RIGA TECHNICAL UNIVERSITY

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NON-TRADITIONAL WOOD COMPOSITE STRUCTURAL ELEMENTS AND THEIR ANALYSIS METHODS

Summary of doctoral thesis

Riga Technical University Promotion Council “RTU P-06” in Field of Building, Transport and Traffic Sciences

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GENERAL CHARACTERIZATION OF WORK

Motivation

One of the most important structural problems is replacement of non-renewable natural resources by renewable resources. Sustainability could be achieved if we use materials that do not need non-renewable energy and material resources during its life cycle.

Natural resources could be rationally used, if we design constructions and materials used in constructions simultaneously. It is necessary to understand the design principles and restrictions of material with certain properties.

Ribbed structural elements that consist of sheets with unsymmetrical and/or symmetrical lay-up give a possibility to design material with necessary stiffness, strength, heat insulation and hygroscopic properties.

Structural strength and stiffness fields could be harmonized with the stress resultant fields by iteratively and purposefully tailoring material and structural properties. This procedure could significantly increase structural specific strength and stiffness, reduce heat conduction and moisture caused deformations.

Wood structural elements in building are usually used in roof structures. However, these structures are work-consuming because of non-industrial technology and lack of unification. We can avoid of these problems by the creation of the non-traditional wood composite structural element.

Classical plywood sheets, which are subjected to specific loads, produce very non-uniform stress resultant fields, are widely used in machinery structures. Usually material strength and stiffness fields are not harmonized with stress resultant fields. Therefore it is necessary to create a non-traditional wood composite structural element with increased specific strength and variable stiffness and develop its analysis method. As well as, it is necessary to show the advantages of the developed structural elements and their analysis methods by applying them to typical load bearing multispan plate subjected to two moving loads and spatial, triangular, three hinged, industrial roof arch.

Aim and tasks of the Work

To create basic design principles and analysis methods of non-traditional wood composite structural elements with increased specific strength, curved and flat structural ribs and outer layers specific wood fiber orientation angle.

The following tasks should be solved to achieve the aim:

1. To create the analysis and design method of optimal manufacturing moisture conditions, temperature, time and rational lay-up of unsymmetrical plywood sheet, and experimentally validate the proposed methods.
2. To develop the analysis method of geometrical properties of ribbed plywood composite structural element with unidirectional ribs, and, by using this method, obtain rational cross section geometrical properties of three span plates with two moving loads.
3. To create design and analysis basic principles of non-traditional variable stiffness composite structural element with flat and curved ribs, which is characterized by increased specific strength, decreased moisture caused deformations and decreased heat conductivity. To create analysis algorithm of optimal wood fiber orientation angle in outer layers of variable stiffness plywood sheet, and calculate optimal outer layers wood fiber orientation angles of single span and three spans commonly used plates.
4. To obtain bending and shear stiffness dependence on ribbed plywood composite plate's ribbed structures geometrical properties and, by using this information, to calculate rational ribbed structure of proposed plate with flat and curved ribs, and evaluate the moisture caused additional stress in the plate.
5. To show the practical applications of created analysis and optimization methods by optimizing three span plates, subjected to multiple load combinations, and triangular three hinged spatial roof arch. To make conceptual experimental validation of the main results.

Topics Presented for the Defense:

1. The analysis method of optimal lay-up, thermal treatment time and temperature of unsymmetrical plywood sheets that are used as ribs.
2. The analysis method and plywood composite structural element with rational ribbed structure and optimal outer veneer orientation angle

providing increased specific strength, decreased moisture caused deformations and decreased heat conduction.

3. Rational triangular, three hinged, spatial roof arch and three span plate structural elements with increased specific strength and experimental method of result validation of ribbed elements.

Scientific Novelty

The new design method for analysis of rational lay-up, moisture conditioning regime, thermal treatment time and temperature of non-symmetrical plywood sheets is created. Experimental validations of proposed method are done.

The design methods for ribbed plywood plate structural elements with increased specific strength, decreased moisture caused deformations, decreased heat conduction are proposed for the first time. A variable stiffness, increased specific strength plywood plate with variable angle of outer layers orientation and its optimization method are proposed.

Experimental model testing of the wood composite element in bending is done and possibilities to use created analysis method by obtaining of rational ribbed structure of three span plates with two moving loads are shown.

The experimental validation of behavior of building roof's composite structural element model is done. Possibilities to use the proposed design method in analysis of rational plywood ribbed structure in spatial, triangular arch industrial structural element of building roof are shown.

Application of the Work

Possibilities of effective usage of such renewable resources as plywood and other structural materials in the plate composite structures are shown.

Possibilities to use renewable natural resource wood product- plywood and other material effective usage in plate composite structures are shown. This method allows to harmonize material strength field with stress resultant fields.

It is possible to design structural elements with increased specific strength, reduced moisture caused deformations and reduced thermal conductivity by the proposed methods.

The proposed plywood structural element is characterized by the increased spatial stiffness in comparison with traditional structural elements. The specific lay-up of plywood ribs provides the decrease of deformations, which are caused by moisture, in transversal direction of the structural plate element.

Research Limitations

The proposed variable stiffness plates are rational for specific load cases and boundary conditions. The proposed analysis methods are valid in cases when maximal stress and deformations do not exceed the design values.

The numerical and physical experiments are carried out by the static loads. Single veneer is assumed to be orthotropic material in macro-scale level. The moisture diffusion is analyzed in transversal direction of plate. The certain distance between the ribs is used to avoid of local buckling.

Research Methodology

The simulations of unsymmetrical sheets by using of commercial finite element software ANSYS and specially written software in MATLAB environment are done. The methods of classical composite material mechanics are used in created software. The moisture diffusion of bound water in plywood elements is modeled by Fick`s law in form of partial differential equation that is solved by finite difference method.

Special MATLAB software, which is based on the proposed method of plate structural elements with discrete variable stiffness analysis, was written. This method is used to obtain optimal bending and shear stiffness distributions by minimizing of structural compliance function and stress field differences by the using of gradient based search algorithm.

The influence of structures geometrical parameters on plate’s load bearing capacity is obtained by using a specially written parametric program in ANSYS. The program for analysis of rationally ribbed structure is written in MATLAB by using of Genetic Algorithm and Artificial Neural Network toolbox with additionally written procedures that connects MATLAB software with ANSYS finite element program.

The proposed optimization method of the variable stiffness plywood with variable wood fiber orientation angle in outer layers was implemented in MATLAB finite element and structural topology optimization codes.

The most important numerical results were verified by small scale structural models. The experiments of unsymmetrical plywood sheets that are subjected to moisture- temperature influence and bending test of ribbed plywood structural elements, with uniformly distributed load, were carried out.

Theoretical and Methodological Basis of Research

The following engineering sciences were used in the research:

- Mechanic of composite materials;
- Structural analysis;
- Wood science;
- Construction science;
- Heat and moisture diffusion mathematical modeling;
- Structural and structural topology optimization;

Content of the Work

The doctoral thesis consists of general characterization of the work, six chapters, conclusions and bibliography. The work consists of 165 pages, 142 figures and bibliography of 127 units.

