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IN-PLANE COMPRESSIVE STRENGTH OF PLYWOOD REINFORCED WITH COTTON PREPREG

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ABSTRACT

The aim of this research is to study the in-plane compressive strength of eleven-layered beech plywood reinforced with non-wood material in its structure.Plywood reinforcement was made by inserting certain numbers of sheets of pre-impregnated cotton fabric (cotton prepreg). Methyl alcohol-soluble phenol-formaldehyde resin was used for fabric pre-impregnation as well as for veneer bonding. The thickness of the veneers used in the plywood structure was between 1.5 and 1.85 mm. Different models of plywood were made by changing the position of cotton prepreg reinforcements in the plywood structure. One control model of plywood without reinforcement was made.
The in-plane compressive strength of plywood models was tested in five directions: parallel to the face grain, perpendicular to the face grain, and at angles of 22.5°, 45°, and 67.5° to the face grain of the plywood panel.
The obtained results showed that the application of cotton prepreg in plywood structures has an impact on the values of the in-plane compressive strength of plywood.

Key words: plywood, reinforcement, cotton fabric, prepreg, pre-impregnated, phenol-formaldehyde resin, compressive strength

1. INTRODUCTION

Plywood is a material that is often used in construction in many applications because of its good strength characteristics, high strength-to-weight ratio, good dimensional stability, and decreased anisotropy compared to solid wood. It is widely used for siding, roofing, flooring, shear walls, and the production of engineered wood products.

Plywood properties can be improved by reinforcing plywood with non-wood materials. Significant improvement of mechanical properties can be achieved by overlaying plywood with fiber-reinforced polymers (Hardeo and Karunasena, 2002; Choi *et al*., 2011; Zīke and Kalniņš, 2011).
Beside reinforcement of plywood with different types of fibers and matrixes (Xu *et al*., 1996; Xu *et al*., 1998; Brezović *et al*., 2003; Brezović *et al.*, 2010; Biblis and Carino, 2000; Hrázský and Král, 2007; Maniņš and Zīke, 2011), possibilities to reinforce wood with pre-impregnated materials (prepregs) were also explored (Rowland *et al.*, 1986).

The study by Kohl *et al*. (2013) showed that the application of pre-impregnated glass, carbon, and aramid fiber materials results in a significant reduction in deflection and an increase in carrying capacity.

The study by Jakimovska Popovska and Iliev (2019) showed that using pre-impregnated fiberglass fabric (fiberglass prepreg) can increase the plywood bending strength and modulus of elasticity in bending.

Other research (Jakimovska Popovska and Iliev, 2021) showed that the application of pre-impregnated cotton fabric in the structure of plywood significantly increases its hardness.

The aim of the research is to study the in-plane compressive strength of plywood reinforced with cotton fabrics pre-impregnated with methyl alcohol-soluble phenol-formaldehyde resin.

2. EXPERIMENTAL METHODS

For the realization of the research, four experimental eleven-layered beech plywoods were made. The thickness of the veneers was 1.5 mm and 1.85 mm, with a moisture content of 9.77 %. The orientation of adjacent veneers in the plywood structure was at a right angle.

Each model has inserted reinforcement sheets of pre-impregnated cotton fabric (cotton prepreg) in its adhesive layers. In three models, each reinforcement layer consists of four sheets of pre-impregnated cotton fabric placed one above the other and inserted symmetrically on both sides with respect to its axis of symmetry. In the first model (CP-1), the reinforcements are inserted in the fifth and sixth adhesive layers, while in the second model (CP-2), they are inserted into the third and eighth adhesive layers. In the third model (CP-3), the reinforcements are positioned as surface layers of plywood. The fourth model of plywood (CP-4) was made by inserting single sheets of cotton prepreg in each adhesive layer of the panel. One control model (C) of plywood without reinforcement was made for comparison of the results. The pattern and cross-section of experimental plywood models are given in a previous research paper (Jakimovska and Iliev, 2021).

In all models of reinforced plywood, the orientation of the wrap of the fabric is parallel to the grain direction of the surface veneers.

The cotton prepreg was made from cotton fabric that was pre-impregnated with methyl alcohol-soluble phenol-formaldehyde resin with 51 % dry matter content in a quantity of 300 g/m2. The same resin was used for veneer bonding, applied to the veneers in a quantity of 180 g/m2. The thickness of the cotton fabric before impregnation was 0.22 mm, while the thickness of the cotton prepreg was 0.6 mm.

