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Determining the Characteristics of Composite Structure Laminae by Optical 3D Measurement of Deformation with Numerical Analysis

Određivanje svojstava kompozitnih uslojenih konstrukcija optičkim 3D mjerenjem deformacija uz primjenu numeričkih analiza

Original scientific paper • Izvorni znanstveni rad
Received – prispjelo: 31. 1. 2011.
Accepted – prihvaćeno: 14. 7. 2011.
*UDK: 630*832.286; 630*836*
doi:10.5552/drind.2011.1103

ABSTRACT • *Experimental determination of the elastic constants of orthotropic composite materials and their bearing capacity (strength) for furniture intended for sitting, and numerical verification of the experiment results by analysing with the final elements, was performed on the basis of the theory of elasticity of orthotropic and anisotropic composite materials. The requisite and sufficient material constants were determined in the experiments: moduli of elasticity and Poisson's coefficients (longitudinal and tangential) and skate modulus for plain stress. These constants, calculated by 3D measurements of deformation, are sufficient for determining the constitutive matrix of the lamina, and for reducing stiffness of the composite irrespective of the thickness of the layers, fibre orientation and choice of material. Experiments were conducted for the stiffness, shear and flexing of uniformly and complexly layered beech veneer sheets, while for new materials experiments for stiffness and shear in a uniform orientation were sufficient.*

Analysis of stiffness and deformations were conducted layer by layer, as well as by reduced volume stiffness for multi-layered orthotropic shells of chair systems by a method of final elements by application of a composite final element, where combined reduced membrane matrices and flexing matrices are used. Numerical verification of the experiments, including systems of furniture intended for sitting – chairs – was conducted using the KOMIPS software system, which contains in its library a composite final element of the sheet. Experiments with chairs were performed with the aim of determining the stiffness of such systems, and they were confirmed by analytical results and measurement of the real movements on selected models. The results of research provide the design, re-design, construction and determination of the dimensions of not just chairs, but also of any other girder or surface system based on laminates.

Keywords: *optical 3D measurement, chair, shell, composite, material constants, stress, beech wood, finite elements*

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SAŽETAK • *Na temelju teorije elastičnosti ortotropnih i anizotropnih kompozitnih materijala eksperimentalno su određene elastične konstante i nosivost (čvrstoća) ortotropnih kompozitnih materijala za namještaj za sjedenje te je provedena numerička potvrda eksperimentalnih rezultata analizom uz primjenu konačnih elemenata. U radu su određene ove konstante materijala: modul elastičnosti i Poissonov koeficijent (uzdužni i tangencijalni) te klizni modul za naprezanje u ravnini. Te konstante, izračunane na temelju 3D mjerenja deformacija, dovoljne su za određivanje konstitutivnih matrica uslojenog drva i za smanjenje krutosti kompozita, bez obzira na debljinu slojeva, orijentaciju vlakanaca i odabrani materijal. Na uzorcima od uslojenih podjednakih bukovih furnira provedena su eksperimentalna mjerenja krutosti, čvrstoće smicanja i savijanja, iako su za nove materijale dovoljna samo ispitivanja krutosti i smicajne čvrstoće u istom smjeru.*
Analiza krutosti i deformacija napravljena je sloj po sloj, kao i za smanjenu volumnu krutost višeslojnih ortotropnih ploča za stolce, metodom konačnih elemenata, uz primjenu kompozitnoga konačnog elementa, pri čemu se primijenjuje kombinacija reduciranih membranskih matrica i matrica savijanja. Numerička potvrda rezultata eksperimenta, uključujući sustav namještaja za sjedenje – stolce – provedena je primjenom softvera KOMIPS, koji u svojoj zbirci ima kompozitni konačni element za ploče. Eksperiment sa stolcima proveden je radi određivanja krutosti takvog sustava te je potvrđen analitičkim rezultatima i mjerenjima stvarnih pomaka na izabranim modelima. Rezultati istraživanja omogućuju dizajn, redizajn, konstruiranje i određivanje dimenzija ne samo stolaca nego i drugih nosača ili površina utemeljenih na uslojenom drvu.