The main results are published in following full publications:

a) In scientific journals:

1. Sliseris J., Rocens K. Curvature Analysis for Composite with Orthogonal, Asymmetrical Multi-Layer Structure // Journal of Civil Engineering and Management. -2010. -Vol. 16. -No. 2. -pp 242-248. (*Journal cited and indexed in databases*: SCOPUS, EBSCO)
2. Šliseris J., Rocēns K. Optimization of multispan ribbed plywood plate macro-structure for multiple load cases // Journal of Civil Engineering and Management. -2012. Accepted to publish. (*Journal cited and indexed in databases*: SCOPUS, EBSCO)

3. Sliseris J., Rocens K. Optimal design of composite plate with discrete varying stiffness // Composite Structures. 2013, -Vol. 98. -pp 15-23. (*Journal cited and indexed in databases*: SCOPUS)
4. Šliseris J., Rocens K. Rational Structure of Panel with Curved Plywood Ribs // World Academy of Science, Engineering and Technology, special journal Issue. – 2011. –Nr. 0076. –pp 317-323. (*Journal cited and indexed in databases*: SCOPUS, EBSCO).

b) In RTU scientific journal:

5. Sliseris J., Rocens K. Curvature analysis for asymetical multi-layer composite // Construction Science. -Riga: RTU, 2009. -Nr. 10(2). -pp 139-146. (*Journal cited and indexed in databases*: EBSCO, CSA/ProQuest, VINITI).
6. Šliseris J., Rocēns K. Non-Uniform Distribution of Moisture Influence on Shape of Plywood Sheet // Construction Science. -Riga: RTU, 2010. – Nr. 11. -pp 56-65. (*Journal cited and indexed in databases*: EBSCO, CSA/ProQuest, VINITI).
7. Sliseris J., Rocens K. Experimental and numerical investigation of plywood panel with curved ribs// Construction Science. -Riga: RTU, 2012. Accepted to publish. (*Journal cited and indexed in databases*: EBSCO, CSA/ProQuest, VINITI).

c) In full paper conference proceedings:

8. Šliseris J., Rocēns K. Non-uniform moisture influence on multilayer corrugated plywood shell// 9th Nordic Symposium on Building Physics. Tampere, Finland, May 29- June 2, 2011. –Vol. 2. -pp 723-730.
9. Sliseris J., Rocens K. Behaviour of multilayer sheet with technogical imperfection // 10th International conference "Modern Building Materials, Structures and Techniques". -Vilnius: VGTU, 2010. -pp 793-798.
10. Šliseris J., Rocēns K. Influence of technological and structure properties on shape of asymmetric plywood sheet // International Scientific Conference "Civil engineering `11". Jelgava: LLU, May 12-13, 2011. –Vol. 3. -pp 131-136. (*Conferene proceeding is cited and indexed in databases*: SCOPUS, EBSCO).
11. Sliseris J., Rocens K. Flexural Plates With Heterogeneous In-Plane Stiffness // 15th European Conference On Composite Materials. Venice, Italy, 24-28 June 2012. -pp 1-7.

d) **Other publications:**

12. Šliseris J., Rocēns K. The Future Of Plywood Production. Furniture Design And Manufacturing Asia, Solid Wood & Panel Technology, November/December 2011, pp. 28-31
13. Šliseris J., Rocēns K. Koksnes materiālu un plastmasu spriegumu un deformāciju aprēķina pamati (Mācību metodiskie norādījumi). RTU, 2010, 74 lpp. ISBN 978-9934-10-088-8.

e) **Submitted publications in scientific journals:**

14. Sliseris J., Rocens K. Discrete flexural stiffness optimization of orthotropic plate. *Structural and Multidisciplinary Optimization* (2012).
15. Sliseris J., Rocens K. Optimization of wood fiber orientation angle in outer layers of variable stiffness plywood plate. *International Journal of Civil and Structural Engineering* (2012).

The results of the Doctoral Thesis are reported and discussed in following international and local scientific conferences:

1. Šliseris J., Rocēns K. Experimental and numerical investigation of plywood panel with curved ribs// Riga Technical University 53rd International Scientific Conference, Riga, Latvia, 11-12 October, 2012.
2. Šliseris J., Rocēns K. Plates And Shells With Discrete Varying Optimal Stiffness. Mechanics of Nano, Micro and Macro Composite Structures, Politecnico di Torino, 18-20 June 2012.
3. Šliseris J., Rocēns K. Flexural Plates With Heterogeneous In-Plane Stiffness. 15th European Conference On Composite Materials, Venice, Italy, 24-28 June 2012.
4. Šliseris J., Rocēns K. Residual Stress In Moisture Sensitive Lamina. 17th International Conference- Mechanics Of Composite Materials, May 28-June 1, 2012, Riga, Latvia.
5. Šliseris J., Rocēns K. Rational topology of plywood composite macro-structure. OAS 2011, August 25-27, 2011 Tartu, Estonia
6. Šliseris J., Goremikins V., Rocēns K. Some rational structures and macrostructures of composites. Aleksandrs Malmeisters memorial symposium „Actual problems in the mechanics of heterogenous materials", October 20-23, 2011, Riga, Latvia.
7. Šliseris J., Rocēns K. Rational stuctures of wood composite. RTU 52nd International scientifice conference. 13 October, 2011, Riga.
8. Šliseris J., Rocēns K. Topology optimization of plywood composite. RTU 52nd International scientifice conference. 13 October, 2011, Riga.

9. Šliseris J., Rocēns K. Racionālas koksnes kompozītmateriāla makro-struktūras. Apvienotais Pasaules latviešu zinātnieku III kongress un Letonikas IV kongress „Zinātne, sabiedrība un nacionālā identitāte" Rīgā, 2011. gada 24.-27. Oktobrī.
10. Šliseris J., Rocēns K. Non-uniform moisture influence on multilayer corrugated plywood shell. 9th Nordic Symposium on Building Physics. Tampere, Finland, May 29- June 2, 2011.
11. Šliseris J., Rocēns K. Influence Of Technological And Structure Properties On Shape Of Asymmetric Plywood Sheet. International Scientific Conference "Civil engineering `11", Jelgava, Latvia, May 12-13, 2011.
12. Šliseris J., Rocēns K. Rational Structure of Panel with Curved Plywood Ribs. ICBSE 2011 : "International Conference on Building Science and Engineering" Venice, Italy, April 27-29, 2011.
13. Šliseris J., Rocēns K. Mainīga mitruma ietekme uz koksnes plātņu formu. RTU 51. Starptautiskā zinātniskā konference. Rīga, Latvija, 2010.gada 11.-15.oktobris.
14. Šliseris J., Rocēns K. Lokālu mitruma izmaiņu ietekme uz spriegumstāvokli izliektā koksnes plātnē. RTU 51. Starptautiskā zinātniskā konference. Rīga, Latvija, 2010.gada 11.-15.oktobris.
15. Šliseris J., Rocēns K. Curvature analysis for composite with orthogonal, asymmetrical multi-layer structure. International conference "Stability and Ductility of Structures". Septemper 24-26, 2009, Vilnius Gediminas Technical University.
16. Šliseris J., Rocēns K. Curvature analysis for asymmetrical multi – layer composite. Rīgas Tehniskās universitātes 50. starptautiskā zinātniskā konference, Rīga, 2009.gada 14.-16. oktobrī.
17. Šliseris J., Rocēns K. Lokālu mitruma izmaiņu ietekme uz spriegumstāvokli izliektā koksnes plātnē. 51. RTU Studentu zinātniskā un tehniskā konference, 2010, 11.-15. oktobris, Rīga.
18. Šliseris J., Rocēns K. Līmētu izliektu lokšņu formas prognozēšanas modelis. 50. RTU Studentu zinātniskā un tehniskā konference. 2009, 6.maijs, Rīga.

