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Experimental and numerical investigation of plywood panel with curved ribs

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Abstract **– Numerical and experimental investigations of plywood unbalanced sheets and plywood panel with curved ribs are done. The moisture diffusion coefficient and deformability of special type of unbalanced sheet that might be used in manufacturing of curved ribs are studied. Results show that rational time of thermal treatment is 2.5-3 hoursand temperature are proposed to provide a shape stability of plywood elements. The behaviour of small scale experimental model of three hinged triangular roof structure that is made of plywood panels with curved ribs is experimentally studied.**

Keywords **– unbalanced plywood, moisture diffusion caused deformations, thermal treatment, plywood triangular roof construction.**

I. INTRODUCTION

Plywood panels with curved ribs provide a lot of advantages-increased strength-to-mass ratio [10, 11], possibility to tailor material properties [8] for specific loading and boundary conditions. Curved plywood ribs could be manufacture by using unbalanced plywood sheets [9]. Sheets obtain curved shape while conditioning in special moisture temperature regime. Therefore moisture diffusion kinetics and deformation process are experimentally and numerically studied in this work.

Wood materials are very sensitive to moisture variations that cause undesirable deformations [6]. Especially, if we use unbalanced composites. Moisturecaused deformations should be reduced for plywood structures. An optimal thermal treatment procedure that minimizes moisture diffusion coefficient and moisturecaused deformations is proposed in this paper.

The behavior of threehinged triangular roof that is made of plywood panels with curved ribs is not experimentally studied yet. This structure is not typical [4] and, therefore, a special experimental setup is created and used to test the construction.

II. DIFFUSION KINETICS OF PLYWOOD SHEET

Moisture diffusion kinetics for thin sheets is modeled by analyzing moisture diffusion only in transversal direction. We used Fick's Law to model moisture diffusion process in transversal direction [7].

Moisture diffusion coefficient is obtained using multiple iterations. The average moisture contents $m_{i,exp}$at certain time steps (index i indicate time step) is obtained experimentally. Experimental moisture measurements aredone by gravimetric method using weights KERN EMP 200-2. The average moisture content m_i through thickness of sheet for the same time steps (N- total number of time steps) is obtained numerically. Numerical results depend on diffusion coefficient. So D iteratively changed until difference between numerical and experimental results is minimal:

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

Many works show that moisture diffusion coefficient depends on temperature and moisture content of wood material [3, 5]. Experimental investigations on diffusion coefficient are done for different samples that are shown in table 1. Samples with size 150x150 mm were manufacture using phenol-formaldehyde glue in hot press, where temperature was 100*C and pressure 1.5 MPa. After curing they were taken out of press and conditioned in room temperature 18*C and air relative humidity 25%.

TABLE 1

STRUCTURE AND MOISTURE CONTENT OF EXPERIMENTAL SAMPLES

SAMPLE NR.	PLY LAY-UP	INITIAL MOISTURE CONTENT				AVERAGE MOISTURE CONTENT AFTER GLUING*
		1	2	3	4	
25	0/0/0/90	8.73%	10.29%	10.26%	7.63%	15.51%
26	0/0/0/90	2.94%	1.39%	1.88%	2.01%	9.23%
27	0/0/0/90	0.66%	0.48%	0.1%	1.06%	8.4%
28	0/0/0/90	8.25%	9.35%	9.46%	9.98%	17.50%
29	0/0/90	1.31%	1.08%	1.50%		10.30%
30	0/0/90	11.41%	10.69%	11.22%		18.07%
106	0/0/0/90	8.83%	9.29%	10.11%	7.92%	15.9%

* Dry remain of glue is subtracted

A special Matlab program was written for diffusion coefficient analysis. It solves moisture diffusion equation by using different diffusion coefficients and choose that one which makes minimal difference between calculated and experimentally obtained moisture content (see eq. 1.). Plots of diffecence between experimentally and numerically obtained average moisture content are shown in Fig. 1., 2., 3., 4., 5.

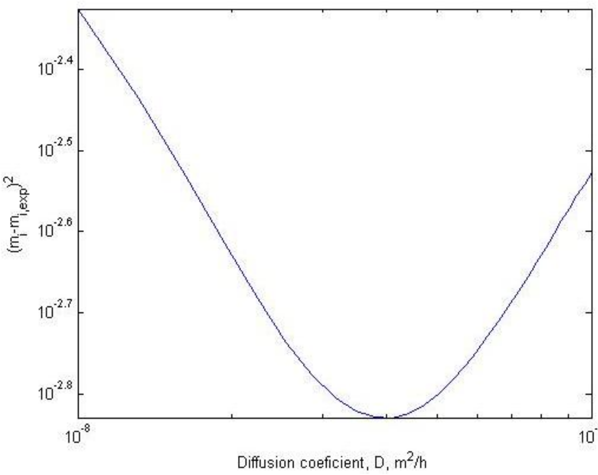


Fig.1. The plot of difference between experimentally and numerically obtained average moisture content depending on diffusion coefficient for sample 25.