Ključne riječi: *optičko 3D mjerenje, stolac, kompoziti, konstante materijala, naprezanje, bukovina, konačni elementi*

1 INTRODUCTION
1. UVOD

Research into the possibilities of rational exploitation of wood demands constant study of the properties of wood, wood products and new materials used as substitutes for wood in certain areas. Wood has excellent aesthetic and constructive properties, ensuring its superiority in many fields of application. However, wood does have some unfavourable properties limiting its use in certain fields of exploitation. For instance, wood has different (anisotropic) properties in different orientations and poor durability in conditions of variable moisture. These shortcomings of wood call for a permanent search for technological and engineering solutions that would provide a reduction of wood anisotropy and an increase in its durability. Development of composites based on wood made of veneer sheets creates a possibility of a considerable reduction in the natural anisotropy of wood. Further research of possibilities of expanding the use of veneer and the employment of certain advantages of veneer slabs have led to considerable use of veneer in the manufacture of furniture made of laminated wood. Laminated wood is a product made of several sheets of veneer glued together and i tused for diverse construction needs and shaped differently. Thin veneer sheets are pressed together for an exactly defined period of time, pressure and temperature. Finished in this way, laminates can be used for various constructions, in particular the manufacture of laminated constructive elements in furniture-making. The types of wood used, veneer thickness, manner of layering, regimes of pressing and processing are factors which considerably affect the mechanical properties of the laminate, therefore also laminated bearings as a product.

Veneer sheets are made of at least three layers (laminae) of veneer, with alternating sheets grain at right angles, and layered sheets are made of several sheets (laminae) of veneer, their fibres running in the same direction.

Construction of chairs can be viewed according to a number of criteria. Viewed by the type of manufacture, chairs can be made of pure wood, layered wood, or a combination of the two, or may be woven, metal or plastic. By the manufacturing technology, chairs are divided into prototypes, series-production units of mass production units. Chairs may be used for residential or public buildings. They can be used at work or for relaxation, when due to altered functional measures they become semi-armchairs, or full armchairs. Initially people sat on stools, chairs that had no back. When a backrest and armrests were added to anatomically properly designed chairs, the feeling of comfort was considerably enhanced. Irrespective of the material of which they are made, problems in the manufacture of chairs may be complex. Industrial production of veneers was first mentioned in 1885 as peeled veneer. In 1834 Frenchman Charles Pikot patented a veneer-cutting machine, but it was first used in 1860. The invention of a wood-peeling machine by Garant in 1944 enabled the rapid rise of manufacture of plywood, where peeled veneers are mainly used, as the so-called blind veneers, which when glued together form plywood. Like all new products, plywood initially did not sell well. The decisive role in increasing the use of plywood, as in the case of chipboards and fibreboards nowadays, was played by the technology of manufacturing furniture. The development of plywood particularly increased the value of beech wood, which had generally only been used as firewood. Owing to its sensitivity to drying and motivated by research in the U.S.A. for different industrial purposes, B. Hausmann made a significant contribution to the use of beech wood for blind veneers around 1910 by constructing an artificial drying facility with an endless fabric loop for the requirements of veneers.

1.1 Historical overview
1.1. Povijesni pregled

Industrial development at the end of the 19^{th} century, and particularly the start of the 20th, with new engineering solutions and the invention of the motorcar, led to chairs acquiring revolutionary new forms. A contribution to this was made by new materials and the enthusiasm of people who desired a maximum level of comfort in their cars, and chairs became a new challenge, wherever they were used. Particularly prominent were flexed solid-wood and veneer-sheet forms, as well as upholstered furniture. Veneer laminate plates were first made in 1850 as combinations of three or more veneer laminas, with the grain orientations alternating by 90^0 to make the plate harder. The manufacture was developed by German American John Brlter, who succeeded in bending the plates along all three axes, using heat. Others commercialised the process, while more serious experiments with the plates were performed by Michael Thonet in 1880. Although known more for his invention of making furniture by bending steamed wood, Thonet is mentioned by most of the 20th century Modernists as influencing them in respect of work with laminated plates. Production of the material, its flexibility and durability were perfected during the First World War by way of widespread use in the manufacturing industries. When the avant-garde architects and designers of the 1920s looked into the possibility of manufacturing cheap mass-produced furniture, veneer laminate plate seemed the ideal solution. The first breakthrough was made in 1918 by the famous Dutch designer, Gerrit Thomas Rietveld, who used a piece of the laminate as the seat in his famous Red and Blue chair (Figure 1).

The construction of the chair is clearly defined by standardised wood elements, which interfuse and overlap mutually. The three decades that followed were marked by numerous now classical designs in which this material was used.

World-famous Finnish Modernist architect Alvar Aalto was a leading force in the design of veneer-plate furniture. Thanks to his constructive genius and the opportunities for widespread use of the material, Aalto founded an experimental workshop in 1929. Together with his wife Aino, Alvar manufactured prototypes and conducted tests for four years, leading to the first-ever elastic chair with a back in 1930, the "Pamio" (Figure 2).

