DOI: 10.23968/2500-0055-2020-5-2-25-31

Civil Engineering

STRENGTH PROPERTIES OF TRUSS ELEMENTS MADE OF ENVIRONMENTALLY-FRIENDLY STRUCTURAL LUMBER

Vladimir Melekhov[1], Viktor Byzov[2], Aleksandr Chernykh[2]*, Shirali Mamedov[2]

[1]Northern (Arctic) Federal University named after M.V. Lomonosov
Severnaya Dvina Emb., 17, Arkhangelsk, Russia

[2]Saint Petersburg State University of Architecture and Civil Engineering
Vtoraja Krasnoarmeyskaya st., 4, Saint Petersburg, Russia

*Corresponding author: ag1825831@mail.ru

Abstract

Introduction: Softwood lumber is widely used to manufacture load-bearing structures. However, the quality of round wood used to manufacture such lumber has been deteriorating lately. Round wood decreases in diameter and often has heart rot. The article looks into the possibility of manufacturing elements of load-bearing structures using beams made of round wood of small diameter that have not been previously used to manufacture structural materials for construction purposes. It is suggested to make beams of such round wood preserving the trunk structure to the maximum (heartwood beams). Due to the preservation of the annual growth ring pattern, such beams have better strength properties as compared to traditional structural lumber. **Purpose of the study:** The study is aimed to determine the strength properties of engineering structures' elements made of heartwood beams sawn from round wood of small diameter. **Methods:** The authors tested an experimental truss made of heartwood beams by means of incremental loading until destruction. **Results:** The strength properties of the truss elements made of heartwood beams sawn from round wood of small diameter were determined. There is a good fit between the calculated values of stress in the truss elements and the experimental data. The structure was damaged in the panel points connecting the compression strut with the elements of the tension and compression chords. The tension elements and their joints remained undisturbed. The experimental structure has a safety factor of 2. Compared to the design load, such a value shows that the experimental truss has the required bearing capacity and is robust. The findings confirm that the strength properties of heartwood beams match the requirements for elements of load-bearing structures. The strength properties of heartwood beams make it possible to use them to manufacture load-bearing structures.

Keywords
Load-bearing structures, strength properties of beams, annual growth ring pattern, experimental-truss testing.

Introduction

Resource-saving and green technologies of raw material processing in industrial production are the basis of the efficient economic development of any state. This also goes for the manufacturing process of wood load-bearing structures. Softwood lumber is used to manufacture elements of load-bearing structures. Structural lumber must have exact geometric shape and strength properties necessary for the manufacture of engineering structures. Lately, the environmental situation has deteriorated, which affects, inter alia, woodland. Heart rot occurs in trunks more and more often (Semenkova, 2002). Lumber used for elements of load-bearing structures must not have heart rot. That is why the process of cutting trunks with heart rot into wood assortments includes the removal of rotten trunk parts. Heart rot invades, first of all, the part of a trunk near the root system, and this part has the largest diameter. As a result, the average diameter of sawn lumber typically decreases. The amount of sawn lumber of a smaller diameter grows. The environmental advantages of wood as a structural material are apparent. However, it is slightly less advantageous in terms of strength properties, deflection, required sections, etc. (Karelskiy et al., 2015; Nekliudova et al., 2014). It is the reason why proper structural analysis for elements of wood engineering structures is so important (Horvath et al., 2010).

Saw logs with a diameter of 14–18 cm account for more than half of the total number of all round wood delivered to the saw mills in the northern part of European Russia (Vorontsov and Surovtseva, 2002). In the future, due to the reduced quality of the forest land allocated to wood production, the number of such saw logs will increase even more. Structural lumber is cut from logs with a diameter of more than 22 cm with the heart removed. Saw logs of small diameter are not used to manufacture elements of load-bearing structures. This is due to the fact that the lumber made of them has a small size and the heart in the middle of the cross-section remains. The existing regulatory documents do not allow for the heart in lumber used to manufacture elements of load-bearing structures. This is due to the fact that less strong wood is located near the medullary sheath. Therefore, the probability of contraction cracks is high and the areas located near the heart may have rot (Chubinskii et al., 2014; Wei et al., 2011).