The originality of work is approved by the patent of Republic of Latvia B32B3/12, Nr. P-12-52: Rocēns K., Šliseris J., Vērdiņš G. „Slāņains kompozīts ar šūnu tipa dobām ribām uz koksnes materiālu bāzes".

The actuality of the work is indicated by high authors Hirsh index 3.0.

CONTENT OF THE DOCTORAL THESIS

The work consists of six chapters, introduction, conclusions and references. The literature review, aim and tasks are described in the first chapter. The moisture and temperature caused deformations of unsymmetrical lay-up plywood sheets and rational main technological properties are analyzed experimentally and numerically in the second chapter. The third chapter is devoted to describe the created optimization method of ribbed plywood composite plate with vertical-flat ribs and to describe optimization of three span plates by the proposed method. The optimization methods of variable stiffness ribbed plates, of wood fiber orientation angle of outer layers, and optimization results of typical cases are described in fourth chapter. The analysis method and some samples of rational geometry of ribs are described in fifth chapter. The sixth chapter is used to show optimization results of typical structures, used in structural and machinery applications, and described experimental validation of the main results.

FIRST CHAPTER

The plywood sheets provide a rational usage of wood because small amount of sawdust remains in veneer cutting process. The deviation of mechanical properties of the plywood is smaller comparing to natural wood.

The plywood sheets with symmetrical lay-up are usually manufactured with *[0°/90°/…/90°/0°]* lay-up. The unsymmetrical sheets are obtained by using unsymmetrical orientation angles, thickness of veneers, mechanical properties or moisture content with respect to middle surface of the sheet.

The deformation numerical analysis of the plywood sheets with unsymmetrical lay-up is more complicated comparing to symmetrical ones. For example, if the sheet with unsymmetrical lay-up is subjected to axial tension, than torsional deformation or negative Poisson ratio could appear. The plywood sheets with unsymmetrical lay-up give us a possibility to manufacture curved shells by using standard hot or cold press with flat pressing surfaces. The shells with negative Gaussian curvature of cylindrical shells could be used in load bearing structures or in furniture manufacturing.

Thin plywood sheets (ratio of thickness length of shorter edge is 1/20 or smaller) could be numerically analyzed by using of classical multilayer plate theory which is based on Kirchhoff's hypothesis.

The moisture and temperature caused deformations and displacements of unsymmetrical plywood sheets could be large, therefore finite deformation theory (geometrical nonlinearity) should be used for accurate simulation. There are two kinds of geometrical nonlinearities. The first kind of nonlinearity arises from large strains. The second kind of geometrical nonlinearity arises from large translation or rotation displacements. The both kinds of nonlinearities are usually necessary to take into account when simulating manufacturing process of unsymmetrical plywood sheets.

Stress-strain state of the ribbed plywood plate could be calculated by homogenization method of ribs in middle layer. It means that ribs are replaced by equal stiffness orthotropic layer and plate is analyzed by using multilayer plate theory. The same theories as in sandwich structures that take into account shear deformations in middle layer could be used. Results of higher precision could be achieved if the ribbed structure is fully modeled by using of shell elements.

When solving technological problems about manufacturing of the plywood shells with unsymmetrical lay-up, it is necessary to take into account the bound water diffusion that could be mathematically described by using Fick`s law and temperature conduction that could be mathematically described by Fourier law. The material nonlinearity of wood should be taken into account, when stress level exceeds linear material behavior limits.

The non-uniform stress resultant fields usually appear in structures that are working in bending. Therefore it is necessary to concentrate more material in places where is bigger stress resultants and less in other places. This approach allows us to tailor material properties for specific purpose and harmonize the material resistance and stiffness fields with the stress resultant fields. Isotropic materials could be successfully optimized by using classical structural topology approach. However, a special optimization technique is necessary for optimization of the wood composite materials.

SECOND CHAPTER

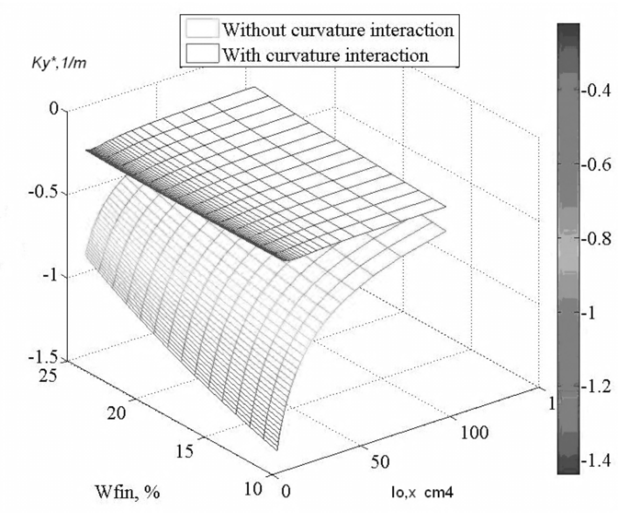
Ribs with curved shape have better spatial strength and stiffness comparing to flat ribs. The plywood shell manufacturing technology could be simplified by using of unsymmetrical lay-up sheets, which are curved by changing bound water moisture content.

The numerical model for deformation analysis that takes into account curvature interaction effect- geometrical nonlinearity and elastic properties dependence on moisture and temperature is proposed in this chapter. The optimal veneer lay-up for specific purpose and temperature condition regime is proposed. As well as, experimental testing results are provided.

It is necessary to take into account geometrical nonlinearity because when the sheet obtains curved shape than its stiffness increase and further curving process in orthogonal direction becomes more difficult. The material nonlinearity is necessary to take into account because wood elastic properties significantly depend on moisture content and temperature. The stress level and time also influence elastic properties. However in this model these nonlinearities are not taken into account.

The algorithm of proposed analysis method is based on one loop that is N times repeated. The loop divides total moisture increment or decrement in N steps. The elastic properties are recalculated in the each step. The deformation analysis is performed in the each step by using of updated elastic properties. Main deformations- curvatures k_x and k_y are modified in each step by multiplying their values with ratio of second moment of area of non-curved and curved structure. The modified deformation vector is added to total deformation vector.

The calculated curvatures could be few times smaller, if the geometrical nonlinearity is taken into account (see. 1. fig.).



1. fig. The main curvature k_y dependence on final moisture content W_{fin} and the second moment of area $I_{0,v}$ of initially flat sheet when moisture content change is 4%.