While Aalto was initiating his wood laminate experiments in Finland, Marcel Breuer, who had already lectured at the Bauhaus, travelled to London early in 1930 and was employed by *Isokon*, who specialised in veneer laminate furniture. Breuer designed one-piece shaped veneer laminate furniture as seen in Figure 3 around 1935.

Figure 2 Console chair with backrest, 1930
Slika 2. Konzolni stolac s naslonom, 1930.

New materials took over in the 1960s and 1970s, but veneer laminates made their comeback in 1988, when British designer Jasper Morisson formed his sleek veneer plate chair for the Berlin Exhibition which he left 'half-finished' with visible cut-outs of the plate, and which was later produced by *Vitra*. From the 1990s veneer sheets have again been a favourite of designers and manufacturers. In the past two decades veneer laminate furniture pieces have appeared and by their technological and design quality they represent the continuation of the foundation laid in the 1930s and lasting until the late 1950s in furniture veneer laminate furniture design.

Frank O. Gehery 'Cross Check' chair, designed by the architect in the period 1989-92, is perhaps the best known for its radical organic design. Gehery experimented for three years on laminate wooden structures with the famous firm *Knoll*.

In designing the chair, the objective was to make use of the structural characteristics and flexibility of the laminate ribbons so as to make from them every part of the chair. The ribbons are interwoven, reminiscent of wickerwork, only on a much larger scale. The chair is structurally stable, flexible and durable, visually very powerful and recognisable (Figure 4).

Finally, the seating furniture with which we are entering the 21st century is best promoted by the Azumi team, who designed in 2002 a bench for the Italian ma-

Figure 1 "Roodblauwe" chair, with backrest, 1918
Slika 1. Stolac *Roodblauwe* s naslonom, 1918.

Figure 3 'Organic armchair', 1935
Slika 3. Organski naslonjač, 1935.

Figure 4 'Gehery Cross Check' chair, 1992
Slika 4. Stolac *Gehery Cross Check*, 1992.

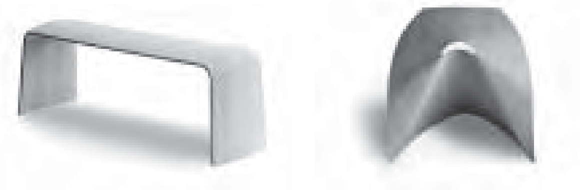

Figure 5 'Volta' bench and 'AP' backless chair, 2002
Slika 5. Klupa *Volta* i stolac *AP*, 2002.

nufacturer *La palma* made of a single piece of veneer laminate, bent along all three axes and 120 cm long with no extra supports, capable of seating two or three persons, as well as a backless chair (Figure 5). The two pieces shown represent a major design challenge in the application of new technologies.

1.2 An overview of research and experiences
1.2. Pregled istraživanja i iskustava

Solid-wood chairs have been the subject of research of many authors, who generaly focused on their dimensioning and constructional joints. C.A. Eckerman analysed the bearing strength of joints in 1966. Tkalec and Prekrat (1997) investigated various joining methods in chairs made of pine and beech. The experimental results showed that the same joints cannot be used with equal success for different types of wood. Gustafsson (1999) introduced the application of final elements in chairs and latticework furniture, with an accent on determination of input parameters of elasticity modules and Poisson numbers. Skakić and Janićijević (2000) researched the strength of chairs in the lateral apron - rear leg joints. Together with a theoretical analysis, by applying final elements and experiments, Smardzewski and Papuga (2004), determined stress and critical spots on the example of a chair in exploitation. Vlaović *et al*. (2010) looked into deformation and the seating comfort index proceeding from the mechanical properties of a chair researched. The influence of shear components on the magnitude of stress in the stretching loads of a seven-lamina veneer sheet were researched by Kljak and Brezović (2007) on standard parallel and cross-layered veneer test-tubes. In the cross-layering veneer, the concentration of the stress was in the section of the test-tube between its wider and narrower parts.

In view of the foregoing, the objective of this paper is to establish the material characteristics of veneer lamina determined by optical 3D measurement of deformations sufficient for determining the rigidity of any veneer laminate (irrespective of fiber orientation and layer thickness). By calculating the rigidity of concrete composites in this manner, a stress deformation analysis can be performed of any chair by introducing reduced membrane stress and bending elasticity matrices.