The technical characteristics of the cotton fabric, the resin characteristics, and the impregnation process of the fabric, as well as the parameters of the pressing process of plywood models, are described in other research (Jakimovska and Iliev, 2021).

The in-plane compressive strength of plywood was tested according to the national standard MKS D.A8.070/85 on test specimens with dimensions of 50·6d·d (mm). This property is tested in five directions, i.e., parallel to the face grain, perpendicular to the face grain, and at angles of 22.5°, 45°, and 67.5° to the face grain of the plywood panel.

Figure 1: *Test specimen during testing the compressive strength of experimental plywood*

For statistical analysis of the obtained data, SPSS statistical software was used. A one-way ANOVA was used to determine the significance of the effect of the cotton prepreg reinforcements on plywood in-plane compressive strength. Tukey’s test was applied to evaluate the statistical significance between the mean values of compressive strength of plywood with different layouts of reinforcement. The tests were conducted at a 0.05 probability level.

3. RESULTS AND DISCUSSION

The obtained results for the in-plane compressive strength of experimental plywood models are shown in Table 1 and Figure 2.

The analysis of the obtained data showed that in all tested directions, reinforced plywood models have higher values of compressive strength compared to the control model made without reinforcements. In all tested directions, the highest value of this property is achieved in model CP-2. Compared to the control model C, the value of compressive strength in model CP-2 is higher for 29.4 % in the parallel direction, 33.3 % in the perpendicular direction, 39.7 % at the angle of 22.5°, 34.6 % at the angle of 45°, and 35.4 % at the angle of 67.5° to the face grain of the panel. Within the reinforced models, the lowest value of compressive strength in all tested directions is achieved in model CP-3, where the reinforcements are positioned as surface layers of plywood.

Table 1: *Statistical values for the compressive strength of experimental plywood*

Compressive strength	**Model**	**N**	**Mean (N/mm^2)**	**Std. Deviation (N/mm^2)**	**Std. Error (N/mm^2)**	**95 % Confidence Interval for Mean**		**Min (N/mm^2)**	**Max (N/mm^2)**
						Lower Bound	**Upper Bound**		
Parallel to the face grain	**CP-1**	5	68.12^{a}	4.00	1.79	63.15	73.09	62.73	72.73
	CP-2	5	76.52^{b}	5.69	2.54	69.45	83.58	67.49	82.43
	CP -3	5	66.69^{a}	3.03	1.36	62.93	70.46	61.46	68.75
	CP-4	5	$69.63^{a,b}$	3.39	1.51	65.43	73.84	66.20	73.71
	C	5	59.12^{c}	2.10	0.94	56.52	61.72	56.65	61.61
Perpendicular to the face grain	**CP-1**	5	73.11^{a}	3.10	1.39	69.26	76.96	69.17	76.57
	CP-2	5	77.65^{a}	3.37	1.51	73.46	81.83	74.21	83.11
	CP -3	5	69.84^{a}	4.82	2.15	63.86	75.82	64.68	74.62
	CP-4	5	76.46^{a}	7.84	3.51	66.71	86.20	62.70	81.65
	C	5	58.27^{b}	1.75	0.78	56.10	60.44	55.72	60.23
22.5° to the face grain	**CP-1**	5	68.66^{a}	1.81	0.81	66.40	70.91	66.66	71.48
	CP-2	5	73.19^{b}	0.64	0.29	72.40	73.99	72.49	74.20
	CP -3	5	64.64^{c}	0.89	0.40	63.53	65.75	63.53	65.90
	CP-4	5	$70.01^{a,b}$	1.86	0.83	67.70	72.32	67.73	72.19
	C	5	52.39^{d}	2.62	1.17	49.15	55.64	48.56	54.44
45° to the face grain	**CP-1**	5	$58.93^{a,b}$	1.27	0.57	57.36	60.50	57.10	60.62
	CP-2	5	64.71^{c}	3.83	1.71	59.96	69.47	59.05	68.91
	CP -3	5	56.36^{a}	0.88	0.39	55.27	57.45	55.41	57.43
	CP-4	5	$61.86^{b,c}$	1.19	0.53	60.38	63.34	60.61	63.38
	C	5	48.06^{d}	2.01	0.90	45.57	50.56	45.02	49.86
67.5° to the face grain	**CP-1**	5	66.54^{a}	1.37	0.61	64.84	68.25	65.17	68.80
	CP-2	5	72.41^{b}	1.38	0.62	70.70	74.12	70.33	73.88
	CP -3	5	62.65^{c}	0.89	0.40	61.54	63.75	61.16	63.53
	CP-4	5	68.82^{a}	1.45	0.65	67.02	70.62	66.57	70.14
	C	5	53.46^{d}	1.65	0.74	51.42	55.51	51.24	55.82