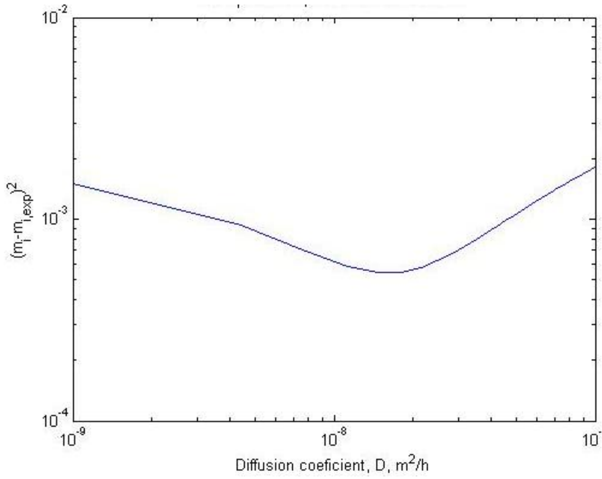


Fig. 2. The plot of difference between experimentally and numerically obtained average moisture content depending on diffusion coefficient for sample 26.

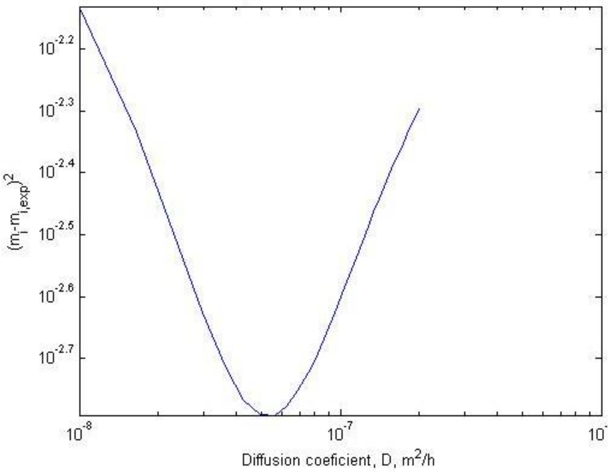


Fig.3. The plot of difference between experimentally and numerically obtained average moisture content depending on diffusion coefficient for sample 28.

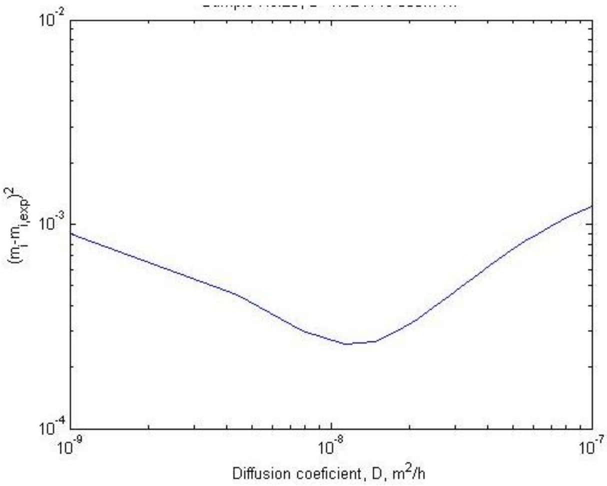


Fig. 4. The plot of difference between experimentally and numerically obtained average moisture content depending on diffusion coefficient for sample 29.

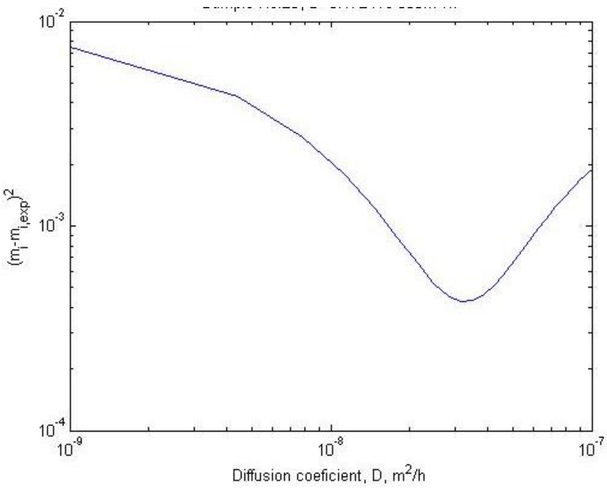


Fig. 5. The plot of difference between experimentally and numerically obtained average moisture content depending on diffusion coefficient for sample 30.