2. MATERIAL AND METHODS
2. MATERIJAL I METODE

2.1 Determination of the requisite parameters for calculating rigidity and stress in wood laminate structures
2.1. Određivanje parametara potrebnih za izračun krutosti i naprezanja u drvenim uslojenim konstrukcijama

The stress-deformation and the inverse deformation-stress relationships of anisotropic material bodies made of laminated wood is shown by a theoretical concept which will not be discussed in this paper. We will deal with defining a composite material model made of wood based on experimental determination of its material constants. The work was conceived so that on the basis of established models of standard methods of testing composite materials an experimental determination of stretching and shearing properties is performed, as well as the flexing properties of composite wood laminates. The influence of the manner of positioning the wood fibres in composite wood laminates was assessed in respect of several aspects, which fully describe the behaviour under static load action.

2.2 The experimental part
2.2. Eksperimentalni dio

The experimental work was focused on two types of laminates from which nine groups of test-tubes were extracted for determining the mechanical properties of the wood laminates. There is insufficient data for a complex and uniform stacking of veneer sheets on the basis of the experiments performed to determine all the properties of beech laminates, which include its orthotropicness similar to solid wood. The material characteristics include determination of three moduli of elasticity, three moduli of shear and three Poisson's coefficients. As regards the subject covered here, we may say that seating furniture – the chairs on which we spend long periods of our lives and which differ according to the place of their use, the materials of which they are made, their construction and the technology of manufacture – are not easy to produce. Design, engineering and manufacturing technology participate in an equal degree in the creation of a new product. Harmonising the three and ensuring the best possible economics always results in the best possible solution.

2.3 Determining the mechanical properties of wood laminates by tensometry
2.3. Određivanje mehaničkih svojstava drvenih uslojenih materijala tenzometrijom

The mechanical properties of wood (veneer) laminates were determined using appropriate test-tubes extracted from laminates where veneer sheets were layered in a complex manner (crossed fibres) - P1 (Figure 6) and uniform (parallel fibres) - P2, (Figure 7).

Based on the experimental results the constitutive matrix of elasticity equals

$$Q = \begin{bmatrix} \frac{E_x}{(1-\nu_{xy}\nu_{yx})} & \frac{\nu_{xy}E_y}{(1-\nu_{xy}\nu_{yx})} & 0 \\ \frac{\nu_{yx}E_x}{(1-\nu_{xy}\nu_{yx})} & \frac{E_y}{(1-\nu_{xy}\nu_{yx})} & 0 \\ 0 & 0 & G_{xy} \end{bmatrix} = \begin{bmatrix} 17.648 & 0.9726 & 0 \\ 0.9726 & 2.136 & 0 \\ 0 & 0 & 1045 \end{bmatrix} \times 10^3\, MPa$$

where the material constants of the analysis composites have the following values (Nestorović, 2010).

E_x=17190 E_y=2078 G_{xy}=1145 MPa v_{xy}=0,456 v_{yx}=0,0565

The above values were used in specific numerical analyses of the chair system.

2.4 Determining the properties of laminae by optical 3D measurement of deformation
2.4. Određivanje svojstava uslojenog drva optičkim 3D mjerenjem deformacija

Sufficiently accurate measurement of stress and deformations in elements of laminates – wood-based laminae – is an area that can be upgraded by modern technological methods of measurement such as optical 3D measurements of deformations and the application of measuring ribbons that contain optical fibres on one or more laminated veneer sheets.

This method was used to verify the elasticity moduli calculated by experimental research using the test-tubes with uniform veneer stacking, by way of the testing of one lamina made of beech veneer with parallel fibre orientation.

Figure 6 P1 sheet – complex layering of veneer sheets
Slika 6. Ploča P1 – složeno uslojavanje listova furnira

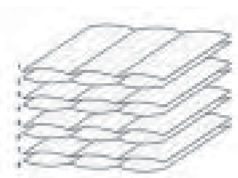

Figure 7 P2 sheet – uniform layering of veneer sheets
Slika 7. Ploča P2 – jednolično uslojavanje listova furnira

2.5 Equipment for testing optical 3D measurements of deformation
2.5. Oprema za optičko 3D mjerenje deformacija

This paper describes the experiment and the numerical methodology of analysing the characteristics of plastic deformations, representative for their rigidity in real time. The equipment used for the experiments included German-made 'GOM' 3D optics (Figure 8) and 'ARAMIS' software. The numerical analysis was performed with software that applies the method of final elements. The main question that needs to be answered is connected to the breaking point of the lamina under test (Figure 10) – does the deformation precede the plastic behaviour, or vice versa? This paper will show how the results of the experiment can be predicted using the method of final elements; this is regarded as a very reliable supporting tool that will help designers improve the structural rigidity of future products. Experimental and numerical analyses conducted so far exhibit a high degree of correlation. The intention was to emphasise the advantages of using modern optical 3D measurement of deformations in identifying the effects of deformations resulting from various stresses. The equipment consists of two mobile optical digital stereo cameras for determining the re-distribution of deformations caused by static and dynamic loads.