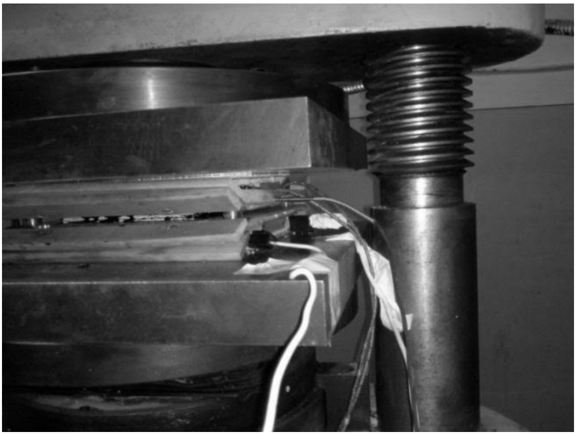
The experimental results showed that stress relaxation and creep effects in orthogonal direction of wood fibers should be taken into account. The proposed numerical model was improved by taking into account stress relaxation and creep effects using theory of standard linear solid body. The assumption of strain linear distribution through the thickness of sheet was used. Two more equations are necessary for complete mathematical formulation. Stress resultant static equilibrium equations were used.

It is important to analyze the manufacturing technological process of cylindrical shells that could be used in ribbed structure.

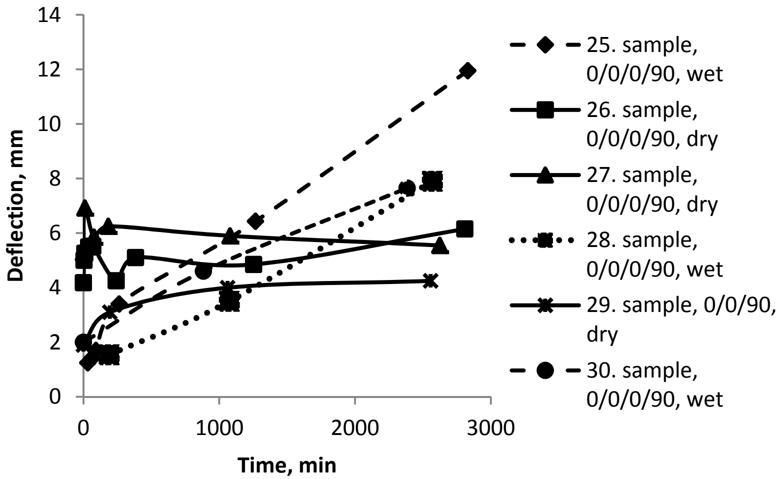
The maximal curvature of cylindrical shell could be obtained by the using of orthogonal, unsymmetrical lay-up *[0°/90°]*. It is necessary to increase thickness of layers that are oriented in longitudinal direction of cylindrical shell to avoid of second curvature. The numerical simulations show that thicknesses of longitudinal layers should be five times bigger than thickness of shear layers. Maximal curvature could be obtained for minimal moisture content change by using this thickness ratio.

The experimental specimens with unsymmetrical structure that consists of birch veneers and phenol-formaldehyde glue were manufactured. The deformations and moisture content change were measured during the experiment. The specimens were manufactured by using press with hot shelves (see 2. fig.) and also press with cold shelves.

The deformations were calculated numerically by using of finite element method. The results show that maximal difference between calculated and measured deformations is below 10% in case if deformations are not large (maximal deflection smaller than 1/25 from length of edge). When the sheet has bigger deformations, than stress level increase and material nonlinearity plays a significant role that is not taken into account, therefore difference between results is up to 30%. The maximal curvature could be increased if veneers before curing is moistened (“wet” samples) and maximal moisture content do not exceed 23% (it might change according to properties of used glue). Otherwise, problems with glue might appear. The deflection plot of different specimens is shown in 3.fig.

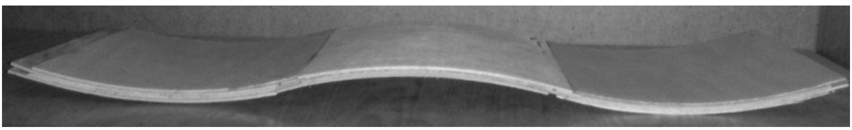


2. fig. The experimental manufacturing setup for pressing and gluing in high temperature.



3.fig. The plot of deflection depending on time for various specimens.

The numerical simulations show that optimal time of temperature conditioning is 24 hours. Special attention should be paid to shape stability of the plywood sheet with unsymmetrical structure. We proposed to make thermal treatment at 140...150 ^{o}C. The thermal treatment reduces moisture diffusion speed and moisture caused deformations of wood. Experimental testing results show that optimal thermal treatment time is between 2.5 to 3 hours. The deformation sensitivity to moisture content change could be reduced up to 45% if thermal treatment time is 2.7 hours and average temperature 145 ^{o}C. The moisture diffusion coefficient in transversal direction is also reduced about 45%.



4.fig. The experimentally manufactured specimen with weaved shape.

Experimentally were manufactured also shell with curved shape (see 4.fig.). This kind of sheets could be successfully used in ribbed plate.

The moisture diffusion coefficient in transversal direction of sheet was necessary to obtain experimentally. An inverse, iterative method was proposed. The method uses experimental and numerical simulation results, and minimizes the difference between them by changing diffusion coefficient, which is used in the simulation. The moisture content in *N* points m_i through the thickness of the sheet was calculated during the simulation. After that there is minimized the difference between calculated moisture content and experimentally obtained average moisture content $m_{i,eksp}$:

$$\min_D \sum_{i=1}^{N}\left(m_i(D) - m_{i,\text{eksp}}\right)^2 \rightarrow min. \quad (1)$$

THIRD CHAPTER

Multispan plates, which are subjected to many load combinations, are widely used in machinery. For example, heavy truck trailer floor (see 5. fig.) which is subjected to two loads, arising from moving forklift machines front wheels. The standard 30 mm thick plywood sheet is usually used in this structure. In certain places with maximal stress appear damages. Therefore, it is necessary to create plywood composite with increase specific strength.

The rational cross section of the plywood composite plate is defined by four parameters $x = \{t_1, t_2, t_3, n\}$, where *n*-total number of ribs and meaning of other parameters is shown in 6. fig. A special optimization algorithm to optimize this plywood composite plate is created. The algorithm consists of 7 main steps:

1. The main structure's properties- length L_1, width L_2, distance between steel supports- b_1, a_1, a_2, maximal thickness *t*, loading area properties: L_4, L_5, and load *Q* on each area *are collected*.
2. The decision of which direction it is necessary to orient plywood ribs according to location of supports is made.
3. The location (X_c, Y_c) of loading area that is the most dangerous (produce maximal stress and deflection) is obtained.
4. The geometrical parameters $x=\{t_1, t_2, t_3, n\}$ of plywood composite macro-structure by using structures total weight as an objective function are optimized.
5. The previous steps are repeated for various main geometrical properties.
6. The optimal Artificial Neural Network (ANN) architecture are chosen. The ANN training by using results from previous procedures is done.

