Features of glued laminated timber anisotropic structure

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Article info review article

Abstract *Glued laminated timber is one of the most efficient constructing materials that allow solving complex architectural and constructional patterns, creating efficient, lightweight, versatile and aesthetically expressional constructions. The major disadvantage of glued wood structures is anisotropy that increases sufficiently in process of its production. Anisotropy of natural and glued laminated timber is considered in the article; particularly it is focused on alteration of elasticity modulus in dependence on angle of load application direction on direction of wood grain. Principal mechanics of natural timber failure is considered in the article. Two methods of timber anisotropy description (orthotropic and transversal isotropic) considered for further development*

Keywords: timber anisotropy, glued laminated timber, orthotropic materials, transverse isotropic materials, wood grain, stress distribution in timber, elasticity modulus of timber, mechnics of timber failure

Content

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1. Introduction

Glued laminated timber is one of the most efficient modern constructing materials. Application of glulam allows accomplishing complex constructive forms, unachievable for metal and reinforced concrete that can distribute and bear load sufficiently more optimal and develop non-standard architectural projects. Timber possesses comparatively inconsiderable sole weight, high chemical corrosion resistance and thermal efficiency. Despite location of major part of pine forests, Russia has not developed wide and significant application of glued laminated timber; however, the rate of its usage for complex engineering solutions nowadays is growing. If the normative fire-resistance of laminated timber will be increased expectedly in technical standards and approach its actual value this rate will grow extensively in Russian Federation.

2. Goal of work

The main goal of work is a starting point of magister dissertation that is dedicated on developing project of physical education facility of “Sirius” educational complex, city of Sochi, particularly its 50m glulam arches. The results of my work are planned to modify methods of glued wood structures analysis, increase durability of timber constructions and junctions of their components. This work is focused on serious drawback glulam structures – anisotropy that has to be considered carefully on old stages engineering conception.

3. Literature review

E.K. Ashkenazy [1,2], who is at the origins of Russian natural and glulam timber science, described features of wood deformation mode in natural conditions and during application as a constructive material. E.N. Serov [3-6] described complex mode of deformation of timber, suggested methods of ideally representation of material model. From this perspective, he also evaluated russian normative documents of glued laminated timber analysis. Serov pointed low fidelity of application of methods for natural lumber analysis for glulam. A.N. Mitinsky [7] presented orthotropic model of timber, described its scientific and practical advantages and disadvantages. Gi Young Jeong and Moon Jae Park researched orthotropic parameters of timber by method of digital image correlation [8]. N.O. Gluhih [9-11] studied cylindrical model of timber anisotropy, described elastic constants. Major part of modern international timber research is concentrated on study of micro- and macrostructure of material and its impact on strength. Articles [12-19] are dedicated to nanoidentaion method – the progressive approach on timber properties research. Transverse isotropic model of timber structure is widely applicable, because it meets the requirements of modern timber engineering. Thus, plurality of studies [3, 18-28] is dedicated to this model. Article [29] by Kouroussis G., Ben Fekih L., Descamps T. is dedicated to determination of timber properties by method of modal analysis.

4. Object of research

Timber developed its specific constructional features that allow tree trunk withstanding natural origin loads in multimillion process of evolution. Trunk is subjected to constant cycles of asymmetrical wind pressure, bears frequently changing atmospheric load. Such load condition has resulted in specific fiber structure of wood and the ratio of its parameters, such as alteration (decrease in direction of top) of trunk mechanical properties, difference in radial and tangential properties of cross section, parameters of annual tree rings, ratio of old and new timber. In result, wood trunk approximates to bend-compressed cantilever beam with constant flexure strength about infinite set of axes, perpendicular to trunk [1-5, 30].