III. MOISTURECAUSED DEFORMATION INVESTIGATION

Samples with three and fourlayer structure and different initial conditions were experimentally and numerically tested. The internal structure of samples is shown in table I., but moisture content change, experimentally obtained deflection $f_{eksp}$and calculated $f_{calc}$are shown in table 2.As we can see for samples with large moisture content change- around 10% and large displacements the difference between calculated and experimentally obtained is about 28%. For samples with small displacement this difference is below 10%. The finite deformation theory was used in analysis, but material nonlinearity was not taken into account. This might be the reason of this difference [1, 12, 13].

TABLE II
CALCULATED AND EXPERIMENTALLY OBTAINED DEFLECTION OF UNBALANCED LAMINA

Sample No.	Moisture change (start..final) %	f_{eksp}, mm	f_{calc}, mm	Difference, %
25	20..11	15	20	25
26	16.4..12.8	8,3	8,1	2,5
28	23..13	13	18	28
29	16,5..13,15	6,6	6,2	6
30	21…12,5	10,6	15,7	32

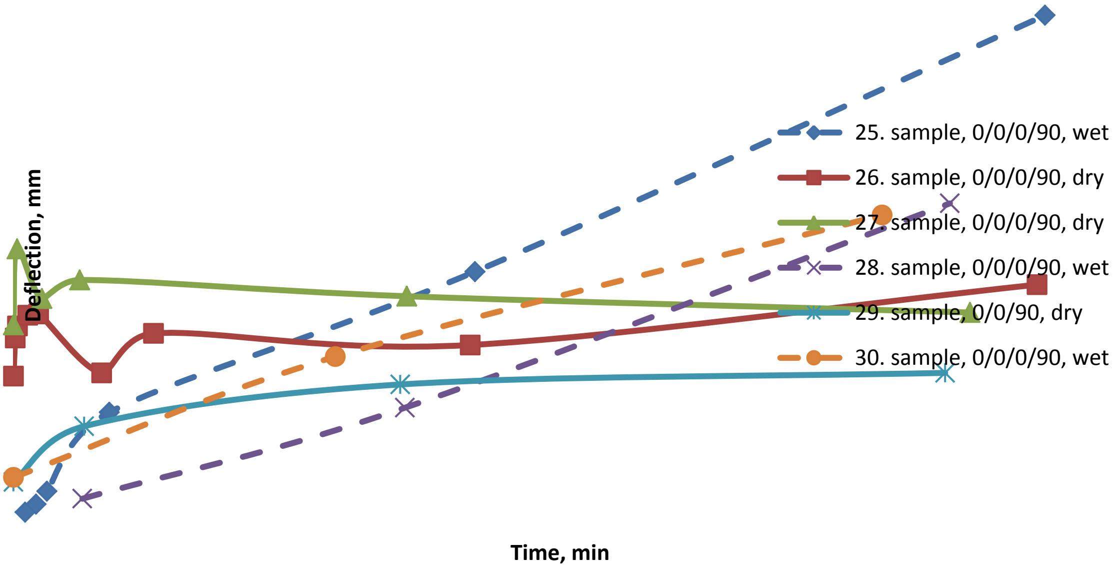


Fig. 6. Deflection change in time for different samples.

Deflection-displacement change was experimentally analyzed in time for samples with initially increased moisture content- wet samples (sample no. 25, 28, 30), and samples with initially decreased moisture content- dry samples (sample no. 26, 27, 29). Deflection change in time is shown in fig.6. As we can see, dry samples very quickly (less than 1 hour after curing in hot press) obtain maximal deflection. Wet samples linearly obtain maximal deflection in much longer time.

Practically, more significant role in production of panels with curved ribs plays curved plywood with weave shape. Therefore, samples with special- discrete variable internal structure (see figs.7., 8.) were prepared and experimentally and numerically tested. Totally three samples were manufactured by using veneers with different initial moisture content- 9.8%, 13.9% and 17.43%. Samples were glued together in cold press by using CASCO SILVE glue (cohesive substance- polyvinyl-acetate, solvent- water). The pressure in press was about 1.5 MPa.

Fig. 7. Sample with three waves.

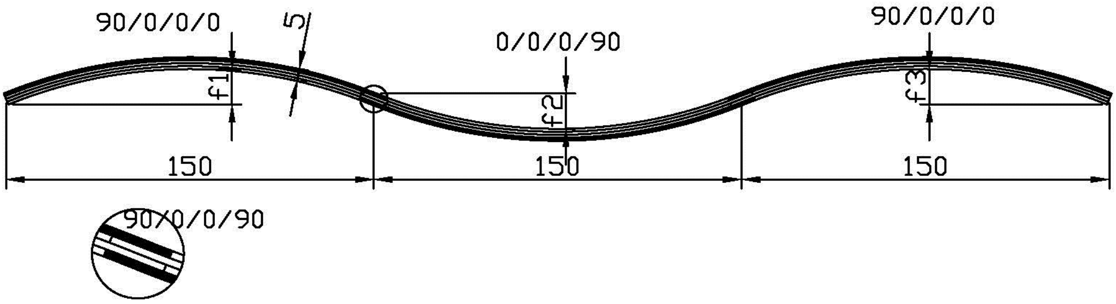


Fig.8. Scheme and internal structure of sample with three waves.