7. ANN testing and applying to practical problems.

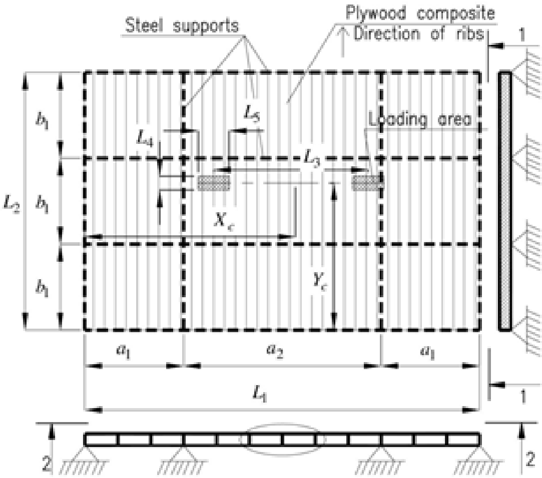
Genetic Algorithm, which is used in the created algorithm, is based on the principles of natural genetics and natural selection (Darwin's theory of survival of the fittest). The basic operators of natural genetics are used- Reproduction, Crossover and Mutation.

A three layer feed forward Artificial Neural Network is suitable for the proposed algorithm. An optimal number of neurons for the plywood composite optimization problem are 20, which were experimentally obtained. The most suitable training algorithm is Levenberg-Marquardt training algorithm. The optimization results show that optimal number of training epochs is 7.

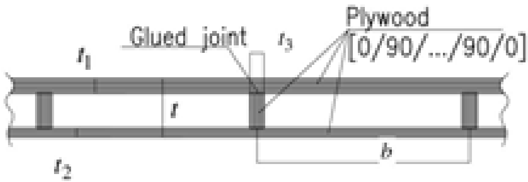
There were used following optimization constraints: stress in compressed flange, stress in tensioned flange, shear stress in plywood ribs, shear stress in glued joints, local bending of top plywood flange.

The maximal values of relative displacements and stress in the plywood plate are shown in 7.fig., 8.fig. depending on location of loads. The most dangerous location of loads, which cause maximal displacements and stress, could be identified by using these plots.

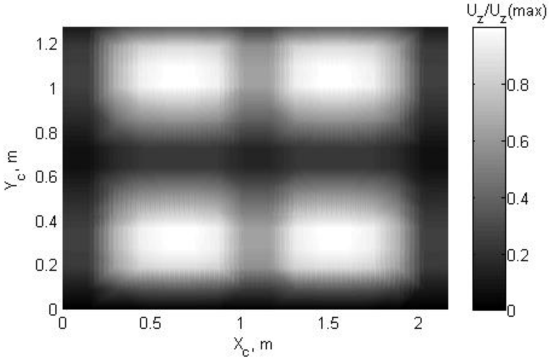
The rational cross section geometrical properties are obtained by proposed method for plates with length varying from 1.5 m to 3 m, width from 0.75 m to 1.5 m and thickness for 30 mm to 60 mm. Four different concentrated loads- 2, 2.5, 3 and 3.5 tons on each loading area were used.



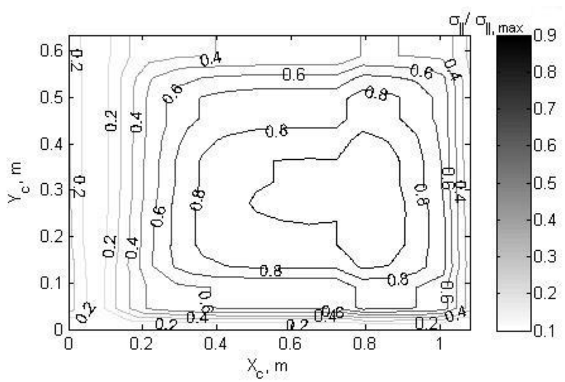
5. fig. A typical scheme of heavy truck trailer floor plate.



6. fig. The geometrical parameters of cross section of plywood composite plate.



7.fig. The plot of relative-maximal deflection depending on center coordinates (X_c, Y_c) of loading area.



8.fig. The maximal stress in direction of wood fiber depending on coordinates of loading area center.

FOURTH CHAPTER

The non-uniform stress and stress resultant fields appear in flexural plate structural elements. This is the main reason to design a variable stiffness and strength plates by tailor material properties of plate for specific purposes.

The variable stiffness of plate is obtained by making a different bending and shear stiffness in each point of plate.

Special methods for optimization of bending and shear stiffness of ribbed composite plate and outer layer wood fiber optimization of plywood lamina are proposed in this chapter. A special method that discretize obtained bending and shear stiffness are proposed as well. Discrete variable stiffness plates are easier to manufacture than plates with continuous variable stiffness. The optimal stiffness distribution for single span and multispan plates, which are subjected to uniformly distributed and concentrated loads, are obtained.

The optimal stiffness distribution of orthotropic plate is defined by five independent functions $x = (x^1, x^2, x^3, x^4, x^5)$ in each finite element. These functions are used to calculate the bending and shear stiffness coefficients of plate. The first order shear deformation theory is used in analysis.

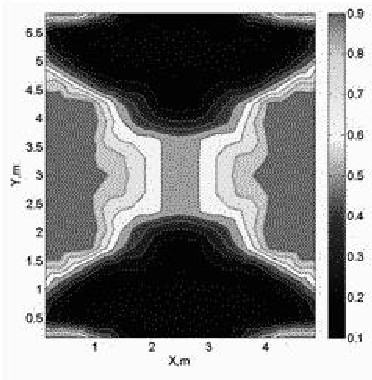
The objective function consists of two parts. The first part is used to minimize normalized structural compliance function. The second part is used to minimize normalized stress field differences that are very important in case of ribbed structures. The minimization of the compliance function provides a structure with maximal stiffness. The stress concentrations in ribbed structure could be significantly reduced by minimizing the stress field differences and making more uniform stress distribution. The optimization problem is solved by gradient based method.

Technically, it is very difficult to manufacture a constant thickness ribbed plywood plate with continuously variable stiffness. Therefore, the special method, which discretizes the continuously variable stiffness into discrete domains, is created. The stiffness distribution functions in each discrete domain have constant values.

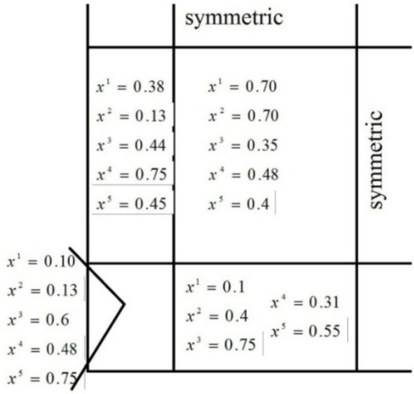
The stiffness discretization method is based on solution of another minimization problem where is minimized the differences between continuously variable stiffness functions and discrete variable stiffness functions in each discrete domain. As a result of optimization, the optimal size of discrete domain and the values of stiffness functions in each discrete domain are obtained. The number of discrete domains user has to specify before optimization. Specific constraints, for example, technological restrictions on the size of the discrete domains could be specified.

The optimization problem with constraints is solved by using Genetic Algorithm. Therefore, it is transformed to optimization problem without constraints by using concept of penalty functions.