*The mean values with the same letters are not significantly different at the 0.05 probability level

The analysis of variance of the obtained data for compressive strength parallel to the face grain (ANOVA: $F (4, 20) = 13.26$; $p << 0,001$) showed that the differences between the mean values of this property of at least two plywood models are statistically significant. The post-hoc Tukey's test for multiple comparisons between models showed that there are statistically significant differences in the mean values of compressive strength parallel to the face grain between the control model and all reinforced models. Within the reinforced models, there are no statistically significant differences between models CP-1, CP-3, and CP-4, where the differences are small and do not exceed 2.93

N/mm2. The differences between the values of models CP-2 and CP-4 are also not statistically significant.

Compared to the values of compressive strength parallel to the face in models CP-1, CP-2, and CP-3, the highest value of this property obtained in model CP-2 is 12.3%, 14.7%, and 9.9%, respectively.

Regarding the compressive strength perpendicular to the face grain, the analysis of the variance (ANOVA: $F (4, 20) = 13.886$; $p << 0,001$) and post-hoc Tukey's test showed that there are statistically significant differences between the value of the control model and the values of all reinforced models. The differences within the reinforced models are not statistically significant, which shows that the position of the cotton prepreg reinforcement does not have a significant impact on the values of compressive strength perpendicular to the face grain of the panel.

Compared to the highest obtained value in model CP-2, the values of models CP-1, CP-3, and CP-4 are lower by 5.8 %, 10.1 %, and 1.5 %, respectively.

The analysis of the obtained results for compressive strength at the angle of 22.5° to the face grain showed that the position of the multilayer reinforcements in the plywood structure (models CP-1, CP-2, and CP-3) has a significant impact on the values of compressive strength in this direction of the panel (ANOVA: $F (4, 20) = 110.57$; $p << 0,001$). The lowest value is achieved when the reinforcements are positioned as surface layers of plywood. The values between models CP-4 and CP-1, as well as between CP-4 and CP-2, are not statistically significant. The values of all reinforced models statistically differ from the value of the control model without reinforcements.

Results from the tests of compressive strength at an angle of 45° to the face grain of plywood also showed that all reinforced models have higher values of this property compared to the control model C. The differences in the values of all reinforced models and the control model are statistically significant (ANOVA: $F (4, 20) = 45.118$; $p << 0,001$). Within the reinforced models, the highest value achieved in model CP-2 is 9.8 %, 14.8 %, and 4.6 % higher when compared to models CP-1, CP-3, and CP-4, respectively.

At an angle of 67.5° to the face grain of plywood, the mean values of models CP-1, CP-3, and CP-4 are lower by 8.1 %, 13.5 %, and 5 %, respectively, compared to the highest obtained value in model CP-2. The analysis of the variance (ANOVA: $F (4, 20) = 262.863$; $p << 0,001$) and post hoc test showed that the values of all reinforced models statistically differ from the value of the control model. Within the reinforced models, the value of model CP-2 statistically differs from the values of the other three models.

