Glued Joint Behavior of Ribs for Wood-Based Composite Plates

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Abstract This article presents experimental investigations of composite sandwich plywood plates with cell type core and their connections between skin layers of birch plywood and a core of straight and curved plywood honeycomb-type ribs. This shape of core ribs provides several improvements for these plates in the manufacturing process as well as improves the mechanical properties of plywood plates. This specific form of ribs allows simplifying the manufacturing of these plates although it should be detailed and improved. The most typical cases (series of specimens) were compared to the results obtained from FEM (ANSYS) simulations. All thicknesses of elements are chosen according to plywood supplier assortment. Standard birch plywood (Riga Ply) plates were used - three layer plywood was chosen for skin elements (Surfaces) and three or five layer plywood was chosen for edge elements. Different bond pressures were taken to compare their influence on joint strength and stiffness.

1. Introduction

The consumption of composite materials has increased over the last few decades [1]. But on the other hand, it would be important to use wood based materials as much as possible and economically viable, as it would satisfy the increased demand for high performance materials.

Wood based panels as well as other wood based structural elements become more significant in construction. Plywood is one of the most common wood based secondary (transformed) materials and its consumption (and production) has been increasing over the past decades, especially in Asia [2], [3]. These plates could be used in civil engineering as covering plates, as separating elements or some furniture elements where they are subjected to bending.

To investigate the plate's stiffness normal stress σ occurs in the structure and is determinant for bending stiffness, but since the height of the plate increases and the material in the middle layer of the plate is reduced, shear stresses τ and the influence of shear deformation increases. The material in the

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middle layer (plate's core) is reduced but it should take mainly the shear stresses becoming the weakest point since the height of the plate increases. The influence of shear strength increases becoming more important in determining strength and stiffness of the plate. As a result, the joint strength between the skins and the core becomes even more important. Therefore, the properties of glued joint (both strength and stiffness) should be investigated.

For economically grounded design it is important to choose the skin layer, core layer and bond material with defined properties to provide the most use of their properties to ensure efficient use. It is advisable to provide that the material breaks in the wood section not at the glued joint in a way that the performance of the skin material is at its maximum.

In literature, the recommended bond pressure for wood materials and sandwich constructions is 3.5 – 10.5 kg/cm^2 (50 – 150 psi) [4] to provide the optimal bond strength and stiffness.

2. Methodology and scope
Serviceability limit state for these composite sandwich plates with the cell type core is mostly determined in the same way as for most standard sandwich plates. Although when the height of the plate increases, the influence of a joint between the skins and the core increases and becomes determinant. In this paper, the joints between the surfaces of the skins and the edges of ribs were analyzed.

2.1. Bending tests
EN 789 [5] is most widely used standard for determination of properties of wood based panels. Standard sets out the guidelines for choosing the dimensions and measurement requirements for determination of properties.

For the case study, the plate with dimensions of 1.2 m (1.1 m span) in longitudinal direction and 0.3 m width was chosen. It has been proved that dimensions and other geometrical parameters have an influence on plate's stiffness and specific stiffness [6]. The plate was loaded with uniformly distributed load with intensity of 1 kN/m^2.

2.1.1. ANSYS Simulations.
The ANSYS finite element model was chosen for calculation of these plates. For numerical simulation of the bending tests, a FEM commercial code ANSYS v.15 (2014) was applied. A parametrical model of the panel was created with variable cross section parameters and bending loading set up options (according to Eurocode 5). The finite element mesh size was chosen 1/5 of the panel height. All plates (upper, lower and waved core plates) were defined by using ANSYS 4-node shell element SHELL 181.

In each step, there was a new numerical model made and calculated and the height of the plate in the first step span was changed; the same was done for different span length.

2.2. Shear tests
Shear properties should be determined for these plates as the decreased strength and stiffness of the core part. Stronger skin materials can resists larger loads than their design load, but the weakest point could be the bond between skins and the core materials. So the shear strength becomes determinant in ribbed sandwich plates, especially at the bond between the ribs and skin layer of the plywood.