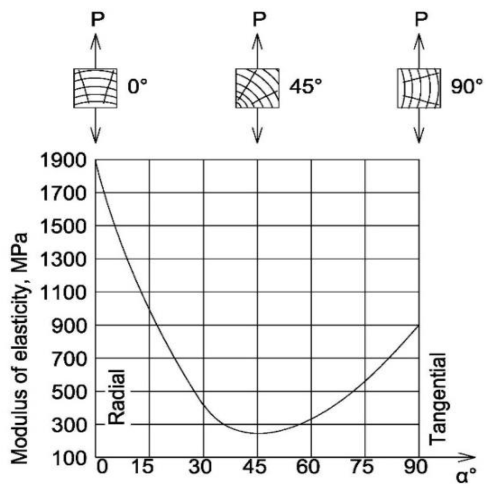

Figure 1. Dependence of pine elasticity modulus on between directions of load application and timber grain.

Even these factors have made natural timber an anisotropic constructional material. Each stage of glued laminated timber production increases this anisotropy significantly. Properties of timber approximate in direction of grain, strength and uniformity increase sufficiently relatively to natural timber. This is a result of methodical selection of wood segments, removal of significant wood flaws. However, properties of timber in direction, transverse to layers of glue, decrease due to following factors [5, 6]. The direction of grain in cross section varies almost in each element of lumber; the presence of skewed grain is unavoidable in process of agglutination. Moreover, glue layer is adjoined to crossed tracheids in zones of snags and skewed grains. Also, anisotropy of glued laminated structures is caused by untypical for natural lumber parameters, such as significantly increased spans and cross sections of structures, ratios of cross section dimensions that can be developed only by application of glued wood. Furthermore, anisotropic features of lumber are sufficiently more expressed in extensional loadings than in compressive ones.

5. Methods of research

Necessity of serious consideration of glued laminated timber structures anisotropy is caused by specificity of dependence of lumber strength on angle of load application to direction of timber grain direction (fig.1). Graphic chart of material strength displays that pine modulus of elasticity can change up to six times in case of alteration of load application angle. Maximal value of elasticity modulus is reached when the load is situated relatively perpendicularly to tree rings or in radial direction, minimal – when the load is situated at 45° to the rings, in this case shear parallel to grain takes place [13-17, 30-34].

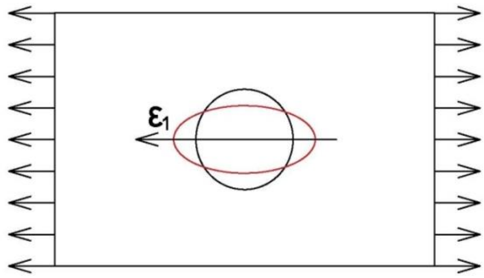

Figure 2. Extension of isotropic plate

The features of anisotropic material behavior is demonstrated in experiment by E. Ashkenazy [1, 2], E. Serov [3-6]. The circle outline has been put on two plates; one is made of conditionally isotropic material – steel (fig. 2); the second one is made of wood (fig. 3). Then, both plates have been subjected to tensile loading that caused following results. The shape of outline, put isotropic plate, has become elliptic, and the direction of main stress σ_1 is corresponding to direction of main deformation ε_1. Extension of anisotropic plate loading of plate by different angles to wood grain direction α brings following results. Directions of main stress and main deformation are non-collinear. Direction of ellipse major axis is deflected by angle φ. This deflection can reach 30° in pine timber species if extension takes place with 20° angle to grain direction. Stress, corresponding to deformation ε_1, has smaller value than σ_1, however it can be even more dangerous, because deflection occurs in direction of lumber strength reduction [12].

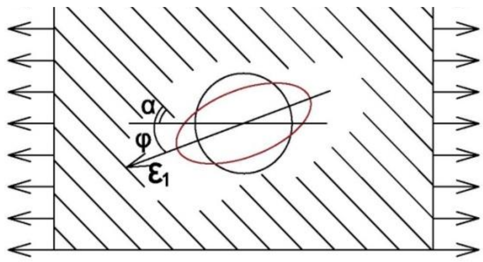

Figure 3. Extension of anisotropic plate

Character of functioning of these natural lumber features after production of glued laminated timber has significant practical value.