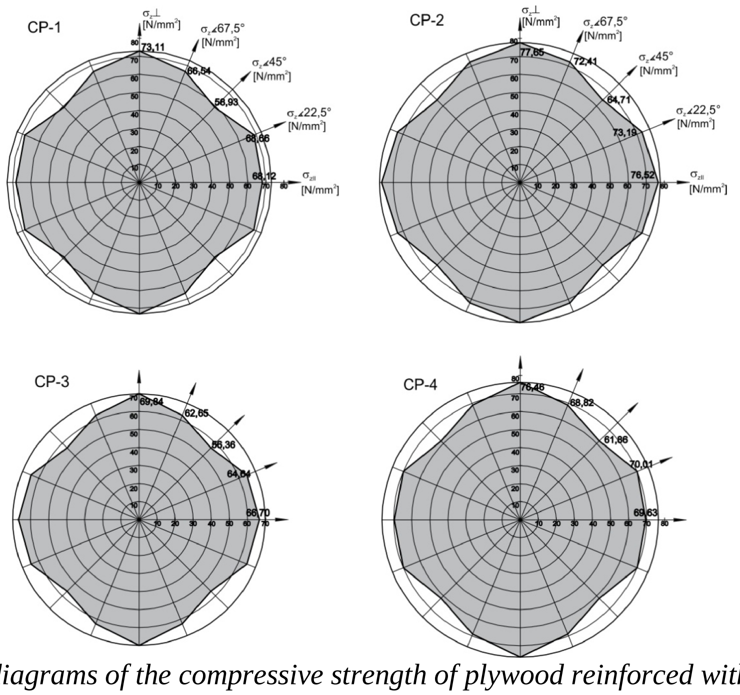

Figure 2: *Polar diagrams of the compressive strength of plywood reinforced with cotton prepregs*

In all reinforced plywood models, the highest value of compressive strength is achieved in a direction perpendicular to the face grain, while the lowest value is achieved at an angle of 45° to the face grain of plywood. The biggest difference between the values of compressive strength parallel and perpendicular to the face grain is achieved in model CP-4 ($\sigma_c\perp > \sigma_c\|$ for 9.8 %). In other models, the difference between these values is smaller, i.e., in models CP-1, CP-2, and CP-3, the mean value of compressive strength perpendicular to the face grain is higher compared to the mean value of compressive strength parallel to the face grain for 7.3 %, 1.5 %, and 4.7 %, respectively.

The mean value of compressive strength at the angle of 45° to the face grain is lower compared to the value of compressive strength perpendicular to the face grain of plywood for 19.4 % in model CP-1, 16.7 % in model CP-2, 19.3 % in model CP-3, and 19.1 % in model CP-4.

The values of compressive strength at the angles of 22.5° and 67.5° are similar to each other, where the value of compressive strength at the angle of 22.5° is higher compared to the values of compressive strength at the angle of 67.5° for 3.2 % in model CP-1, 1 % in model CP-2, 3.2 % in model CP-3, and 1.7 % in model CP-4.

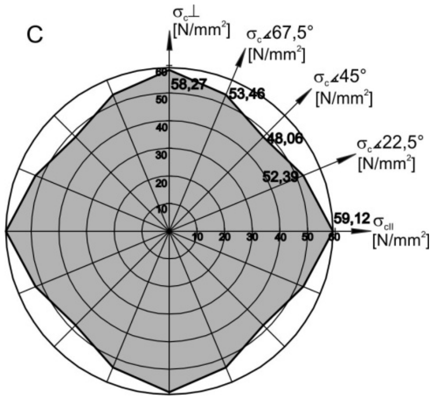

Figure 3: *Polar diagram of the compressive strength of the control model of plywood without reinforcements*

In the control model of plywood without reinforcements, the difference between the values of compressive strength parallel and perpendicular to the face grain is very small, and it is 1.5 % ($\sigma_c\| > \sigma_c\perp$). Compared to the mean value of compressive strength parallel to the face grain, the values of this property at the angles of 22.5°, 45°, and 67.5° are lower by 11.4 %, 18.7 %, and 9.6 %, respectively.

On Figures 4 and 5, the stress-strain diagrams during testing compressive strength for model CP-2 and the control model C are presented. The stress-strain diagrams for other reinforced models are similar to those for model CP-2.

The analysis of the stress-strain diagrams of experimental plywood models showed that the failure of the material happens after pronounced plastic deformations.

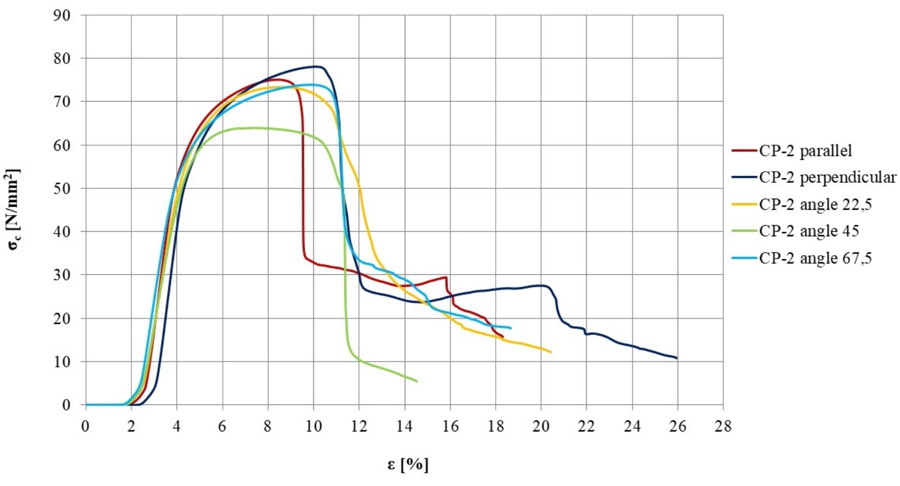

Figure 4: *Stress-strain diagram during testing the compressive strength of model CP-2*