Saw logs of small diameter are made of the top area of trunks. Finnish scientist Ylinen (Ylinen, 1952) developed the most complete mechanical theory of the tree trunk. He considers a coniferous tree trunk to be a complex reinforced layered structure of uniform strength capable of significant elastic deformations. The layered structure of the wood in the trunk implies that more flexible layers of spring wood alternate with summer wood, which is tougher. Such a trunk structure ensures high stability in case of vertical loads caused by the mass of the trunk and the crown. The top part of the tree trunk mainly has small healthy intergrown knots that reinforce the structure of wood, and the medullary sheath is characterized by a high degree of intergrowth with the surrounding wood.

We suggest making beams that use the cross-section of lumber to the maximum from round wood of small diameter. That is why it is expedient to make beams with a section of 100 x 100, 115 x 125 mm and 125 x 125 mm of round wood with a diameter of 14, 16 and 18 cm in the top, respectively. These beams preserve the tree trunk structure to the fullest. The majority of annual growth layers preserve the ring structure. The medullary sheath is near the cross-section center. These are so-called heartwood beams (Figure 1).

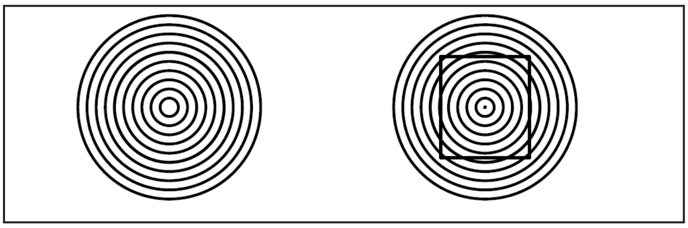

Figure 1. A diagram of manufacturing heartwood beams from round wood of small diameter.

Elements of load-bearing structures manufactured from heartwood beams operate under the conditions of transverse bending and compression along the wood grain with a bend. According to some studies (Byzov and Melekhov, 2011), the normal stresses occurring in such beams, having primarily a ring structure of annual growth layers, are 33–38% less than the normal stresses in traditional lumber.

The overview performed makes it possible to determine the purpose and tasks of the studies conducted. The purpose of this study is to determine the strength properties of engineering structures' elements made of heartwood beams sawn from round wood of small diameter. It requires solving the following tasks:

- Production of heartwood beams that have strength properties necessary to manufacture elements of load-bearing structures.
- Determination of the strength properties of the beams by testing the load-bearing structure made of such beams.

Methods

Pine heartwood beams with the cross-section sizes of 115 x 125 and 125 x 125 mm were sawn. The beams were dried until the moisture content of 18 ± 2%. Then, the beams were sorted visually into strength classes in accordance with the EN 338:2003 requirements. The beams obtained were of strength classes C24 and C14.

Various types of trusses are the most common load-bearing structures consisting of elements made of whole-section timber. Trusses with spans of 18 m are the most sought-after. In the course of the study, a truss with elements made of heartwood beams was tested. The truss structure has parallel chords and a triangular lattice (Figure 2).

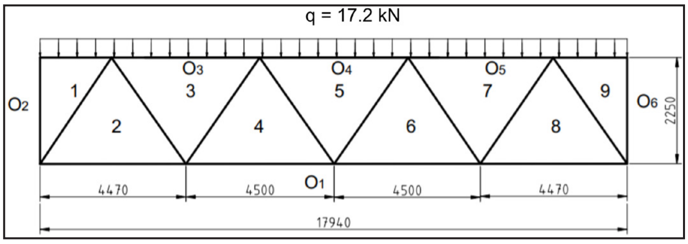

Figure 2. A diagram of the experimental engineering structure made of beam elements: O_1, O_2, O_3, O_4, O_5, O_6 are external areas defined by the structure contours and the lines of external forces; 1, 2, 3, 4, 5, 6, 7, 8, 9 are internal areas defined by the structure bars; q is a uniformly distributed load.