2.2.1. Shear test standards.
Several shear standards exist to determine the shear properties of composite sandwiches and glued joints [7, 8, 9, 10, 11, and 12]. Single lap joint is mostly used for determination of glued joint shear properties, although some problems remain like eccentricities or complicated joints when designing a joint with cut-ins. In this case, the double lap joint was chosen ASTM D3528-96 [13] that provides two possibilities of double lap glued joint to be used on tension machines with grips for shear tests.

2.2.2. Specimen for shear test.
The provided methods of testing shear properties in standard tests mostly consider just glued overlap bond between two surfaces, but there is poor information on edge-to-surface joints.

For determination of shear strength, extra type of specimens with double overlap was chosen. The lap joint consists of surface elements 4x25x55 and edge elements 4(6,5)x25x75 with overlap 25mm on both sides and a gap 5 mm between edge elements (figure 1).
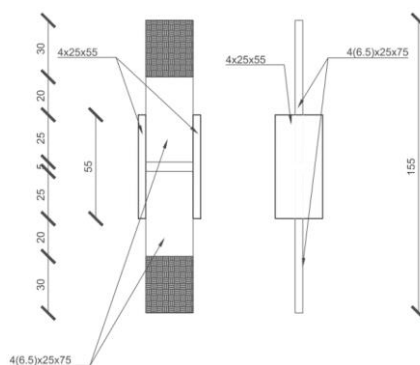

Figure 1. Shear specimen with dimensions.

All parts of specimen were formed with circular saws and taken direct without any additional processing and glued in conditions of relative moisture 6-8%.

Sample size could be calculated from the given formulas in ASTM E122-00 [14]

$$n = (3\,V_0/e)^2 \qquad\qquad (1)$$

Number 3 is the recommended value for determination of some value, but it could be reduced when the precision requirements of the samples are reduced. As a result, value 3 is decreased to 1.96 and coefficient of variation is expected around 7% and the value e is assumed as 5%. So the sample size in this case is determined with the previously given formula (1) and the calculated value of 7.5 and assumed as 7 specimens in one sample.

A total of 63 glued plywood double lap shear glued connections were tested using shear standard tension test method. The specimens are labeled with PW-symbol-number. PW stands for Plywood Joint, the second symbol means the orientation of edge plywood elements and the number means the thickness of edge plywood elements. Orientation of outer layer fibers of skin parts are in the same direction as the applied tension load but for the edge elements labeled as (II) for outer layer fibers – in the same direction and ($\perp$) for transversal direction to the applied tension load.

In ANSYS Simulations for shear, the properties and element types were chosen the same as for bending simulations.

2.3. DIC method

Digital Image Correlation method was investigated for several specimens from each sample series. The method based on fixing pixel positions and analyzing their position in loading process strain can be determined by applying a correlation algorithm [15]. In this experiment, strain was measured in the middle of the specimen and close to the glued joint to determine the difference in particular points or eccentricity of the joint.

2.4. Material properties

In this study, the analyzed plywood was designed from standard birch values [16] assumed as one ply properties and applied to each layer of plywood composite element.

Polyvinyl acetate glue PVA D3 [17] was chosen for all glued joint parts. This type of glue provides water resistant joints according to EN 204 [18]. This type of glue is used for gluing of wooden joints in structural as well as carpenter works. It is suitable for hot press and high frequency drying applications in that way increasing the efficiency of the manufacturing process. In this experiment, only the edge part was covered with glue and then the surface part was placed on this glue covered edge and after that pressed with various pressures as defined in this research. The processing temperature was 20ºC as recommended. As the hardening of the glue is dependent on the temperature, material, porosity and humidity, since the hot press was not used, the recommended hardening and pressure were bonded for at least 24 h.