5.1. Orthotropic anisotropy model of natural and glued laminated timber structure

There are three principal models of timber structures anisotropic stance: cylindrical, orthogonal (orthotropic) and transverse isotropic (trans-tropic) [1-4, 20-23, 30-33]. Orthotropic model of anisotropy (fig. 4) is based on assumption that there are three symmetry planes in elemental volume of timber. These planes are perpendicular to three major directions: tangential direction t (radial plane ar), radial direction r (tangential plane at) and transversal direction (plane rt, perpendicular to direction of grain a). Tangential plane can be considered as a symmetry plate of elemental volume on condition that curving of annual growth rings is insufficient in the analyzed volume. Plane rt, perpendicular to grain, can be considered as symmetry plane if properties of material do not change significantly along the trunk. This point is actual for natural lumber elements with sufficient length. This condition is usually fulfilled in glued laminated timber [12-17].

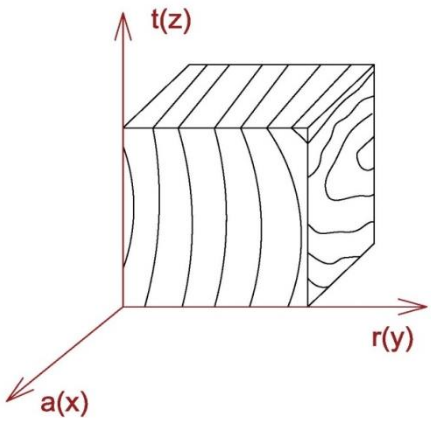

Figure 4. Orthotropic model of timber anisotropy

Glulam is made of fragments that can be sorted without consuming much labor, to provide uniformity in this direction. After agglutination, material will possess sufficient homogeneity along a-direction. Transversal plane at can be considered as plane of symmetry only if properties of young-growth and old-growth wood would be assumed as inessential. In other word, it means denial of layer structure of timber. However, the last assumption is optional, because models with two and three planes of elastic symmetry are both determined by same amount of equations, nine. Thus, consideration of presence of the third symmetry plane in elementary volume loses its importance [34-36].

Description of timber as a material, elementary volumes of which can be referred with orthotropic anisotropy properties can be considered nowadays as one of the most consistent, widespread and experimentally justified methods. It is applicable only for structures with insignificant curving of tree rings [37-39]. Glued laminated timber structures are made of agglutinated thin planks; their cross section has not enough area to develop major curving of tree rings. Thus, this method is adequate for glued laminated structure description. However, this method is inconvenient for solution of engineering tasks due to its cumbersomeness and difficulty of versatile solution adaption [40-42]. Practical tasks require other methods of anisotropy description.

5.2 Transversally isotropic model of anisotropy of natural and glued laminated timber structure

Transversally isotropic [3] (fig.5) or trans-tropic system is based on assumption that difference of lumber properties in direction, orthogonal to grain, can be considered as negligible. This model is simpler and more convinient orthotropic one, and it is aplicable for wide spectre of applications, inculuding tasks without certain orientation of radial and tangential directions [18-26, 43].

In this case, axis of anisotropy (direction of extremal values of material properies) that are located in the same plane of symmetry are equivalent to each other [44-45]. In other words mechanical properties on direction of these axes can be considered to be the same. Plane that pasess through such axes is termed as symmetry plane of infininte order. Such system is applicable to glued laminated timber structures, because in multilayer timber stack every plank has its own individual orientation of annual tree rings [46-47]. Application of narrow lumber sortiment causes split of angle between vertical and tangential axis from 0° till 90°.

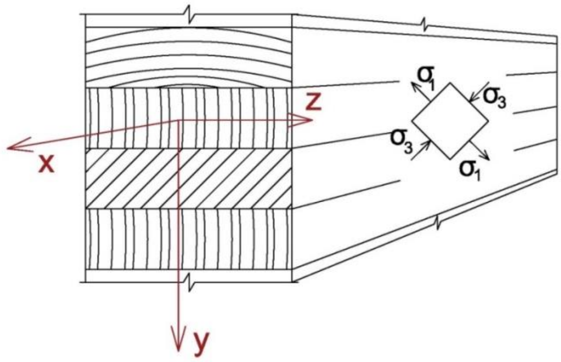

Figure 5. Transversal model of timber anisotropy

In one hand, the split of angle value allows approximation of elasticity modulus (fig.1) for whole stack of lumber. In the other hand, such simplification of anisotropy model does not allow to consider features of functioning of composite material. This factor brings necessity of integration of orthotropic elements into transversal one to obtain adequate equations for approximated parameters of lumber [40-42].