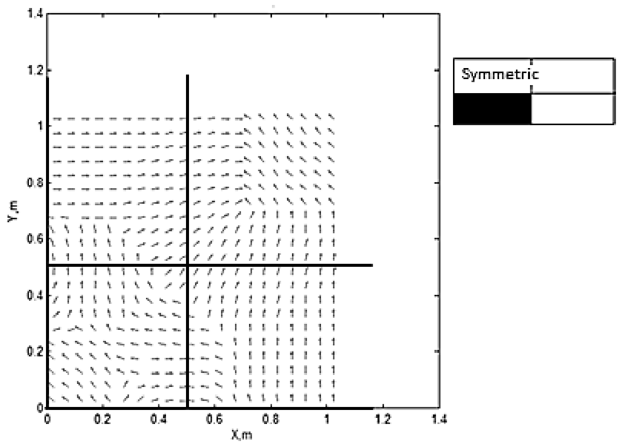
As an example, the plot of optimal shear stiffness function in direction of x axis (horizontal axis) is shown in 9. fig. for simply supported on all edges, single span plate, which is subjected to uniformly distributed load. The appropriate results of stiffness discretization are shown in 10.fig. Due to symmetry, there is shown only one quarter of plate. Dark lines indicate borders of the discrete domains. The value of structural compliance function was reduced by 35% and stress field differences by 10% for this specific problem.



9. fig. The plot of optimal shear stiffness function x^4 (it is used to calculate shear stiffness coefficient D_{44}).



10.fig. The bending and shear stiffness functions of plate with discrete variable stiffness (due to symmetry only quarter of plate are shown).



11. fig. The optimal wood fiber orientation in outer layers of the three span plate (spans in both directions are 0.5(m), 1.1(m) un 0.5 (m)) plate (due to symmetry only quarter of plate is shown and dark lines indicate supports).

In some cases, it is rationally to optimize wood fiber orientation angle of outer layers, which have significant influence on stiffness and strength. The special optimization method, which is based on minimization of structural compliance by searching for optimal outer layer wood fiber orientation angle in each finite element, is created.

The algorithm consists of three loops. The outer loop is running until convergence criteria (for example, structural compliance does not change significantly) are satisfied. All finite elements, from *1* to *Ne (total number of finite elements),* are analyzed in the middle loop. The discrete fiber orientation angles are tested inside the third loop. A special procedure $R(x)=x_j$ inside all loops are created, to change fiber orientation angle in domain with center in *j-th* finite element and radius R_{inf}. The finite element analysis is performed inside all loops. According to obtained results, there are calculated structural compliance matrix *C(i,j)* (indexes indicate *i-th* finite element and *j-th* discrete value of fiber orientation angle). A standard, four node finite elements, which is based on Kirchhoff- Love linear theory, is used in the simulation. Each plywood layer is assumed to be linear orthotropic material.

Some typical plates where optimized by the proposed method. The optimal outer layer wood fiber orientation angles of three span plates, which are made of 19 layer birch plywood sheet, are shown in 11. fig. The numerical results show that, if we optimize only one outer layer, than maximal deflection could be reduced for 14%, but if two outer layers then for 20%. If we optimize more than two outer layers, than stiffness do not increase significantly.

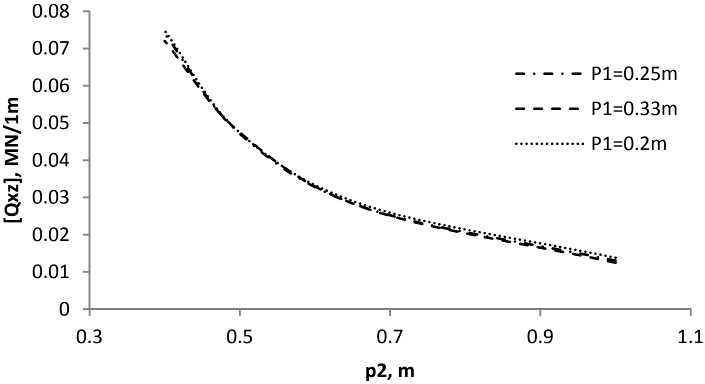
FIFTH CHAPTER

The geometrical dimensions (thickness, curvature and intensity of ribs and thickness of flanges) of ribbed structure should be calculated in each discrete domain, to practically apply the plywood composite plate. The ribbed structure should have specific load bearing capacity in each discrete domain. The maximal stress resultants, which could be safely carried by actual plate in each discrete domain, should be maximally similar to applied load produced maximal stress resultants in each discrete domain.

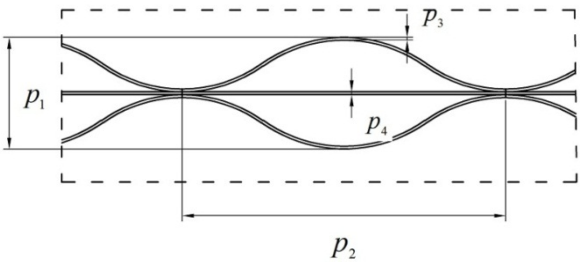
The rational geometrical properties of plate $p = p(p_1, p_2, \dots, p_n)$ (in this case we analyze structure that is shown in 13. fig.) are obtained by minimizing functional, which consists of difference between maximal stress resultants that could be safely carried by structure and actually acting stress resultants in each discrete domain. In each discrete domain, the optimization is separately done. We take into account significance coefficient for each stress resultant. This coefficient allows avoiding of structure with less load bearing capacity than necessary.

The sample plot of maximal shear force in direction of ribs, which could be safely carried by plate depending on width $p_1$and length p_2 of ribs, is shown in 12. fig. The orientation angle of wood fibers, intensity and geometry of ribs are obtained by solving separate optimization problem in each discrete domain. However, user should specify approximate interval, where to search for necessary parameters. If specified intervals of design variables are be too big, than might appear problems of non-convergent solution.

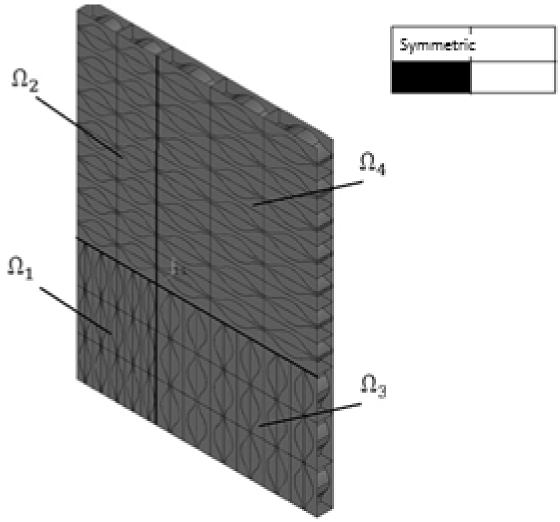
The optimal ribbed structure of rectangular, simply supported plate, which is subjected to uniformly distributed load, is shown in 14. fig.



12. fig. The maximal shear force Q_{xz}^{max} (orthogonally to longitudinal direction of ribs), which could be safely carried by plate depending on shape of ribs.