The truss elements undergoing deformation under transverse bending and compression along the grain are made of beams of relevant strength classes. The truss design load q is 17.2 kN/m. The structure height is 2580 mm. The width of the chords is as follows: the width of the upper chord — 423 mm, the width of the lower chord — 403 mm. The camber of the truss is 135 mm, the length of the chords is 18,420 mm. The structure is made of spruce beams of different sizes. The upper and lower chords of the structure are made of four beams. The length of the beams is 6140 mm. The upper compression chord is made of beams with a cross-section of 125 x 125 mm, the lower tension chord is made of beams of 115 x 125 mm, and beams of 125 x 125 mm are used for struts. Compression support struts consist of two beams with a cross-section of 125 x 125 mm. The moisture content of the beam wood was 12 ± 2% at the time of the testing.

We assessed the stress–strain state of the experimental structure consisting of beam elements made of beams manufactured from round wood assortments of small diameter.

Various loading conditions were applied when testing the structures. In each particular case, loading conditions were chosen depending on the type of the structure and the objective of the tests. The entire span should be loaded in order to get the maximum values of longitudinal forces in the panels of the upper and lower chords of structures of any shape, as well as the maximum values of structure deformations. The following loading conditions were considered:

- four point forces in all panel points of the upper chord;
- two point forces in the middle panel points of the upper chord;
- two point forces in the panel points of the upper chord outermost from the supports;
- two point forces in the panel points of the upper chord outermost from the left support.

In cases when more unfavorable conditions of structure elements' operation occur at partial loading, loading conditions with the load affecting the half of the span should be considered. That is why additional loading conditions were considered:

- uniformly distributed load along the entire span of the structure;
- uniformly distributed load along the half of the span of the structure.

An analysis of the loading conditions under consideration shows that, when the structure is loaded along the entire span, the maximum forces occur not only in the chords but also in the struts. Therefore, the loading conditions when four point forces affect all panel points of the upper chord were chosen to study the experimental structure. Such loading conditions match the actual operating load (uniformly distributed load along the entire span of the structure) the best. The requirements for beams used to manufacture the structure elements were adopted with account for such loading conditions.

Results and discussion

Stresses occurring in the elements of the tested structure at the design load q = 17.2 kN and assumed cross-sections of the elements are given in Table 1.

Table 1. Stresses in structure elements.

No.	Truss element	Notation	Force in elements, kN	Cross-section, mm	Stress, MPa		
					tension	bending	compression
1.	Beam elements of the lower chord	-	75.03	115 x 125	5.22	-	-
2.	Central beam elements	-	75.03	125 x 125	-	10.95	4.80
3.	Outermost beam elements	-	54.33	125 x 125	-	10.95	3.48
4.	Struts	1-2; 8-9	97.45	125 x 125	-	-	6.24
5.	Struts	2-3; 7-8	110.39	125 x 125	7.06	-	-
6.	Struts	3-4; 6-7	112.11	125 x 125	-	-	7.17
7.	Strut	4-5	51.74	125 x 125	-	-	3.31
8.	Strut	5-6	53.47	125 x 125	3.42	-	-
9.	Vertical posts	0_2-1; 0_8-9	19.14	125 x 125	-	-	1.22

For beams of C24 strength class, the characteristic values of strength in bending under a load applied to the edge is 24 MPa, compression along the grain — 21 MPa, and tension along the grain —14 MPa. In accordance with the EN 1995:2011 requirements, we determined the design strength values for beams of C24 class under these stress–strain states. The design values were: 14.8 MPa in bending with a load applied to the edge; 12.9 MPa in compression along the grain; and 8.6 MPa in tension. Besides, we calculated the design resistance for beams of C14 class in compression along the grain. The design value of stress for this stress–strain state is 9.8 MPa.

Tensions of 5.22, 7.06 and 3.42 MPa occur in the tension elements of the lower chord and in the tension struts. These stresses do not exceed the design values for C24 strength class. Therefore, structural beams of C24 strength class were used for these elements.

At the design load, bending stress R_b = 10.95 MPa occurs in the beam-columns of the upper chord of the structure, compression stress R_c = 4.80 MPa occurs in the central beam elements, and compression stress R_c = 3.48 MPa occurs in the outermost elements. Bending stress matching design resistance given for lumber of C24 strength class occurs in the upper chord elements. In addition to transverse bending, the elements undergo compression along the wood grain. Compression stress in the central elements is 4.8 MPa, and in the outermost ones — 3.48 MPa. These values do not exceed design resistance for C24 strength class, which makes it possible to use heartwood beams of C24 strength class for their manufacturing.

