. The analysis of the behavior of natural structures of laminated wood domes and the numerous preliminary
calculations have shown the possibility of saving materials by reducing the height of cross-sections of meridional ribs. This is especially effective when you include in the design of skins, performing the role of the building shell, the collaboration with frame elements (annular and longitudinal ribs) [2].

In the works of foreign and Russian authors, numerous studies have been carried out concerning various elements of joints of wooden structures. A comparative analysis based on a series of numerical simulation experiments in the ANSYS software for determining the bearing capacity and the optimal arrangement of CFRP dowel pins in the joints of wooden structures. A comparative analysis of the stress-strain state of the compound with the results of calculations is carried out according to the procedure stipulated by the current norms and rules of the strength [3]. Experimental and numerical study of the behavior of timber beam-to-steel column connections under cyclic loads [4].

3. Features of the work of wooden structures in seismic conditions

Timber structures traditionally provided satisfactory seismic performance due to multiple known features. However, the consequences of the last major earthquakes have clearly proofed that seismic timber design must further improve. Also, at present, wooden structures are focused on high-rise construction and therefore increased seismic requirements are imposed on them. Altogether, this has led to the fact that seismic protection technologies have gained great importance in research related to woodworking, which is devoted to more than 80 publications only in the last decade [5].

In general, wooden structures can be designed to meet the life safety criterion and to deform inelastically without inducing collapse under major earthquakes. At the same time, structural and non-structural damage associated with inelastic reactions is usually very expensive to repair, which gives impetus to research in the field of increasing the seismic resistance of structures using wooden structures. In [6], a description is given of the development, experimental testing, and numerical simulation of a new hybrid joint, which was developed to improve the seismic characteristics of the frames. In [7], questions of numerical studies of the seismic characteristics of a hybrid shock-absorbing structure of wood and steel are considered. Here, friction dampers are utilized to upgrade the seismic performance of timber-steel hybrid structure, which has been proposed as an alternative structural solution for multi-story buildings. The effectiveness of various design solutions applied to high-rise wooden structures was investigated as a means of reducing seismic accelerations [8].

4. Modeling problems in finite element analysis problems

Currently, the design of complex technical objects is impossible without the use of automated software systems (PCs). About wood structures, it should be noted that in the modern design there is a need for software that allows adequate simulating the complex behavior of the wood system, accessible to practitioners.

To assess the stress-strain state of building structures among numerical methods, the finite element method has become widespread. Most computer systems and software complexes related to finite element analysis of building structures include a library of isotropic or anisotropic materials with the assumption of their isotropy. However, as shown in [9], this approach is not applicable to solving spatial problems. When modeling wood material as isotropic, there is a significant decrease in the accuracy of calculations up to complete inaccuracy. In view of this fact, it is not possible to correctly model the processes of manufacturing, installation and operation of building structures made of wood.

When calculating metal and reinforced concrete structures, shear deformations are neglected, which is quite justified, since they are negligible for metal and reinforced concrete, which cannot be said about wood. Ignoring this issue leads to inaccurate calculation results. Therefore, the determination of the stress-strain state in the calculus of wooden structures must be carried out taking into account shear deformations.

Several publications by Russian and foreign researchers are devoted to the study of various aspects of the problem of modeling wooden structures. In V. N. Volynsky's monograph [10], the main factors influencing the strength of wood are temperature, humidity, and loading speed. At the same time, Turkish scientists [11] model wood as an isotropic material. The results of studies of the elastic deformability
of wood across the fibers obtained by V. N. Glukhikh [12] allow us to determine with high accuracy the relationship between the physical and mechanical characteristics of wood and environmental parameters. In [13], a finite element model of the elastic modulus of the LVL material of the Ultralam brand is described with a different number of layers and a combination of their stacking according to the mutually perpendicular and parallel arrangement of wood fibers in them. In the research, we have used numerical simulations of LVL bending tests using the FEM method according to GOST 33124–2014 in the SCAD program. The obtained data were processed in Mathcad and Excel software package. Simple analytical dependences were obtained. They allow calculating the elastic modulus of all types and thicknesses of Ultralam LVL at any given angle of wood fibers. In [14], some provisions regarding the application of non-linear static analysis of timber structures are introduced. In scientific work [15], novel building systems such as post-tensioned (PT) timber have been developed. Several numerical models of PT timber beam tests are developed and validated using general-purpose FEM software ABAQUS. This research program serves to evaluate the current capabilities or shortcomings of modeling PT timber in both ambient and fire conditions and to develop a methodology for analyzing the performance of the system.