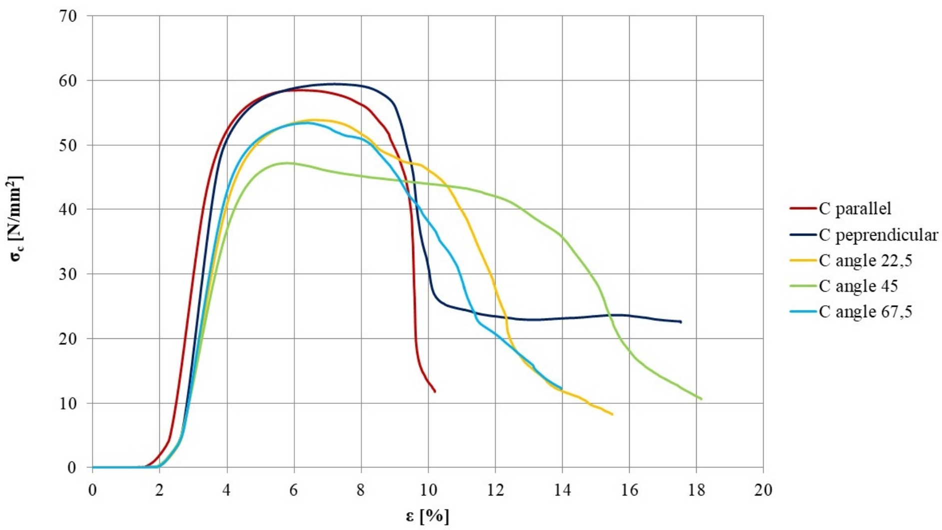

Figure 5: *Stress-strain diagram during testing the compressive strength of the control model C*

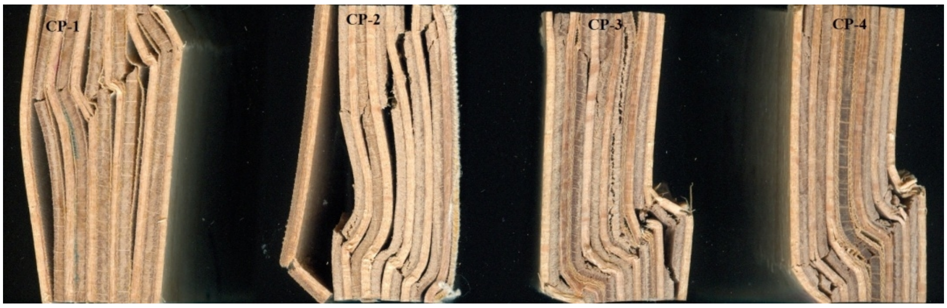

Figure 6: *Failure mode of the test specimens of reinforced models during testing the compressive strength parallel to the face grain*

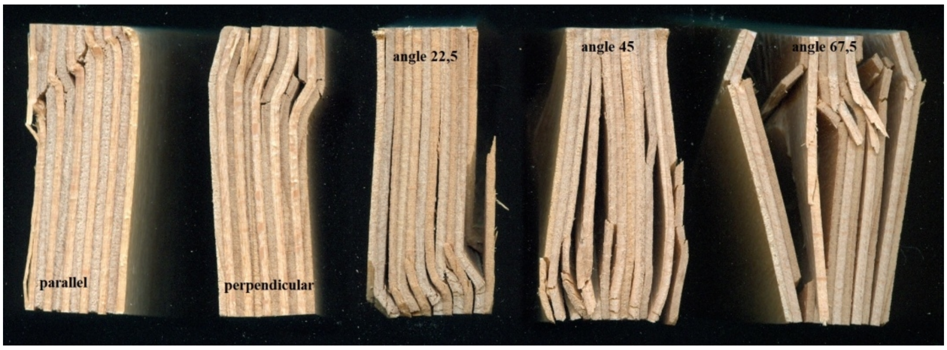

Figure 7: *Failure mode of the test specimens of the control model during testing the compressive strength*

All experimental plywood models in all tested directions exceed the minimal value of compressive strength defined in the national standard MKC D.C5.043 for load-bearing panels for use in construction.