These equations have been obtained by A.N. Mitinsky [7] for elastic parameters of timber accounted in combination of orthogonal and transversal systems of anisotropy (fig.6). In this system, glued laminated timber construction (fig.5) is submitted as transversally isotropic system comprised from orthotropic elements.

Modulus of elasticity along direction of grain growth matches for orthotropic system E_a and for transversal system E_1 in most cases (letter index for elasticity modulus stands for orthotropic system, number index stands for transversal). Alteration of elasticity modulus in direction, perpendicular to grain growth, in dependence on angle α to radial direction is formulated as equation of quartic curve:

$$\frac{1}{E_\alpha}=\frac{\cos^4\alpha}{E_r}+\frac{\sin^4\alpha}{E_t}+\frac{1}{4}\left(\frac{1}{G_{rt}}-\frac{2\mu_{tr}}{E_r}\right)\sin^2\alpha \qquad (1)$$

Where E_r and E_t- modulus of elasticity of timber in radial and tangential direction, G_{rt}- shear modulus, μ_{tr} – Poisson’s ratio.

A.N. Mitinsky suggested approximated formula for modulus of elasticity across the grain direction (2) [7].

$$\frac{1}{E_2}=\frac{1}{n}\left(\frac{1}{2E_{(0)}}+\frac{1}{E_{(1)}}+\frac{1}{E_{(n-1)}}+\frac{1}{2E_{(n)}}\right) \qquad (2)$$

Where, E_2- approximated modulus of elasticity across the grain, $E_{(0)}, E_{(1)}, \ldots, E_{(n)}$ – modulus of elasticity across the grain on borders of zones, corresponding to edge values of deflection angle of annual tree rings.

E.K. Ashkenazy [1, 2] suggested formula with sufficient accuracy. Curvilinear trapezoid (fig.1) that depicts elasticity modulus alteration is divided on two sectors: first spreads from E_0 to E_{45}, the second – from E_{45} to E_n. This assumption and application of invariant for orthotropic material ratio $\frac{\mu_{tr}}{E_r} = \frac{\mu_{rt}}{E_t}$ results in equation (3).