3. Bending tests

Normal stresses in plate skins (figure 2) and shear stresses in the joint at the ribs (figure 3) and deformations [6] [19] were analyzed for plates with cell type hollow ribs. The results of serviceability limit state (SLS) show that for plates up to 1/25 from plates' height the plate's skin is the most loaded.
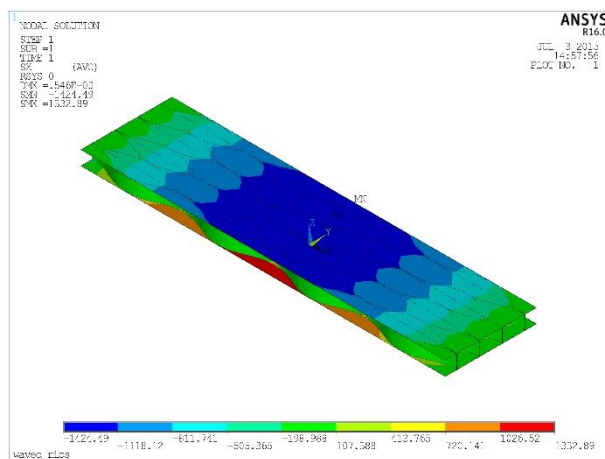

Figure 2. Normal stresses with maximum in plate skins for the plate with the cell type hollow core.
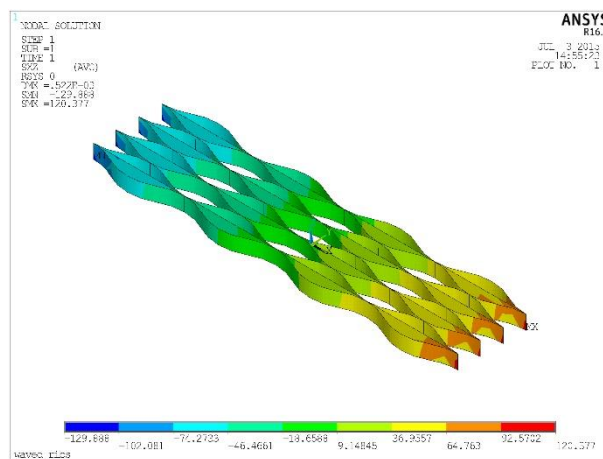
Figure 3. Shear stresses in plate's ribs for the plate with the cell type hollow core.

By increasing plate's height to span ratio up to 1/5, the ultimate limit state for plates skins are reached before the SLS (figure 4). The glue layer of plate skin-to-core still has a reserve of about 200%. But if thicker or other material plate skins were taken, this joint could become the weakest point.
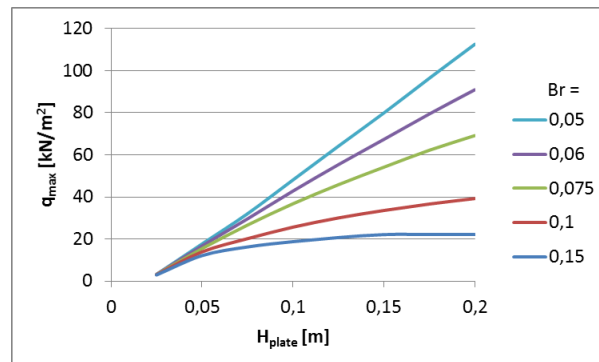
Figure 4. Maximal load for various heights of plate H_{plate} and widths of rib B_r.

4. Shear tests

4.1. Shear strength
The shear test specimen chosen in chapter 2.2 was simulated with ANSYS software code with the real dimensions of specimens for comparison of deformations and ultimate load.

4.1.1. FEM results.
As the linear properties of materials were assumed, ANSYS model was used for determination of shear stresses and it showed that shear stresses in the edge elements were distributed eccentrically (at the edge part that is closer to the center of the surface part they are the smallest (near to 0) but at the edge of the surface element they are the largest and for 1 kN tension load they are 4.0 N/mm^2 (figure 5), although for normal stresses, respectively, for 1 kN are 1.81 N/mm^2 and 18.81 N/mm^2 (figure 6) so in this case the difference is almost 10 fold.
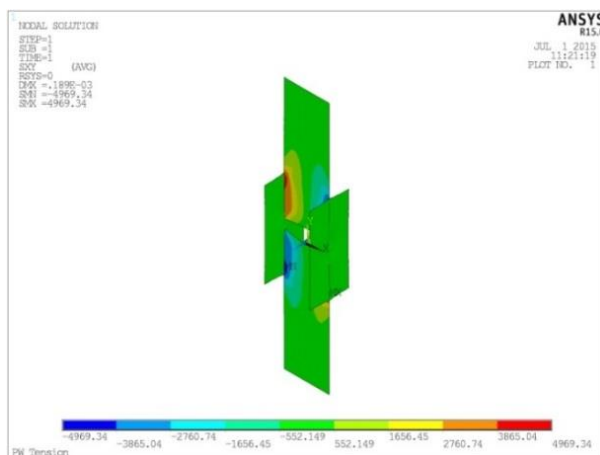