Samples were conditioned in room temperature 18*C and average air relative humidity about 50% after curing process. Deflections f_1, f_2, f_3 (see fig. 8.) were measured during the conditioning process. The deflection plot for sample with initial moisture content 9.8% is shown in fig. 9. As we can see, calculated deflection is bigger than experimentally obtained. It might be because of wood nonlinear material properties- creep, relaxation effects that were not taken into account during numerical simulation.

A sample with initial moisture content 17.43% obtainssignificantly bigger average deflection (about 10.5 mm) comparing to other samples (see fig. 10.).

Maximal deflection could be increased, if we increase initial moisture content, but special glue should be used. For typical glues PVA, Phenol-formaldehyde, moisture content of wood should be less than 18 %.

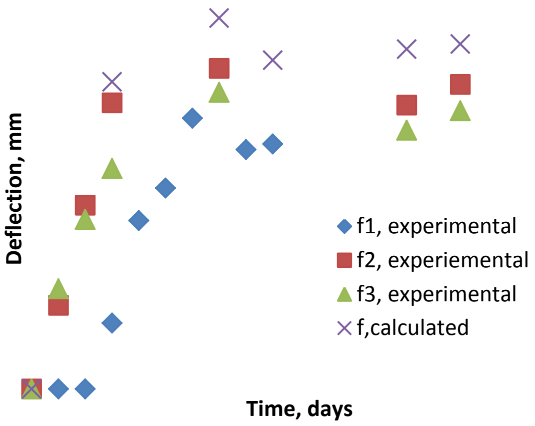


Fig. 9. Experimentally and analytically obtained deflection in time.

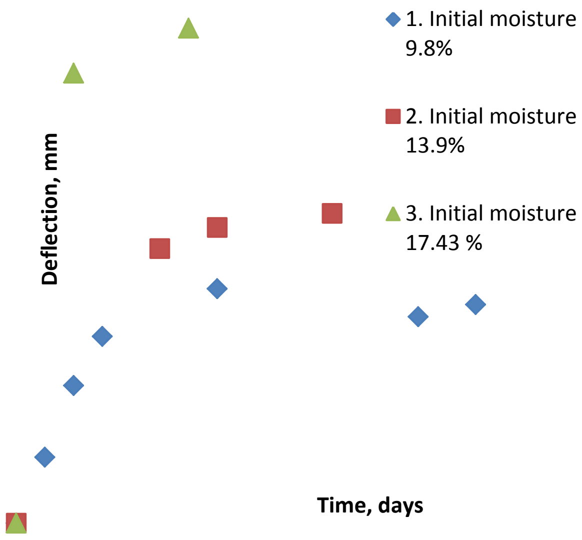


Fig. 10. Average deflection of samples with different initial moisture content.

IV. THERMAL TREATMENT INFLUENCE

Curved plywood elements which are used in structural application should be stable in environment moisture-temperature fluctuations. Plywood structural elements have large deviation of mechanical properties [2] that might cause undesirable deformations. A stable shape could be obtained by making special coverings of plywood that significantly decrease moisture diffusion speed. Another way is to do thermal treatment in temperature about 130..150 *C for certain time that depends on size of elements. The shape stability and moisture diffusion kinetics of thermally treated samples were experimentally analyzed. Experimental setup is shown in fig. 11. It consists of thermal box, special frame which limits deformations of samples and temperature controlling system. Thermal treatment was done in temperature 140*C.Higher temperature is not recommendedto use, because wood might lost its strength properties, but lower temperature increase treatment time.

The moisture diffusion coefficient was measured after thermal treatment and we can see in table III it is decreased about 45%. Samples were thermally treated two hours.

Next task was to obtain an optimal thermal treatment time. Optimal means that there is minimal moisturecaused deformations of plywood.

Samples were thermally treated for three different times and compared moisture caused deflection change. Results are shown in fig. 12. As we can seefrom plot in fig.12., the optimal thermal treatment time is about 2.5 hours in temperature 140 *C. The optimal time was obtained for samples with fourlayer veneer structure. For plywood with other thickness and structure it might be different.

Fig. 11. Thermal box which was used in thermal treatment of samples.