4. CONCLUSIONS

The application of cotton prepreg in the structure of plywood significantly increases its compressive strength in all tested directions.

Application of cotton prepreg sheets as reinforcement of plywood structure leads to an increase in compressive strength of up to 29 % in the direction parallel to the face grain, up to 33 % perpendicular to the face grain, up to 40 % at the angle of 22.5° to the face grain, and up to 35 % at the angle of 45° and 67.5° to the face grain.

Different positioning of the cotton prepreg reinforcements in the plywood structure has an impact on the plywood compressive strength in all panel directions.

Regarding the reinforcement position, the best results are achieved with the application of multilayered cotton prepreg inserted in the third and eighth adhesive layers of plywood (model CP-2). Moving the reinforcement layers to the surface of the plywood decreases its compressive strength.

REFERENCES

[1] Biblis, E.J.; Carino, H.F., 2000: Flexural properties of southern pine plywood overlaid with fiberglass-reinforced plastic. Forest Prod J., 50 (1): 34-36.

[2] Brezović, M.; Jambreković, V.; Pervan, S., 2003: Bending properties of carbon fiber reinforced plywood. Wood Research, 48 (4): 13-24.

[3] Brezović, M.; Kljak, J.; Pervan, S.; Antonović, A., 2010: Utjecaj kuta orientacije sintetskih vlakana na savojna svojstva kompozitne furnirske ploče. Drvna ind., 61 (4): 239-243.

[4] Choi, S.W.; Rho, W.J.; Son, K.J.; Lee, W.I., 2011: Analysis of buckling load of fiber-reinforced plywood plates for NO 96 CCS. Proceedings of the Twenty-first International Offshore and Polar Engineering Conference, 2011, Maui, Hawaii, USA, pp: 79-83.

[5] Hardeo, P.; Karunasena, W., 2003: Buckling of fiber-reinforced plywood plates. Proceedings of Second International Conference on Structural Stability and Dynamics, 2002, Singapore, pp. 442-447. https://doi.org/10.1142/9789812776228_0062.

[6] Hrázský, J.; Král, P., 2007: A Contribution to the properties of combined plywood materials. J For Sci, 53 (10): 483-490. https://doi.org/10.17221/2087-jfs.

[7] Jakimovska Popovska, V., Iliev, B. 2019: Bending properties of reinforced plywood with fiberglass Pre-Impregnated Fabrics, Proceedings of 30th International Conference on Wood Science and Technology-ICWST and 70th anniversary of Drvna industrija Journal "Implementation of wood science in woodworking sector", 12th -13th December, Zagreb, 2019: 77-85.

[8] Jakimovska Popovska, V., Iliev, B. 2021. Janka hardness of plywood reinforced with pre-impregnated cotton fabrics, Proceedings of the 5th International conference „Wood technology and product design", 14-17th September, Ohrid, 2021: 7-14.

[9] Kohl, D.; Million, M.; Böhm, S., 2013: Adhesive bonded wood-textile-compounds as potentially new eco-friendly and sustainable high-tech materials. Proceedings of the Annual Meeting of the Adhesion Society 2013, Florida, USA, pp: 27-29.

[10] Maniņš, M.; Zīke, S., 2011: Textile fabrics reinforced plywood with enhanced mechanical properties. Abstracts of the International Scientific Conference „Civil Engineering'11", 2011, Latvia, pp: 35.

[11] Macedonian standards.

[12] Rowlands, R.E.; Van Deweghe, R.P.; Launferbeg, T.L.; Krueger, G.P., 1986: Fiber-reinforced wood composites. Wood and Fiber Science, 18 (1): 39-57.

[13] Xu, H.; Tanaka, C.; Nakao, T.; Nisano Y.; Katayama, H., 1996: Flexural and shear properties of fiber reinforced plywood. Mokuzai Gakkaishi, 42: 376-382.

[14] Xu, H., Nakao, T., Tanaka, C., Yoshinobu, M., Katayama, H., 1998: Effects of fiber length orientation on elasticity of fiber-reinforced plywood. Journal of Wood Science, (44): 343-347.https://doi.org/10.1007/bf01130445

[15] Zīke S.; Kalniņš K., 2011: Enhanced impact properties of plywood. Proceedings of the 3rd International Conference Civil Engineering'11, 2011, Latvia, pp: 125-130.