The compression struts and vertical posts undergo stresses of 6.24, 7.17, 3.13 and 1.22 MPa. The value of design resistance for lumber of C14 strength class, which is 9.8 MPa, exceeds these stresses. To manufacture this lumber, structural beams of C14 strength class were used (Rikynin and Vladimirova, 2012).

We calculated the percentage ratio of the volumes of wood consumed to manufacture beam elements with different stress–strain states. The corresponding values are given in Table 2.

Table 2. Ratio of the volumes of wood used to manufacture beam elements.

No.	Element and its stress–strain state	Volume of wood	
		m^3	%
1.	Tension beam elements of the lower chord, tension struts	1.286	48.7
2.	Beam-columns of the upper chord	0.921	34.9
3.	Compression struts and vertical posts	0.431	16.4
	TOTAL:	2.638	100.0

As follows from Table 2, almost 84% of the beams correspond to C24 strength class. Beams with a lower strength (C14 strength class) were used to manufacture the structure elements operating in compression along the grain. It is possible since the strength rates of beams in compression along the grain ensure resistance to the loads that occur in the elements when the structure is loaded. Thus, all the beams were used to manufacture the structure elements.

In the structure under consideration, the volume ratio of wood used to manufacture the structure elements with different strength matches the actual distribution of the strength values with regard to all the beams. However, an analysis of load-bearing structures' designs shows that, as for less tough wood, higher volumes are required to manufacture load-bearing structures (as compared to tougher wood). The actual strength distribution of the beams shows that tougher wood accounts for a higher volume than less tough wood. In other words, an inverse ratio is observed. In practice, it means that, when manufacturing load-bearing structures, some beams of higher strength are used while such strength is not required. Therefore, in order to use wood more efficiently and reduce material consumption in load-bearing structures, the sections of beam elements should be selected with account for the volume ratio of wood of different strength groups.

The structure was tested through load increase with an increment of 64 kN and deformation measurement. The panel points were made with the use of steel plates and cover plates with a thickness of 8 mm. They were attached to the chords and struts using self-tapping screws with a diameter of 6 mm and a length of 60 mm. The panel points attaching the struts to the chords were made using tube sections with an OD of 73 mm and a wall thickness of 8 mm. The forces from the axes (tubes) were transferred to the metal plates and cover plates, and then, to the wood through the self-tapping screws. The out-of-plane stability of the compression and tension chords was ensured with wood blocks interconnecting the chord beams in six places along the structure length in the compression chord and in four places — in the tension chord.

The deformations of the wood were determined using strain gauges with a base of 50 cm and dial gauges with a division value of 0.01 mm. Graphs showing structural deflections at incremental loading were constructed based on the measurements of the deformations obtained during the tests (Figure 3).