TABLE III

Experimentally Obtained And Calculated Moisture Diffusion Coefficient Of Plywood With Average Moisture Content 16% And Temperature 20 *C

Sample No.	Average diffusion coefficient* D, $\frac{m^2}{h}$, before thermal treatment	Average diffusion coefficient* D, $\frac{m^2}{h}$, after thermal treatment	Difference, %
25	$4.10 * 10^{-8}$	$2.10 * 10^{-8}$	50%
26	$1.46 * 10^{-8}$		
27	$8.00 * 10^{-8}$		
28	$5.58 * 10^{-8}$	$3.27 * 10^{-8}$	40%
29	$1.12 * 10^{-8}$		
30	$3.17 * 10^{-8}$		
Calculated (3, 5)	$9.13 * 10^{-8}$		

* desorption diffusion coefficient.

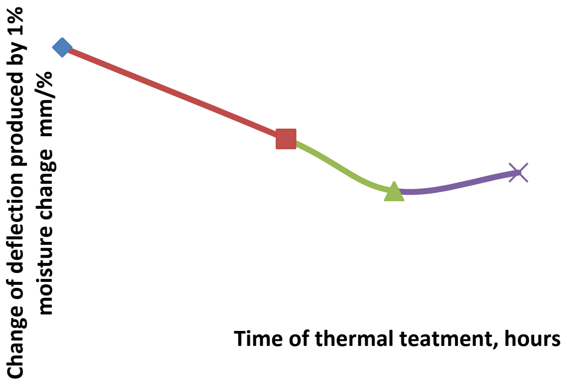


Fig.12. Influence of thermal treatment on moisture caused displacements.

V. BEHAVIOR OF PANEL WITH CURVED RIBS

The behavior of plywood panel, that is made of curved plywood ribs as it is shown infig.13. was experimentally investigated [4]. The experimental model is around five times smaller than actual- typical roof structure. The structure consists of two panels that are inclined in 46.5 degrees angle. The structure works like threehinged triangular arch. Curved ribs were manufactured from standard 3-ply symmetrical Riga ply birch plywood- BB\W. Ribs with curved shape might be manufactured by using plywood with unbalanced-unsymmetrical lay-upas it is shown in figs. 7., 8. Each side of structure consists of threelayer plywood composite. The middle layer consists of curved and flat plywood ribs (see fig. 13.), but outer layers consist of 3-ply birch plywood. Ribs consist of 5x6 typical elements. Structure is glued by using CASCO SILVA wood glue in cold press.

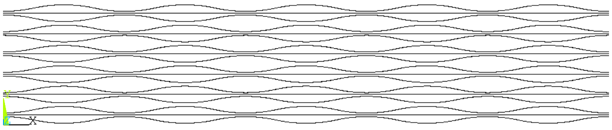


Fig. 13. The ribbed structure of experimental sample.