5. Optimization of building structures in software systems

Many problems of structural engineering, such as the rational selection of sections or the topology of structures require the use of optimization algorithms. Interest in the problem of optimal design and the development of appropriate algorithms falls on the second half of the twentieth century, where most of the tasks were formulated in the form of nonlinear programming. For the first time, the most general statement of the optimization problem was proposed by L. Schmitt [16]. He combined finite element analysis of structures with nonlinear programming methods. In 1979, a monograph was published by American scientists Edward J. Haug and Jasbir S. Arora [17], which gave a serious impetus to the development of the applied direction of optimization. It outlined general approaches to solving the problems of analysis and synthesis of mechanical systems. The 70-80s of the last century also accounted for numerous software implementations of optimization algorithms.

Since the 90s, a large number of studies have appeared in the field of engineering system optimization, which uses metaheuristic algorithms that explore the search space using random selection, combination and variation of the desired parameters based on mechanisms reminiscent of biological evolution, or physical processes occurring in nature. Here are some examples of heuristic algorithms: genetic algorithms (GA) [18], ant algorithm (ACO) [19], bee colony algorithm (ABC) [20], particle swarm method (PSO) [21], fire algorithm (FA) [22], raven search algorithm (CSA) [23], gray wolf algorithm (AGW) [24], bat algorithms (BA) [25], annealing simulation algorithm (SA) [26] and others [27-230]. In [31-36], practical problems of optimizing building structures using metaheuristic algorithms are presented.

The basis of optimization methods for building structures is research on the extremum of the target function, which is associated with the parameters of the sections of these structures, as well as with the nature of their stress-strain state, where it is possible to take into account viscous, brittle, fatigue failure, loss of stability, or destruction from other factors. The quantitative data of the target function are determined by two indicators: the unit cost of resources and the volume of resources. Genetic algorithms, in particular, have proven to be an effective basis for general tasks that model the most diverse problems of engineering practice. In [37], the TOSCA code is described, which uses genetic algorithms to solve many optimization problems that arise in the design of structures. In [38], an approach to polymorphic uncertainty modeling for timber structures is introduced. The preliminary steps aim at optimization in the design of timber structures, provided that the polymorphic uncertain design, as well as a priori parameters, are considered.

At the moment, quite a lot of research has been done related to the development of numerical optimization algorithms. However, these studies have not found practical application in Russian PCs. The
most common used in Russian PC design are SCAD, LIRA-CAD, Micro-FE, and others, including developed modules of finite element analysis and structural analysis, do not contain design calculation modules that correspond to the specified optimality criterion.

6. Conclusion
The above analysis revealed the need for algorithmic and software capable of adequately simulating the complex behavior of wood-based structures, taking into account factors such as the anisotropic structure of wood and accounting for shear deformations.

Due to the fact that wooden structures are now more and more focused on high-rise construction, they are required to improve seismic protection characteristics, which, of course, should be taken into account when designing structures based on wood in seismically active areas.

Modern approaches to the automated design of structures (including wooden ones) put forward the requirements of ensuring their load-bearing capacity at a given level of reliability, as well as the fulfillment of all architectural and structural requirements, provided that the project cost reaches minimum values. Such a problem can be solved on the basis of optimization algorithms. Hence, there is a need to develop methods for optimizing wood-based building structures that would allow rational technical solutions to be obtained quickly and with minimal time and money. Further research in the direction of optimization and modeling of flat and spatial structures based on wood can be effectively implemented by constructing optimization models of not yet implemented design solutions using non-linear programming methods and metaheuristic algorithms.