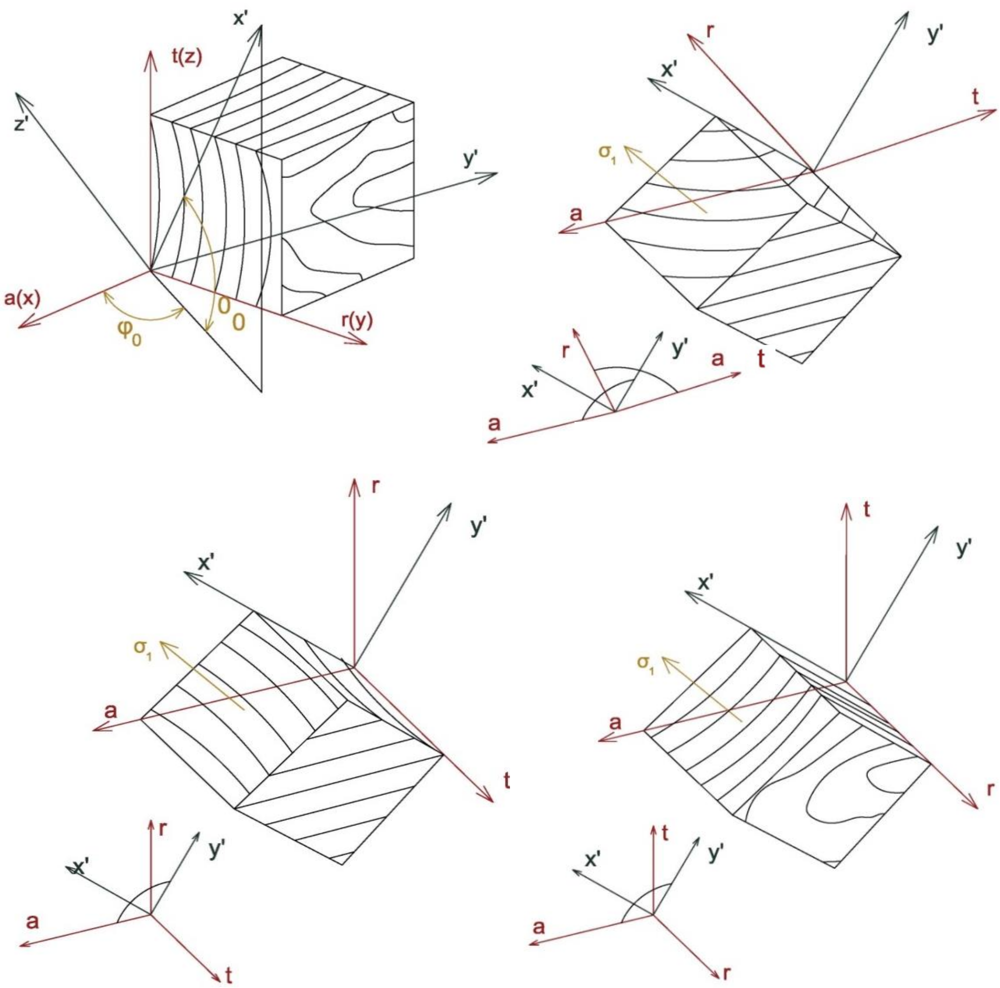

Figure 6. Three basic orthotropic elements that compile lumber as transversally isotropic material.

$$\frac{1}{E_2} = \frac{1}{8}\left(\frac{3-\mu_{tr}}{E_r} + \frac{3-\mu_{rt}}{E_t} + \frac{1}{G_{rt}}\right) \quad (3)$$

6. Results and discussion

As initial article in this topic, the work allows authors collective to get into discussion with established researchers of glued laminated timber structures. Monitoring of different science data bases shows application of wide amount of methods [49, 50]. However, attention was focused on methods used research [46] of micro- and macro-mechanical verification of timber elasticity modulus; analysis of properties in microstructure has been performed by nanoidentaition method that is seems to be widely applicable by European timber researchers [15, 16]. Authors of this article plan to apply this method with consideration of associates' experience in following researches.

7. Conclusions

Feautures of mechanical properties distribution in timber have been researched in the article and following models of their description – orthotropic, transversally isotropic and their combination - have been installed. Two possible directions of following research work have been settled: development of existing models of anisotropy description and their combinations and localization of dangerous zones, caused by anisotropy features, and reinforcement of timber with other materials.

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Особенности анизотропного строения клееной древесины

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Информация о статье — УДК 69

Аннотация

Клееная древесина – один из наиболее эффективных современных мтрительььных материалов, позволяющих решать сложные архитектурные, инженерные и конструкторские задачи, создавать энергетически эффективные, легковесные, относительно быстровозводимые и эстетически выразительные конструкции. Одним из главных недостатков клееной древесины является ее выраженная анизотропность, которая усиливается на этапах изготовления клееных деревянных конструкций в направлении поперек волокон. В данной статье сравниваются анизотропные свойства природной и клееной древесины, в частности влияние модуля упругости в зависимости от угла приложения нагрузки относительно направления волокон, принципиальная механика разрушения природной древесины, два метода описания анизотропии: ортотропный и трансверсально изотропный, описаны их сильные и слабые стороны, предложены два направления дальнейших исследований по этой теме.

Ключевые слова — анизотропия древесины; клееная древесина; ортотропные материалы; трансверсально изотропные материалы; волокна древесины; распределение напряжений в древесине; модуль упругости древесины, механика разрушения древесины

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