ARAMIS analyses, calculates and records deformations of sections, or of the entire structure.

Fields of application of the measuring equipment are as follows:

- Detection of 3D deformations, shifts and vibrations
- Measurement of dynamic behaviour up to 25 Hz
- Linear and non-linear behaviour of viscous-elastic materials
- Creep testing and testing the effects of ageing of complex structures

Based on diagrams establishing an interdependence of the distances between the points of measurement, *L*, and the force, *F*, as well as time, the elasticity modulus of the lamina is determined. Taking the value noted in status 1 (linear status) of *L*=114.027 mm, and the force *F*=200 N (Figure 9), for the dilatation stress, the following values can be calculated:

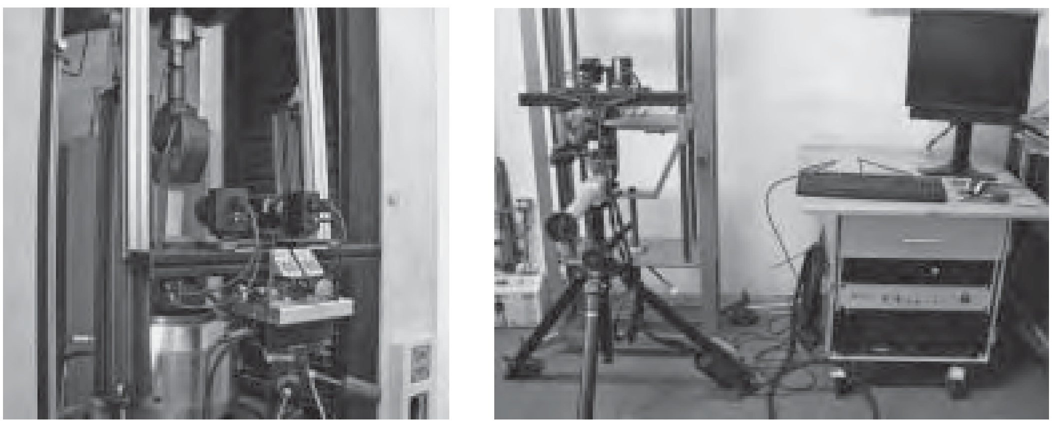

Figure 8 Optical 3D static measurement of deformations
Slika 8. Optičko 3D statičko mjerenje deformacija

$$\varepsilon = \frac{L - L_0}{L_0} = \frac{114.027 - 113.996}{113.996} = 0.00027194$$

$$\sigma = \frac{F}{b \cdot d} = \frac{200}{29 \cdot 1.5} = 4.5977\,MPa$$

from which the following result for the elasticity modulus E_x (only in longitudinal direction) is obtained

$$E_x = \frac{4.5977}{0.00027194} = 16.907 \text{ GPa} \approx 17.0 \text{ GPa}$$

which was confirmed in practice by experiments on uniform-orientation lamina test-tubes using tensometry. This experiment is currently the most advanced type for determining the properties of test materials in a relatively simple manner, and replaces complex experiments that use measuring ribbons.

The software package for analysing laminated structures. Stress-deformation analysis of the construction of chairs was conducted using the KOMIPS ('Computer Modelling and Calculation of Structures') software developed by dr. Taško Maneski (Maneski, 1998): This programme system, based on the method of final elements, possesses an extensive library of elements, from one-dimensional all the way to general three-dimensional elements, providing a possibility of modelling the geometry and physical discretisation of very complex structures. The software system has a pre-processor and a post-processor, enabling the user to make simple description and control of geometry and the analysis of the results achieved. In respect of the number of final elements, degrees of freedom and stress, KOMIPS has no limitations.