References
[1] SP 64.13330.2017. Wooden structures. The updated edition of SNiP II-25-80 (with Change N 1, 2).
[2] Pyatikrestovsky K P and Sokolov B S 2018 Nonlinear analysis of statically indeterminate wooden structures and optimization of cross section dimensions of dome ribs. *International Journal for Computational Civil and Structural Engineering* **14**(4) pp 130-139 DOI:10.22337/2587-9618-2018-14-4-130-139
[3] Vodiamnikov M A 2018 Results of numerical modeling of the stressed-deformed state of the joint connection of wood constructions with cfpr dowel pins. *International Journal for Computational Civil and Structural Engineering*, **14**(2) pp 48-56 DOI:10.22337/2587-96182018-14-2-48-56
[4] Sirumbal-Zapata L F, Málaga-Chuquitaype C and Elghazoul A Y 2019 Experimental assessment and damage modelling of hybrid timber beam-to-steel column connections under cyclic loads. *Engineering Structures*, **200**. https://doi.org/10.1016/j.engstruct.2019.109682
[5] Ugalde D, Almazán J L, Santa María H et al 2019 Seismic protection technologies for timber structures: a review. *Eur. J. Wood Prod.* **77** pp 173–194. https://doi.org/10.1007/s00107019-01389-9
[6] Gohlich Ryan, Erochko Jeffrey and Woods Joshua E 2018 Experimental testing and numerical modelling of a heavy timber moment-resisting frame with ductile steel links. *Earthquake Engineering and Structural Dynamics* **47**-6, pp 1460-1477
[7] Zheng Li, Hanlin Dong, Xijun Wang and Minjuan He 2017 Experimental and numerical investigations into seismic performance of timber-steel hybrid structure with supplemental dampers. *Engineering Structures. Elsevier* **151** pp 33-43 https://doi.org/10.1016/j.engstruct.2017.08.011
[8] Poh'sie G H , Chisari C, Rinaldin G , Amadio C and Fragiacomo M 2016 Optimal design of tuned mass dampers for a multi-storey cross laminated timber building against seismic loads . *Earthquake Engng Struct. Dyn.* **45**: 1977– 1995. doi: 10.1002/eqe.2736.
[9] Kotlov V G and Sharynin B E 2018 Development of a model of the wood material for the finite element analysis of building structures (Part 1) *Vestnik. Volga State Technological Universi ty. Ser.: Materials. Constructions. Technology* **2** (6) pp 58-63. UDC 624.01
[10] Volinsky V N 2012 Vzaimosvyaz'i izmenchivost' fiziko-mekhanicheskikh svojstv drevesiny: monografija [Interrelation and variability of physical and mechanical properties of wood: monograph], 2-ned ed., ISPR, Saint-Petersburg: LAN Publishing House, 224.

[11] Bulent Kaygin, Huseyn Yorur, Burhanettin Uysal 2016 Simulating Strength Behaviors of Corner Joints of Wood Constructions by Using Finite Element Method. Drvna Industrija. 67(2), 133-140. DOI: 10.5552/drin.d.2016.1503

[12] Gluhih V N 2007 Upurugaya deformativnost' drevesiny poperek volokon [Elastic deformation of wood across the fibers], IVUZ. "Lesnoj zhurnal" [IVUZ. "Forest journal"] 5.

[13] Tsulin E Yu, and Shmidt A B 2018 Numerical Simulation of LVL Elastic Modulus with Different Combinations of Mutually Perpendicular Veneer Layers. Lesnoy Zhurnal [Forestry Journal] 6, 138–148. DOI: 10.17238/issn0536-1036.2018.6.138

[14] Follesa M, Fragiacomo M, Casagrande D, Tomasi R, Piazza M, Vassallo D, Canetti D and Rossi S 2018 The new provisions for the seismic design of timber buildings in Europe. Engineering Structures 168 pp 736-747

[15] Quiquero H, Gales J, Abu A et al. 2020 Finite Element Modelling of Post-tensioned Timber Beams at Ambient and Fire Conditions. Fire Technol 56 737–767. https://doi.org/10.1007/s10694-019-00901-0

[16] Schmit L A. Structural design by systematic synthesis. Proceedings of second ASCE conference of electronic computation. 1960 pp 105-122.

[17] Haug Edward J and Jasbir S Arora. Applied Optimal Design: Mechanical and Structural Sys tems. New York: Wiley 1979 pp 487-498

[18] Dao S D, Abhary K, and Marian R 2017 An innovative framework for designing genetic algorith structures. Expert Systems with Application 90 pp 196-208. https://doi.org/10.1016/j.eswa.2017.08.018.

[19] Kaveh A and M H Ghafari 2015 Plastic analysis of planar frames using CBO and ECBO algo rithms. Inter-national journal of optimization in civil engineering 4(5) pp 479-492.

[20] Dogan A, Gurcan Y, Thomas S 2017 ABC-X: a generalized, automatically configurable artificial bee colony framework. Swarm Intelligence 11(1) pp 1-38. https://doi.org/10.1007/s11721-017-0131-z.