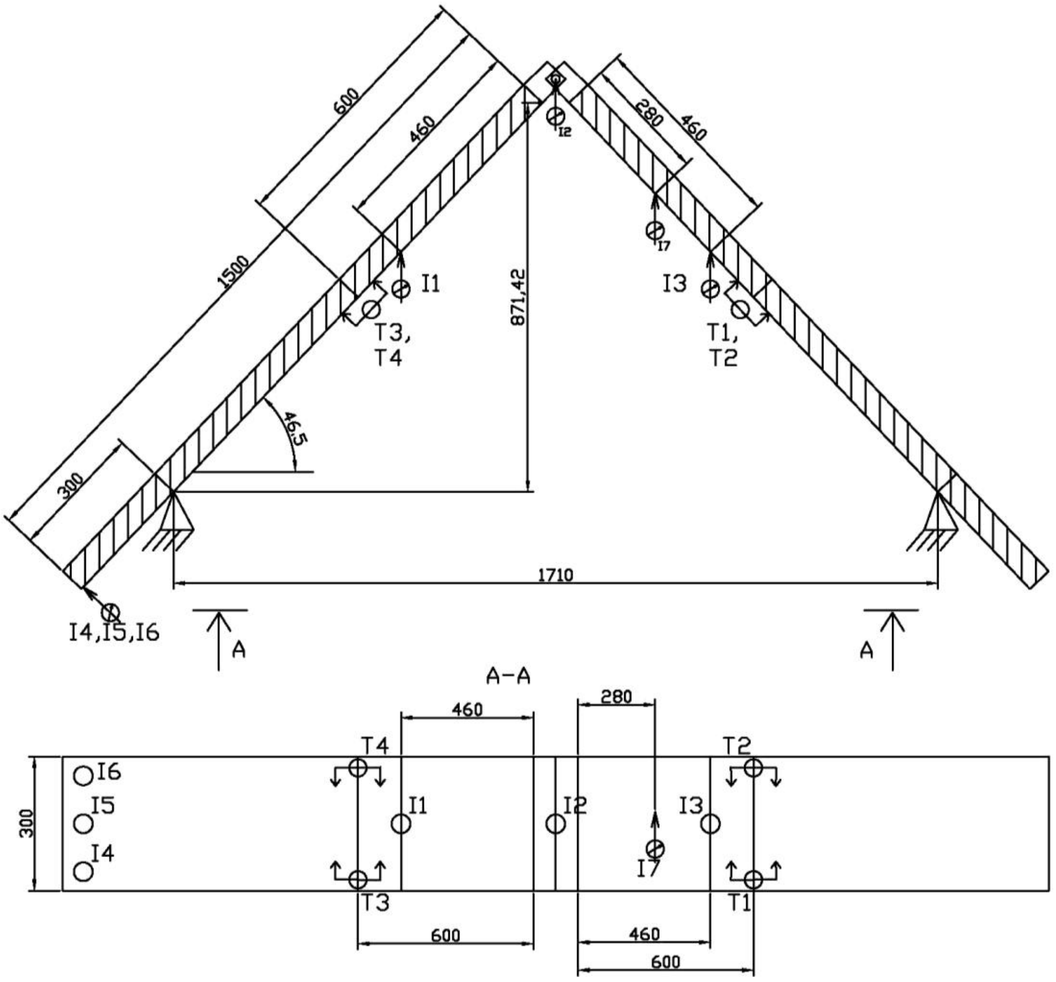


Fig. 14. The scheme of experimental model of roof structure.

Dimensions and location of deflection and strain measuring devices I1,I2,I3,I4,I5,I6,I7, T1,T2,T3,T4of experimental model are shown in fig. 14. Vertical deflection is measured in three places I1, I2, I3, by mechanical measuring devices PAO 102. Transversal deflection of roof console is measured in three places by I4, I5, I6 by mechanical measuring devices SHOCK-PROOF SCALA. Outofplane displacements are measured by device PA 102 in point I7 (see fig. 17). Four strain measurements are donein quarter of total span.Ineach side of structure two strain measurements are done in points T1, T2 and T3, T4 (see figs. 14.,16.) by mechanical measuring device YPM LISI TA-2. The precision of deflection measurements was 0.01 mm, but for strain measurements it was 0.001mm.

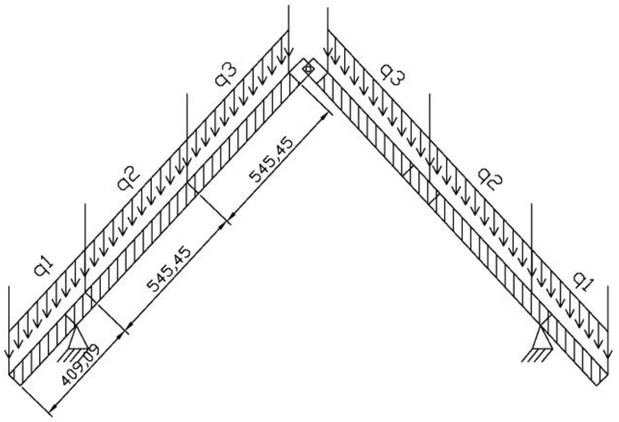
The load is applied using steel weights with average weight 0.19 KN for each and dimensions 350x130x70 mm. Nine load combinations were used in experimental investigations (see fig. 15.). Maximal load was applied by putting weights in three rows as shown in fig. 18. Only symmetrical load was applied with maximal intensity 14 KPa.

Plots of vertical deflection in points I1, I2, I3 is shown in fig. 19. Maximal vertical deflection is around 2 mm.Calculations shows that maximal normal stress in direction of wood fibers is around 12 MPa and shear stress in ribs is around 2 MPa. The stress does not exceed 50% of failure strength.

Strain measurements in both sides shows good agreement as it is shown in fig. 20. The strain measurement device in point T3 broke down during experiment therefore it is not shown in plots.

Plots of transversal deflection of console of structure are shown in fig.21. We can see that deflection that is close to edges of structure (I4, I6) is bigger than in the middle of structure (I5).

Outofplane displacements was measured in one side of structure in point I7. Results are shown in fig. 22. Maximal outofplane deflection during loading stage is 0.25 mm, but in unloading phase it is 0.45mm. If we compare these displacements with span of structure – 1710 mm, than it less then 1/3500, so it could be ignored. Deflection and strain measurements show that there are very small remaining deformations. It means that delamination between skins and ribs do not start.



Load No.	$q_1, \frac{kN}{m^2}$	$q_2, \frac{kN}{m^2}$	$q_3, \frac{kN}{m^2}$
1.	4.67	0	0
2.	4.67	4.67	0
3.	4.67	4.67	4.67
4.	9.33	4.67	4.67
5.	9.33	9.33	4.67
6.	9.33	9.33	9.33
7.	14.0	9.33	9.33
8.	14.0	14.0	9.33
9.	14.0	14.0	14.0

Fig.15. Load cases on experimental roof model.