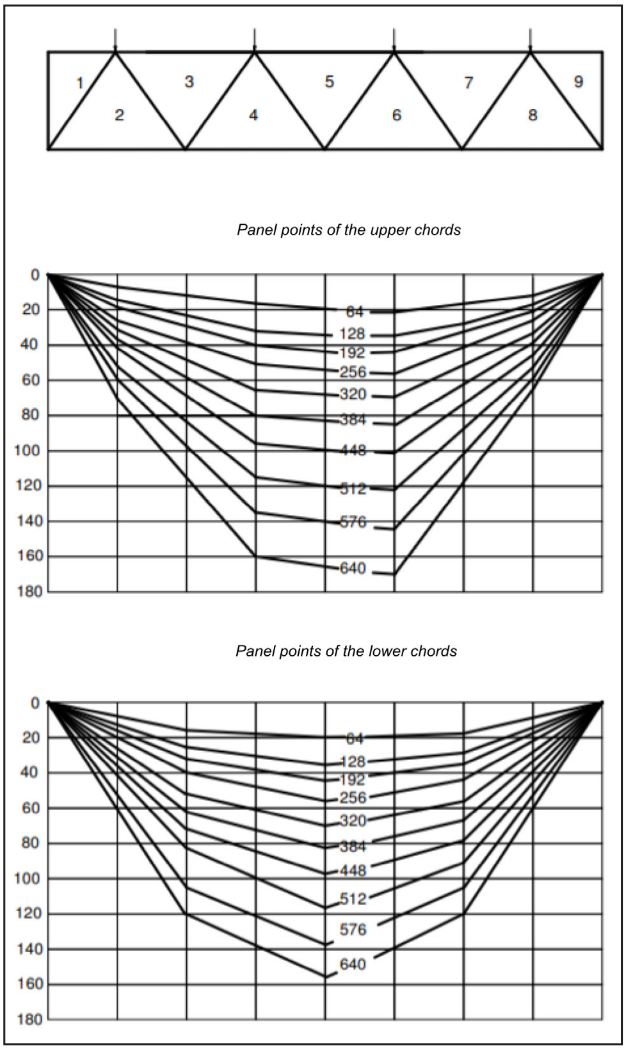

Figure 3. Graphs of structural deflections at incremental loading.

The graphs make it possible to trace the displacement of the panel points of the upper chord. An analysis of the graphs shows that these displacements are asymmetrical with regard to the vertical axis. By comparing the stresses in the bars, calculated theoretically, with the data obtained during the tests, we observed a good fit. For example, in strut 2-3 (strain gauge M-5), the stress calculated theoretically is 14.85 MPa, while the experimental value is 12 MPa. In the compression chord – bar O_3-3 (strain gauge M-4), the stress calculated theoretically is 7.8 MPa, while the experimental value is 8.4 MPa. The destruction of the structure occurred at the tenth stage of loading, with a total load of 640 kN. The maximum deflection was 158 mm, or 1/112 of the span. The safety factor of the experimental structure was 2.0. The reason for the destruction was a crack in the ends of the compression strut beam. In addition, compression support struts broke in the panel points of the tension and compression chords. The head metal plate bent and the end of the beam element cracked in the panel point where compression strut 3-4 adjoined the chord. Further testing was stopped. Visual inspection showed that there were no apparent signs of the destruction of other structure elements. The tension joints were not destroyed. The chord elements and tension struts did not have noticeable deformations.

Conclusions

The following conclusions can be made as a result of the study:

1. There is a good fit between the calculated values of stress in the truss elements and the experimental data.
2. The structure was damaged in the panel points connecting the compression strut with the elements of the tension and compression chords. The tension elements and their joints remained undisturbed.
3. The experimental structure has a safety factor of 2.
4. The strength properties of heartwood beams make it possible to use them to manufacture load-bearing structures.

References

Byzov, V. Ye. and Melekhov, V. I. (2011). Process of manufacturing roof trusses from structural lumber of large cross-section with heartwood inclusions. In: *Proceedings of the 2nd Inter-Regional Scientific and Practical Conference "Innovative development, modernization and reconstruction of utility facilities in the modern context"*, pp. 232–238.

Chubinskii, A. N., Tambi, A. A., Teppoev, A. V., Anan'eva, N. I., Semishkur, S. O. and Bakhshieva, M. A. (2014). Physical non-destructive methods for the testing and evaluation of the structure of wood-based materials. *Russian Journal of Nondestructive Testing*, 50 (11), pp. 693–700. DOI: 10.1134/S1061830914110023.

Horvath, B., Peszlen, I., Peralta, P., Horvath, L., Kasal, B. and Li, L. (2010). Elastic modulus determination of transgenic aspen using a dynamic mechanical analyzer in static bending mode. *Forest Product Journal*, 60 (3), pp. 296–300. DOI: 10.13073/0015-7473-60.3.296.

Karelskiy, A. V., Zhuravleva, T. P. and Labudin, B. V. (2015). Load-to-failure bending test of wood composite beams connected by gang nail. *Magazine of Civil Engineering,* 2, pp. 77–85.

Nekliudova, E. A., Semenov, A. S., Melnikov, B. E. and Semenov, S. G. (2014). Experimental research and finite element analysis of elastic and strength properties of fiberglass composite material. *Magazine of Civil Engineering,* 3, pp. 25–39.