[21] Bonyadi M R and Michalewicz Z 2017 Particle Swarm Optimization for Single Objective Continuous Space Problems. A Review. Evolutionary Computation 25(1) pp 1-54 https://doi.org/10.1162/evco_r_00180

[22] Nekouie N and Yaghoobi M. 2016 A new method in multimodal optimization based on firefly algorithm. Artificial Intelligence Review 46(2) pp 267-287. https://doi.org/10.1007/s10462-016-9463-0.

[23] Alireza A 2016 Novel metaheuristic method for solving constrained engineering optimization problems: Crow search algorithm. Computers & Structures 169 pp 1-13 https://doi.org/10.1016/j.compstruc.2016.03.001.

[24] Mirjalili S, Mirjalili S M and Lewis A 2014 Grey Wolf optimizer. Advances in Engineering Software 69 pp 46-61. https://doi.org/10.1016/j. advengsoft.2013.12.007.

[25] Cai X, Wang H, Cui Z, Cai J, Xue Y and Wang L 2017 Bat algorithm with triangle-flipping strategy for numerical optimization. International Journal of Machine Learning and Cyber netics 9(2) pp 199-215. https://doi.org/10.1007/s13042-017-0739-8.

[26] Samma H, Mohamad-Saleh J, Suandi S A and Lahasan B 2019 Q-Learning-based simulated an nealing algorithm for constrained engineering design problems. Neural Computing and App lications.1-15. https://doi.org/10.1007/s00521-019-04008-z.

[27] Ho-Huu V, Nguyen-Thoi T, Vo-Duy T and Nguyen-Trang T 2016 An adaptive elitist differential evolution for optimization of truss structures with discrete design variables. Computers & Structures 165 pp 59–75. https://doi.org/10.1016/j.compstruc.2015.11.014.

[28] Cheng M -Y, Prayogo D, Wu Y-W and Lukito M M 2016 A Hybrid Harmony Search algorithm
for discrete sizing optimization of truss structure. *Automation in Construction* **69** pp 21-33. https://doi.org/10.1016/j.autcon.2016.05.023.

[29] Jalili S and Talatahari S 2017 Optimum Design of Truss Structures Under Frequency Constraints using Hybrid CSS-MBLS Algorithm. *KSCE Journal of Civil Engineering* **22**(5) pp 1840-1853. https://doi.org/10.1007/s12205-017-1407-y.

[30] Khatibinia M and Yazdani H 2018 Accelerated multi-gravitational search algorithm for size optimization of truss structures. *Swarm and Evolutionary Computation* **38** pp 109-119. https://doi.org/10.1016/j.swevo.2017.07.001.

[31] Rao R V and Saroj A 2018 Multi-objective design optimization of heat exchangers using elitist-Jaya algorithm. *Energy Systems* **9** pp 305-341. http://dx.doi.org/10.1007/s12667-016-0221-9.

[32] Lieu Q X, Do D T T and Lee J 2018 An adaptive hybrid evolutionary firefly algorithm for shape and size optimization of truss structures with frequency constraints. *Computers & Structures*. **195**, 99-112. https://doi.org/10.1016/j.compstruc.2017.06.016.

[33] Degertekin S O, Hayalioglu M S 2009 Optimum design of steel space frames: tabu search vs. simulated annealing and genetic algorithms. *International Journal of Engineering and Applied Sciences (IJEAAS)* **1**(2) pp 34-45.

[34] Kaveh A and Zakian P 2017 Improved GWO algorithm for optimal design of truss structures, *Engineering with Computers* **34**(4) pp 685-707. https://doi.org/10.1007/s00366-017-0567-1.

[35] Jalili S and Hosseinzadeh Y 2018 Combining Migration and Differential Evolution Strategies for Optimum Design of Truss Structures with Dynamic Constraints. *Transactions of Civil Engineering* **43**(1) pp 289-312. doi:10.1007/s40996-018-0165-5.

[36] Venkata Rao R, Ankit Saroj. 2017 A self-adaptive multi-population based Jaya algorithm for engineering optimization. *Swarm and Evolutionary Computation*. **37**, 1-26. http://dx.doi.org/10.1016/j.swevo.2017.04.008.

[37] Chisari C and Amadio C 2018 TOSCA: a Tool for Optimisation in Structural and Civil Engineering Analyses. *Int J Adv Struct Eng* **10** pp 401–419. https://doi.org/10.1007/s40091-018-0205-1.

[38] Schietzold F N, Graf W and Kaliske M 2018, Polymorphic Uncertainty Modeling for Optimization of Timber Structures. *Proc. Appl. Math. Mech.* **18**: e201800426. doi:10.1002/pamm.201800426