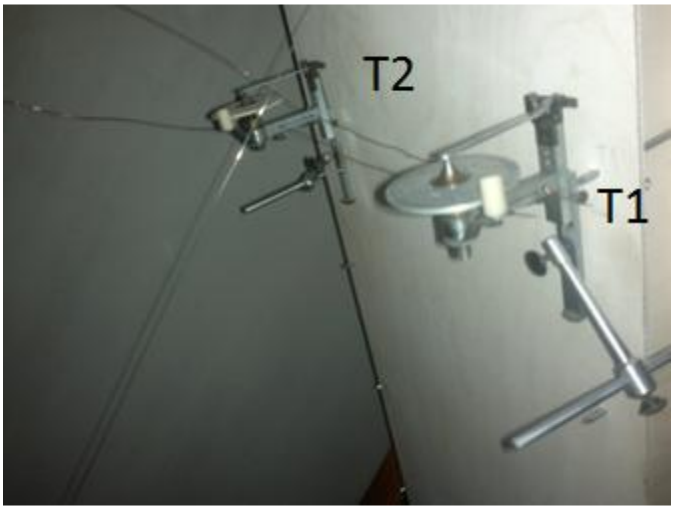


Fig. 16. Strain measuring devices T1, T2 (model YPM LISI TA-2) with precision 0.001mm.

Fig. 17. Outofplane displacement measuring device in point I7 (PAO 102) with precision 0.01mm.

Fig. 18. Experimental roof model, which is loaded with load case No.9. (14 KPa uniformly distributed) by steel weights.

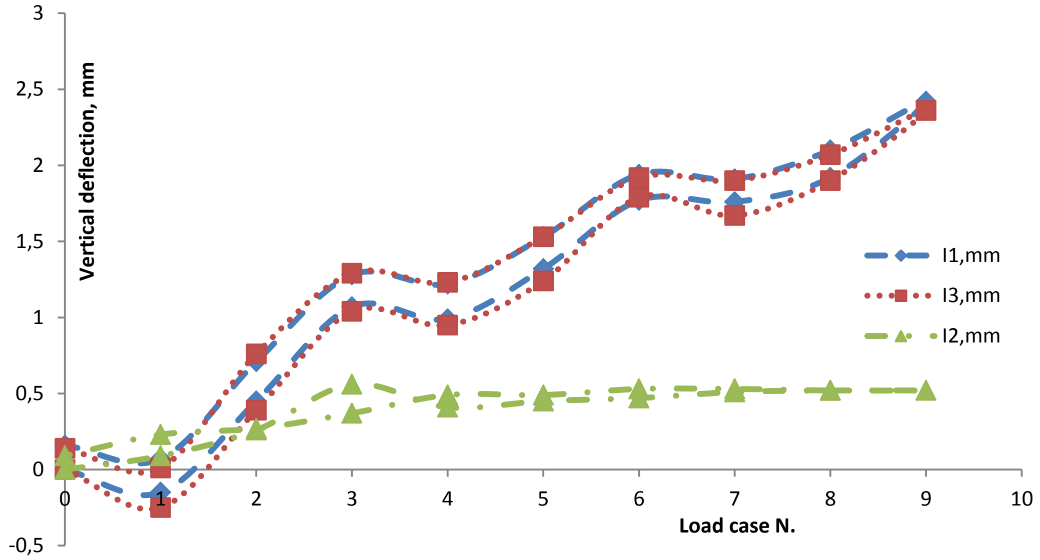


Fig. 19. Vertical deflection measurements (I1, I2, I3) for different load cases.

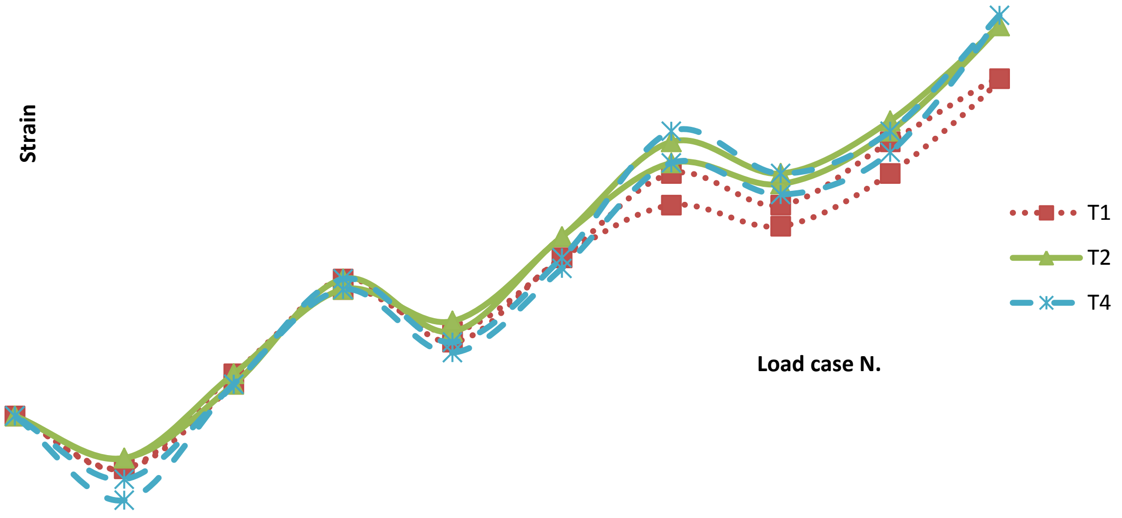


Fig. 20. Strain measurements (T1, T2, T4) depending on load case.