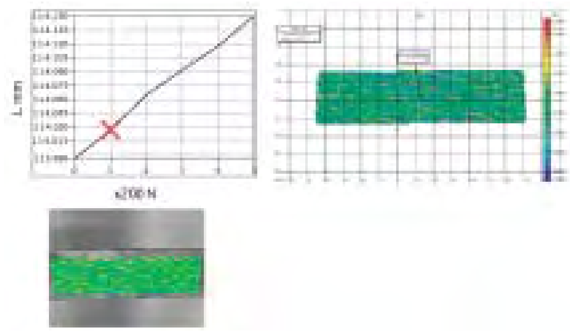

Figure 9 Graphic presentation of momentary stress of a lamina acted on by a force of 200 N
Slika 9. Grafički prikaz kratkotrajnog naprezanja uslojenog materijala pod utjecajem sile od 200 N

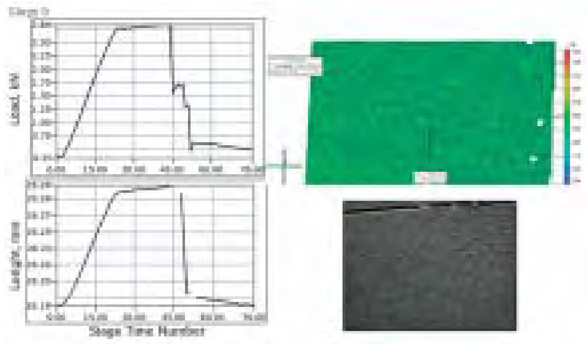

Figure 10 Diagrams of the flow of force (kN) and elongation (mm) in stretching test-tubes until the breaking point
Slika 10. Dijagram kretanja sile (kN) i produljenja (mm) tijekom testa istezanja do trenutka loma

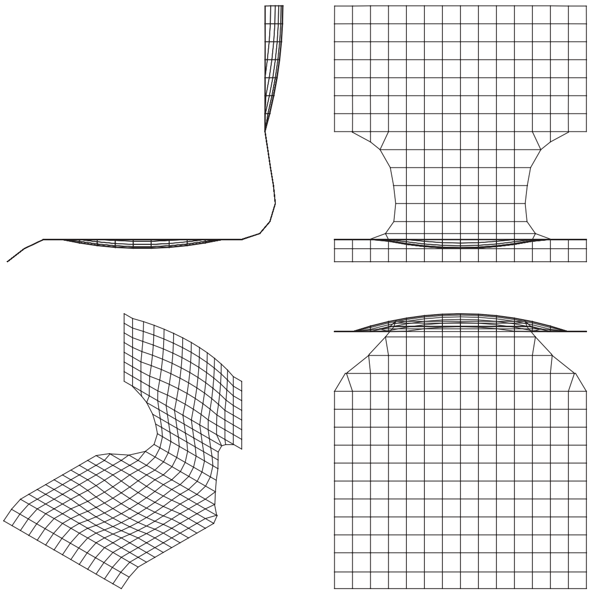

Figure 11 A freely formed shell
Slika 11. Slobodno oblikovana ljuska

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

This paper is especially focused on the final element of the laminate, given that it represents the basis for all our numerical analyses. Calculating the stiffness matrix of the laminate final element calls for volume integration. The problem of volume integration can be translated into integration by the area of the final element by introducing the so-called reduced stiffness of the laminate, which makes the procedure of formulating the stiffness matrix more efficient and identical to the classical plate theory. For those reasons a new subroutine was developed in the software used to calculate the reduced stiffness of the laminate.

3.1 Numerical analysis of laminated wooden structures by using the final elements method
3.1. Numerička analiza uslojene drvne konstrukcije primjenom metode konačnih elemenata

Differential equations of plate membrane stress and flexing are well-known. Integration of these equations, i.e., development of an analytical solution, for arbitrary geometry and arbitrary marginal conditions in a general case, is not possible. This problem was also overcome long ago by the development of a method of mathematical and physical discretisation.

Wooden structures laminated geometrically of a geometrically freely shaped shell with axonometric projection are given in Figure 11. Load and deformation of freely formed shell is shown in Figure 12. The results of stress deformation analysis for the adopted network of final elements by applying reduced stiffness are presented graphically in Figure 13.

3.2 Properties of the layers
3.2. Svojstva slojeva

Composite t = 8 x 1.0 = 8.0 mm   0/90/0/0 / 0/0/90/0 (orientation of the laminae in the laminated plate)