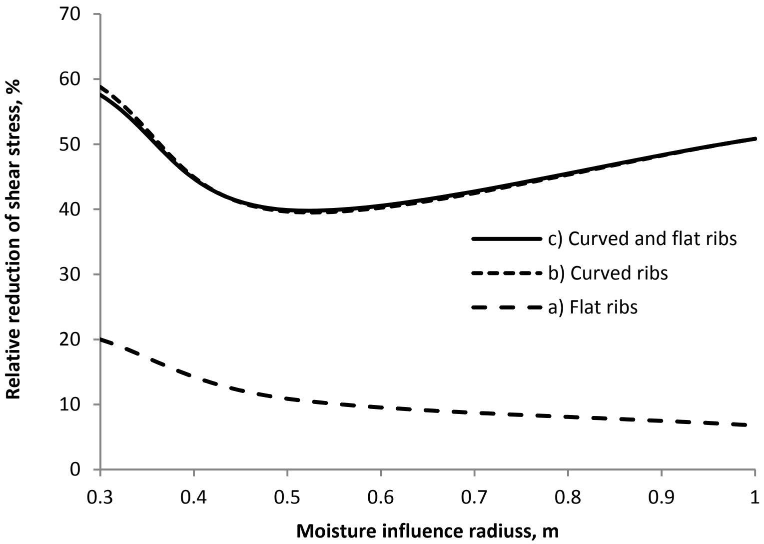
13. fig. The typical element of ribbed structure, which consists of curved and flat plywood ribs.



14. fig. The optimal structure of ribbed plate with discrete variable stiffness (due to symmetry quarter of plate are shown).

The numerical results show that it is possible to increase stiffness about 50% for simply supported plate with uniformly distributed load and discrete variable stiffness. The increase of stiffness could be about 60% for the same plate with continuously variable stiffness and ratio of edge length to width equal to 1.

The load bearing capacity of wood based structures could be significantly reduced by local moisture influence. A special numerical simulation of moisture caused stress was done for the proposed ribbed structure. The moisture change in local area was simulated. Technologically produced imperfections in structure could cause the moisture content change in local area of plate. Rectangular plate, which is constrained around all edges, was subjected to moisture change about 1 % in certain domain in the center of plate. The moisture caused stress were compared to plate with four different ribbed structures: flat vertical ribs, curved vertical ribs, curved and flat vertical ribs and curved horizontal ribs- corrugated core. The maximal stress appeared to the plate with corrugated plywood core. The maximal moisture caused shear stress could be reduced about 50%, if we use plate with vertical curved or/and flat ribs, comparing to the plate with corrugated plywood core (see 15. fig.).

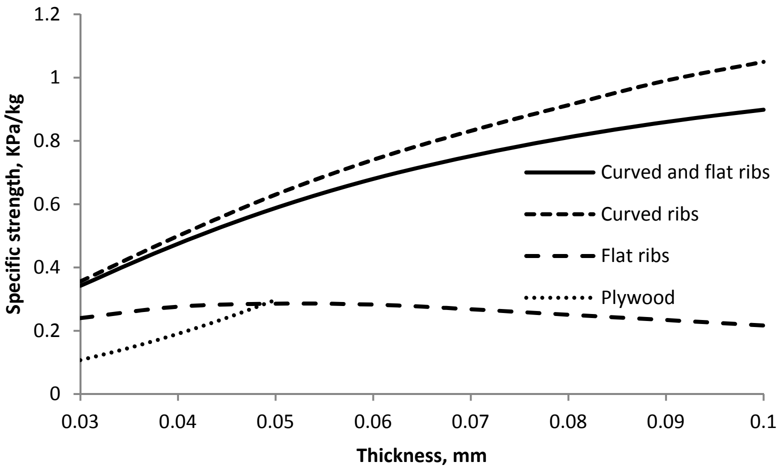


15. fig. The plot of moisture content change in local area caused reduction of shear stress of plate with flat, curved and curved and flat vertical ribs comparing plate with corrugated plywood core.

SIXTH CHAPTER

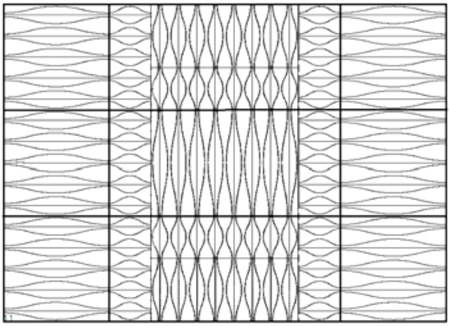
Plates with optimal discrete variable and constant stiffness are compared to standard plywood according to specific strength criteria. The proposed ribbed structure is applied to typical plates, which are used in heavy truck trailer floor plate and triangular three hinged roof structure.

The behavior of ribbed structure in longitudinal and shear directions is numerically analyzed. The plot of specific strength in shear direction of ribs, depending on plate's thickness, is shown in 16. fig.

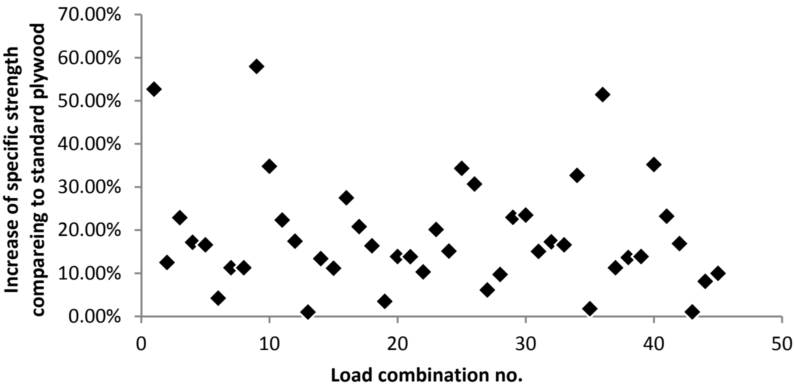


16. fig. The plot of specific strength depending on thickness of plate according to maximal deflection criteria $\frac{f}{L} = \frac{1}{200}$ for simply supported plate with uniformly distributed load and 1.1 m span.

The proposed optimization technique of ribbed structure was applied to optimize a three span plate that is used in heavy truck trailer floor structure. This plate is subjected to two moving loads. The optimal ribbed structure is shown in 17. fig. The load could move and therefore multiple load combinations should be analyzed. For simplicity there was analyzed only most dangerous locations of loads- placed in center of spans. For this case totally 45 load combinations were analyzed. The specific strength of ribbed plate is significantly bigger than standard birch plywood sheet. Plate with discrete variable stiffness and total thickness 40 mm shows average increase of specific strength about 20% (see 18. fig.) comparing to standard 21 ply birch plywood. The increase of plate with uniform ribbed structure the increase of specific strength is around only 8.5% comparing to standard 21 ply birch plywood.

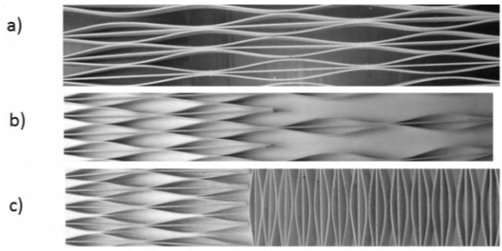


17. fig. Ribbed structure of plate with discrete variable stiffness (lines in bold indicate supports of plate).



18. fig. The increase of specific strength of optimally ribbed plate with 50mm thickness comparing to standard birch plywood.