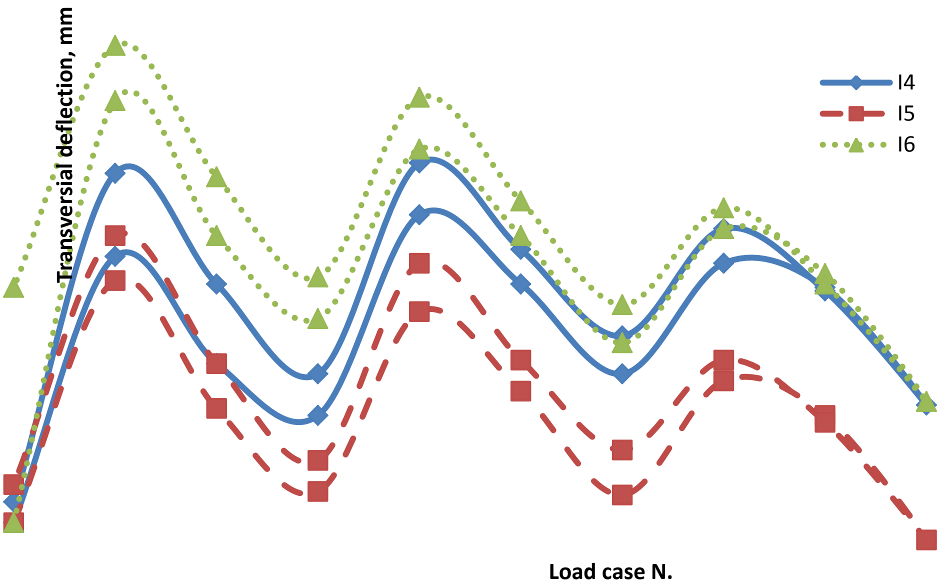


Fig. 21. Transversal deflection (I4, I5, I6) of roof console, which is measured for different load cases.

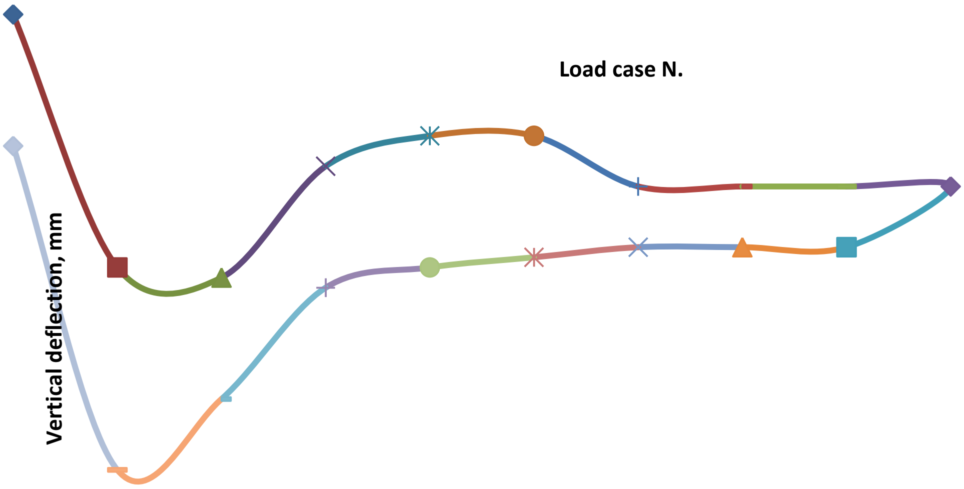


Fig. 22. Outofplane displacements (I7) for various load cases.

VI. CONCLUSIONS

A model of novel threehinged triangular plywood composite panel with ribbed structure is experimentally investigated. Moisturecaused displacements and thermal treatment effect of unbalanced plywood ribsare experimentally and numerically investigated.

Experimental and numerical results show that curved plywood ribs could be manufacture with unbalanced structure. The necessary curvature of ribs could be obtained by conditioning in special moisture-temperature regime after curing in hot or cold press. Rational time of thermal treatment at temperature 140 *C is 2.5..3 hours depending on thickness of element.

Measurements of deflection and strain show that deformations are symmetrical in symmetrical points of structure. There are small remaining displacements after unloading.

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