Figure 5. Non-uniform distribution of shear stresses along the joint.
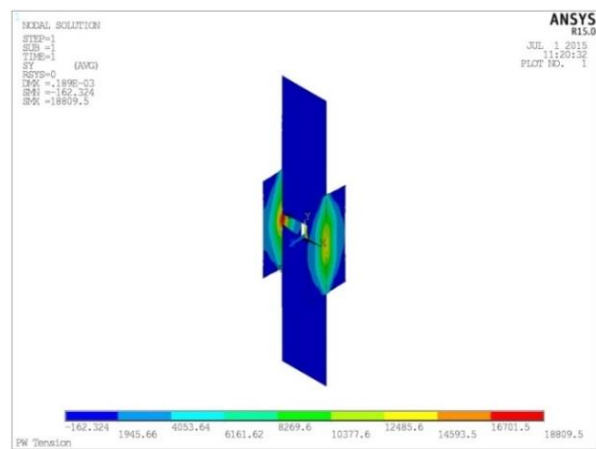

Figure 6. Non-uniform distribution of normal stresses along the joint.

4.1.2. Experimental investigations.
The samples previously calculated and analyzed with ANSYS were tested. As mentioned above, nine samples were made with different bond pressure, edge plywood orientation and thickness. The specimens and test equipment are shown in figure 7.

Figure 7. Specimen placed in the testing machine (Instron 3000).

In figure 8; figure 10; figure 12 the ultimate load for different level of bond pressure was achieved. The load-deformation plots for all specimens of the samples with most common bond pressure 0.5 N/mm^2 are shown in figure 9; figure 11; figure 13.
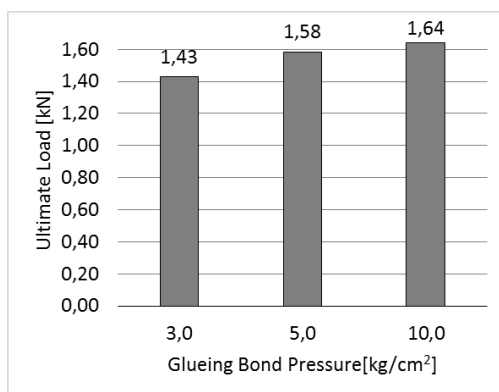

Figure 8. Ultimate load for different level of pressure with outer layer fibers of the middle layer (4.0 mm) in longitudinal direction.
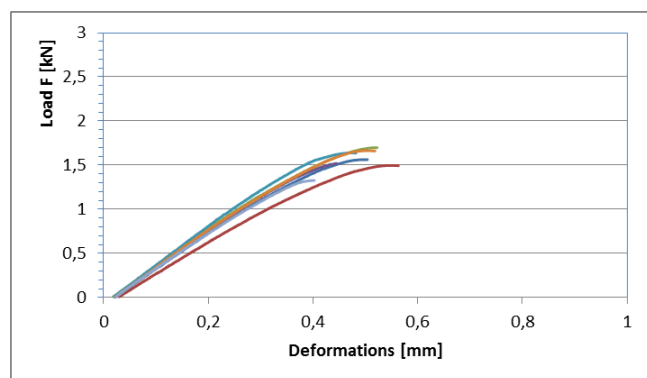
Figure 9. Load-deformation plot for specimens with bond pressure 5.0 kg/cm^2 and outer layer fibers of the middle layer (4.0 mm) in longitudinal direction.
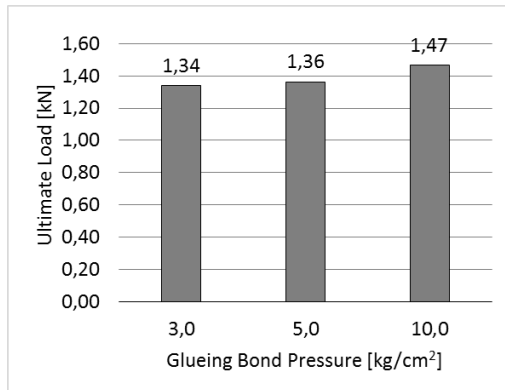
Figure 10. Ultimate load for different level of pressure with outer layer fibers of the middle layer (4.0 mm) in transversal direction.
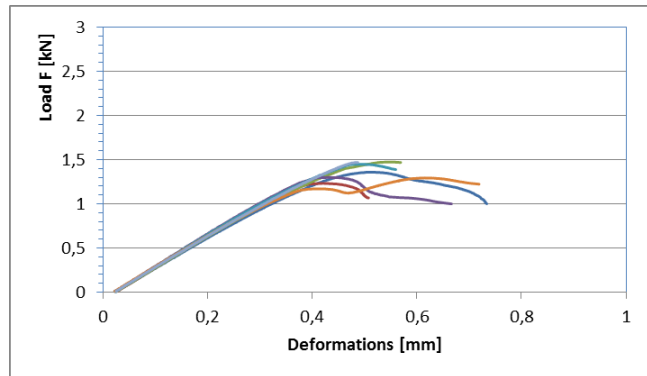