The numerical results were verified by making physical experiments of single span plate with uniform and discrete variable ribbed structure (see 19. fig.). The maximal difference between experimental and numerical results of main displacement components in static bending test is less than 10%. Therefore, numerical models work with necessary accuracy.



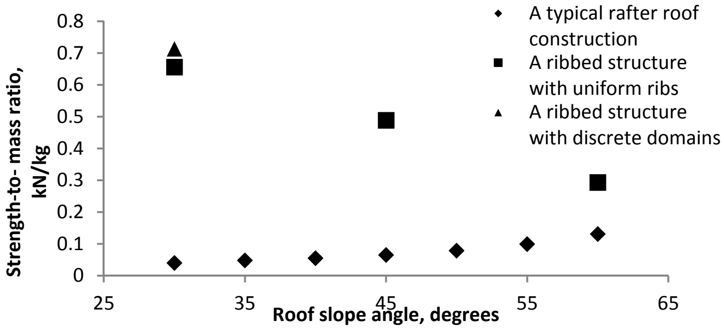
19. fig. Ribbed structures of three different specimens (a- uniformly ribbed structure, b,c- discrete variable ribbed structure).

Wood materials are widely used in building roof structures. The most common roof structure is triangular roof structure where the main load bearing element is triangular, three hinged arch. Traditionally this structure is made of glued or natural solid wood planks. The manufacturing process is not industrial. However, wood truss roof structures are industrial, but they usually decrease the living space. We applied the proposed ribbed plywood plate structure for this case. The manufacturing of ribbed plate structure could be fully automated. Installation process in building site is not complicated and less time consuming. The heat insulation could be made of foam type materials during manufacturing process.

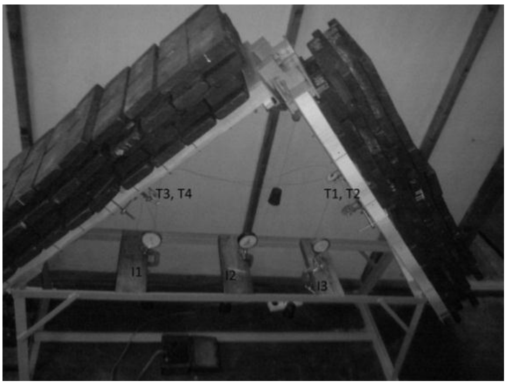
The application of proposed ribbed structure for roofs with spans form 5m to 10 m and roof slope angle for 30 to 60 degrees with roof overlap 2 m was numerically analyzed.

The specific strength could be increased about 12% if we use plate with 4 discrete domains instead of plate with uniform ribs (see 20. fig.). The optimally ribbed structure increase specific more than 2 times comparing to solid wood structure if span of structure is 8m and 60 degrees slope angle. However, when slope angle increase than efficiency of ribbed plywood structure comparing to solid wood structure significantly decrease.

The numerical results were experimentally verified by small scale model. The span of the experimental model was 1710 mm, slope angle 46.5 degrees, thickness 58 mm and width 300 mm (see 21. fig.). The main experimentally obtained results are in good agreement with numerical results. For example, the difference between experimentally measured strains and numerically obtained is less than 10%.



20. fig. The comparison of specific strength to various roof structures with 8m span, 250 mm total thickness and uniformly distributed load depending on roof slope angle.



21. fig. Experimental model of triangular roof structure.

CONCLUSIONS

The basic design and manufacturing principles and basic analysis methods of non-traditional increased specific strength wood composite structural elements with curved and flat structural ribs and specific wood fiber orientation angle of outer layers are created.

- Experimentally obtained results shows that moisture caused displacements of unsymmetrical plywood sheet could be reduced by 45% after thermal 2.5…3 hour treatment at 145 $^{\circ}$C temperature. The transversal diffusion coefficient reduces about 45% after thermal treatment. Numerical results shown that sheet with unsymmetrical orthogonal lay-up obtains maximal curvature when the ratio of thickness of longitudinal and shear layers are 4...5 and thermal conditioning time after gluing in hot press 100…110 $^{\circ}$C is around 24 hours.
- A special optimization method of cross section characteristics of multispan plywood ribbed plate is created. The usage of specially modified Genetic Algorithm which searches for most dangerous load combinations and feed forward Artificial Neural Network (ANN) provide a successful optimization of cross section characteristics of multispan plywood ribbed plate (correlation coefficient of ANN predicted cross section properties and optimal properties is more than 0.98). Optimal thickness of skins and ribs, intensity of ribs in ribbed plywood three span (ratio of spans in one direction is 1:2:1, but in other direction spans are equal) plate are obtained by proposed method for plates with thickness form 30mm to 60 mm.
- Stiffness could be increased about 50% and stress field differences decreased about 10% for rectangular simply supported plate with uniformly distributed load if we use a specially created optimization technique of variable stiffness ribbed plates. The stiffness could be increased about 20% for three span variable stiffness plywood plates with specially oriented wood fibers in outer layers that are subjected to uniformly distributed load, but in case of single span plate 13% increase of stiffness could be achieved by using proposed optimization method.
- The discrete variable ridded structure, which was optimized by minimizing theoretical load bearing capacity (maximal stress resultants that could be safely taken by structure) and necessary one, provide an increase of specific strength for 50%. However, the analysis of stress concentration effects of plates with thickness 100, 150 and 250 mm, thickness of standard plywood sheets form 6 mm to 20 mm, width of ribbed element from 200mm to 333 mm

and length of ribbed cell from 400 mm to 1000 mm shows that actual increase of specific strength is up to 27% comparing to non-optimized ribbed structure. The local moisture influence caused direct stress could be reduced about 15% and shear stress about 50% comparing to plate with corrugate plywood core.

- The increase of specific strength of discrete variable stiffness three span plates with two moving loads is up to 20% for plate with 40 mm thickness. The increase of specific strength of plate with uniform ribbed structure and thickness 40 mm is only 8.5% increase comparing to standard birch plywood. The main numerical results were experimentally verified by small scale structural model bending test (difference between calculated deformations and measured do not exceed 15%).
- The specific strength of triangular three hinged roof structure could be increased about 12% by using plate with 4 discrete domains instead of plate with uniform ribbed structure. The increase specific strength of optimally ribbed structure is a few times (in case of 60 degrees slope angle and 8 m span the increase of specific strength is 2 times) comparing to solid wood structure. The numerical simulation results is experimentally verified by small scale model testing and maximal difference between numerical and main experimentally measured strains and displacements do not exceed 15%.

DOCTORAL THESIS NOMINATED TO OBTAIN DOCTORAL DEGREE OF ENGINEERING SCIENCES IN RIGA TECHNICAL UNIVERSITY

Defence of the doctoral thesis will take place in the assembly hall of RTU Civil Engineering Faculty, Azenes street 16, Riga at 2.15 p.m. April 12, 2013.

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CONFIRMATION

I confirm that I worked out this doctoral thesis, which is submitted for consideration of obtaining of doctoral degree of engineering sciences in Riga Technical University. The doctoral thesis is not submitted in any other university for obtaining of doctoral degree.

Jānis Šliseris …………………………….(Signature)

Date: ………………………

The doctoral thesis is written in Latvian and consists of general description, six chapters, conclusions and references. The volume of the work is 165 p., 142 figures and 127 references.