Rikynin S. N. and Vladimirova E. G. (2012). Sawn timber grading on quality groups. *Forestry Bulletin,* 3, pp. 89–92.

Semenkova, N.G. (2002). *Phytopathology. Wood-decay fungi, rots, and pathological changes in wood color (keys).* 2nd edition, Moscow: Moscow State Forest University, 58 p.

Vorontsov, Yu. F. and Surovtseva, L. S. (2002). Efficiency of sawmills' specialization according to diameter groups of sawn raw material. *Bulletin of Higher Educational Institutions. Lesnoy Zhurnal (Russian Forestry Journal)*, 5, pp. 89–93.

Wei, Q., Leblon, B. and La Rocque, A. (2011). On the use of X-ray computed tomography for determining wood properties a review. *Canadian Journal of Forest Research,* 41 (11), pp. 2120–2140. DOI: 10.1139/x11-111.

Ylinen, A. (1952). Über die mechanische Schaftformtheorie der Bäume. *Technische Hochschule in Finnland, Wissenschaftliche Forschungen*, 7, 51 p.

ПРОЧНОСТНЫЕ ХАРАКТЕРИСТИКИ ЭЛЕМЕНТОВ ФЕРМЫ ИЗ ЭКОЛОГИЧЕСКИХ КОНСТРУКЦИОННЫХ ПИЛОМАТЕРИАЛОВ

Владимир Иванович Мелехов[1], Виктор Евгеньевич Бызов[2], Александр Григорьевич Черных[2]*, Ширали Махаррамович Мамедов[2]

[1]Северный (Арктический) федеральный университет имени М. В. Ломоносова
Набережная Северной Двины, 17, Архангельск, Россия

[2]Санкт-Петербургский государственный архитектурно-строительный университет
2-ая Красноармейская ул., 4, Санкт-Петербург, Россия

*E-mail: ag1825831@mail.ru

Аннотация

Для изготовления несущих строительных конструкций широко применяются пиломатериалы хвойных пород. Качество круглых лесоматериалов используемых для изготовления таких пиломатериалов в последнее время постоянно снижается. Уменьшается диаметр лесоматериалов и в них часто встречается ядровая гниль. В статье рассматривается возможность изготовления элементов несущих конструкций из брусьев, получаемых из круглых лесоматериалов небольших диаметров, ранее не применявшихся для изготовления конструкционных материалов для строительства. Предлагается из таких лесоматериалов получать брусья с максимальным сохранением структуры ствола дерева – сердцевинные брусья. Эти брусья вследствие максимального сохранения кольцевой структуры годичных слоев древесины обладают более высокими прочностными характеристиками по сравнению с традиционно применяемыми конструкционными пиломатериалами. **Цель исследования.** Проверка прочностных характеристик элементов строительных конструкций, изготовленных из сердцевинных брусьев, выпиленных из круглых лесоматериалов небольшого диаметра. **Методы.** Испытание экспериментальной фермы из сердцевинных брусьев путем поэтапного загружения и доведения до разрушения. **Результаты.** Определены прочностные характеристики элементов фермы с элементами, изготовленными из сердцевинных брусьев, выпиленных из круглых лесоматериалов небольшого диаметра. Наблюдается хорошее совпадение рассчитанных значений напряжений в элементах фермы со значениями, полученными экспериментально. Разрушение конструкции произошло в узловых соединениях сжатого раскоса с элементами, растянутого и сжатого поясов. Растянутые элементы и их стыки остались неразрушенными. Экспериментальная конструкция имеет запас прочности равный двум. Двукратный запас прочности по сравнению с расчетной нагрузкой показал, что экспериментальная ферма обладает необходимой несущей способностью и является надежной конструкцией. Результаты исследований подтверждают, что прочностные характеристики сердцевинных брусьев соответствуют требованиям, предъявляемым к элементам несущих строительных конструкций. Прочностные характеристики сердцевинных брусьев позволяют применять их для изготовления несущих строительных конструкций.

Ключевые слова

Несущие строительные конструкции, прочностные характеристики брусьев, кольцевая структура годичных слоев древесины, испытания экспериментальной фермы.