H1	*H2*	*Q11*	*Q12*	*Q16*	*Q22*	*Q26*	*Q66*	*Theta*
4.0	3.0	1.77E+04	9.73E+02	0.00E+00	2.19E+03	0.00E+00	1.05E+03	0.00E+00
3.0	2.0	2.19E+03	9.73E+02	0.00E+00	1.77E+04	0.00E+00	1.05E+03	9.00E+01
2.0	1.0	1.77E+04	9.73E+02	0.00E+00	2.19E+03	0.00E+00	1.05E+03	0.00E+00
1.0	.0	1.77E+04	9.73E+02	0.00E+00	2.19E+03	0.00E+00	1.05E+03	0.00E+00
.0	-1.0	1.77E+04	9.73E+02	0.00E+00	2.19E+03	0.00E+00	1.05E+03	0.00E+00
-1.0	-2.0	1.77E+04	9.73E+02	0.00E+00	2.19E+03	0.00E+00	1.05E+03	0.00E+00
-2.0	-3.0	2.19E+03	9.73E+02	0.00E+00	1.77E+04	0.00E+00	1.05E+03	9.00E+01
-3.0	-4.0	1.77E+04	9.73E+02	0.00E+00	2.19E+03	0.00E+00	1.05E+03	0.00E+00

H1, *H2* (mm) – top and botom surface of laminate, *Q*ij (kN/cm^2) – 2D stress state elastisity matrix of laminate, *Theta* (°) – angle of the main stress direction.

3.3. Reduced elasticity matrices of laminates
3.3. Reducirane elastične matrice uslojenog materijala

	1,1	1,2	1,6	2,2	2,6	6,6
QA(i,j)	1.3789E+04	9.7300E+02	0.0000E+00	6.0590E+03	0.0000E+00	1.0450E+03
QB(i,j)	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00	0.0000E+00
QD(i,j)	1.3064E+04	9.7300E+02	0.0000E+00	6.7837E+03	0.0000E+00	1.0450E+03

Where *QA(i, j)*, *QD(i, j)*, *QB(i, j)* (kN/cm^2) – are elements of membrane, bending and coupled reduced laminate elasticity matrices, respectively.

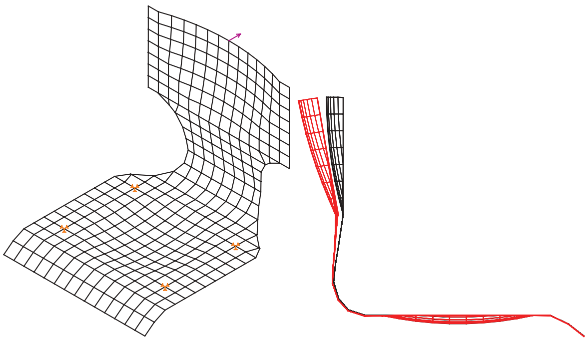

Figure 12 Load and deformation of freely formed shell
Slika 12. Opterećenje i deformacija slobodno oblikovane ljuske

Measurement of the flexing of the back of the laminated freely formed shall was performed experimentally. An angle of f_{max} = 8.3 mm was calculated at a force of 100 N, and 21 mm at a force of 250 N. It should be noted that the numerical values of the flexing exhibit very good correlation with experimental values (Figure 14). It may be concluded that an increased concentration of stress has taken place on the radius of the back. The concentration of stress would probably be reduced by a less pronounced radius (Figure 13). Flexing and forces were measured on the back of a freely formed shell, at its highest point. The flexing was measured by German-made FLUKE 416D laser equipment, which has an accuracy of 1 mm. Force was measured using a Taiwan-made FORCE GAUGE FG – 5100 dynamometer, with an accuracy of 1 N and a measurement range of 0 to 1500 N.

Figure 15 shows changes of normal stresses according to the thickness of laminate for the case of the true stiffness of the laminate (solid line) and reduced stiffness of the laminate (dotted line) for the case of a composite plate (Figure 15). It may be concluded that for both diagrams the same areas are formed of reduced (dotted line) and non-reduced (full line) stiffness, leading to identical (corresponding) results.

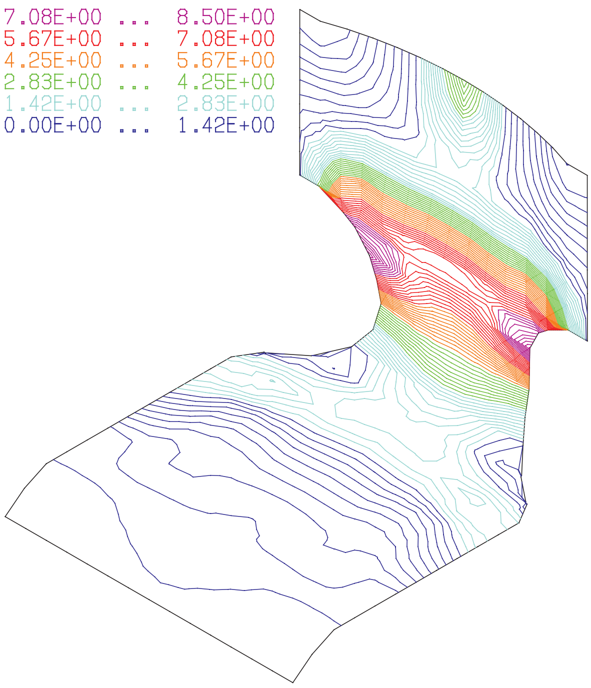

Figure 13 Stress field (Von Measses) of freely formed shell by applying reduced stiffness
Slika 13. Polja naprezanja (Von Measses) slobodno oblikovane ljuske primjenom reducirane krutosti

4 CONCLUSIONS
4. ZAKLJUČCI

Beech wood veneer may be used with arbitrary layering to form various composites, of which different pieces of furniture for sitting can be made of freely-formed shape.

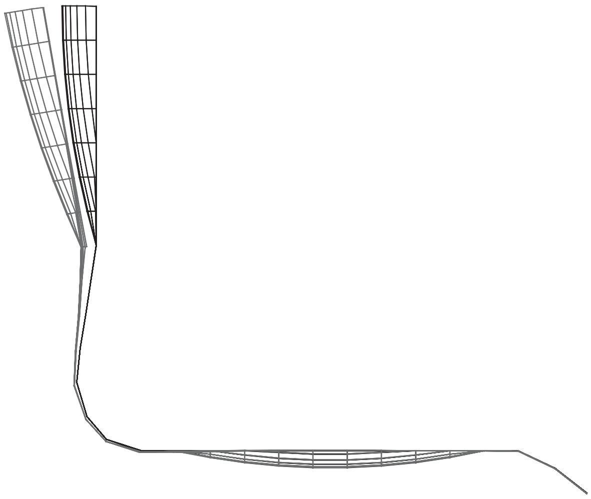

Figure 14 Deformation of freely formed shell by applying reduced stiffness
Slika 14. Deformacija slobodno oblikovane ljuske primjenom reducirane krutosti

Tension / *Naprezanje*, MPa

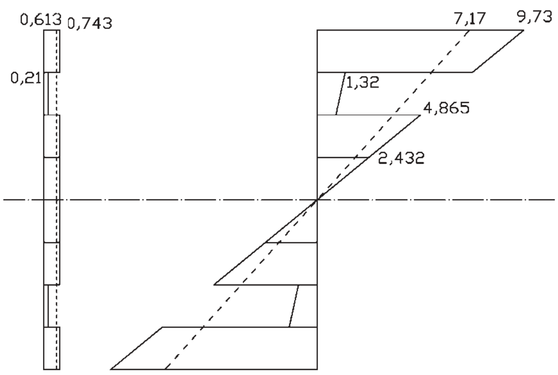

Figure 15 Changes of normal stresses by laminate thickness for reduced and non-reduced plates
Slika 15. Promjene normalnih naprezanja po debljini uslojenog materijala za reducirane i nereducirane ploče

The material properties of veneer laminae determined by optical 3D measurement of deformations are sufficient to calculate the stiffness of any veneer laminate (irrespective of fibres orientation and layers thickness). This measurement efficiently replaces complex and expensive deformation measurement by tensometric method.

Having calculated the stiffness of concrete composites in this way, by introducing reduced elasticity matrices of membrane stress and flexing (Figure 16), the stress deformation analysis can be performed of any chair, using an appropriate software package.

On the basis of the foregoing, a pragmatic example could be that of a reclining 'Savannah Rocker III' chair manufactured in 2009 (Figure 17) by British designer Jolyon Yates. The chair is made of uniform beech laminate and has dimensions of 990 mm x 520 mm x 990 mm.

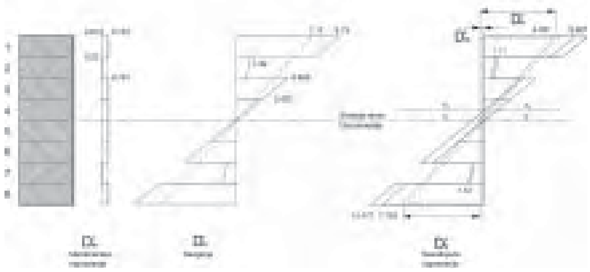

Figure 16 Reduced stresses
Slika 16. Smanjena naprezanja

Figure 17 Freely formed chair of uniform laminate
Slika 17. Slobodno oblikovani stolac od jednolično uslojenog drva

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