Figure 11. Load-deformation plot for specimens with bond pressure 5.0 kg/cm² and outer layer fibers of the middle layer (4.0 mm) in transversal direction.
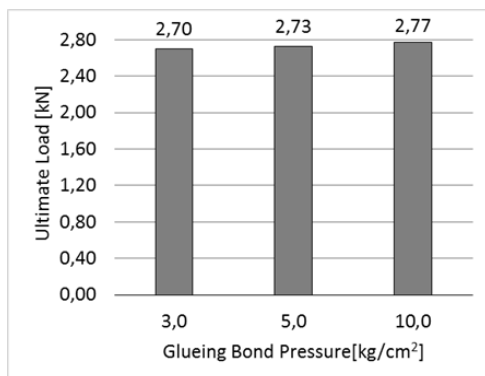

Figure 12. Ultimate load for different level of pressure with outer layer fibers of the middle layer (6.5 mm) in longitudinal direction.
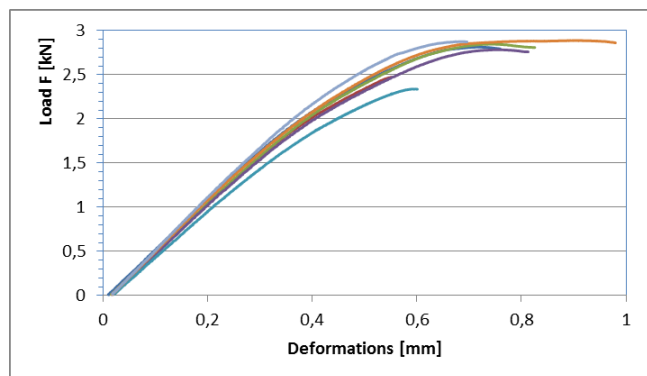

Figure 13. Load-deformation plot for specimens with bond pressure 5.0 kg/cm² and outer layer fibers of the middle layer (6.5 mm) in longitudinal direction.
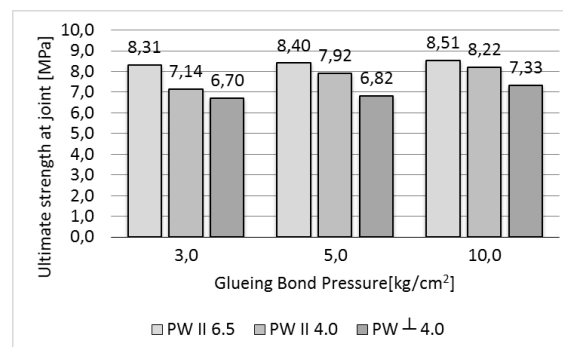

Figure 14. Ultimate strengths for different levels of pressure for all samples.

The main dimensions of specimens were shown in figure 1. Detailed specifications of the tested specimens are summarized in table 1. Results show that by increasing bond pressure from 0.3 N/mm^2 to 0.5 N/mm^2 the ultimate strength increases by 11% and 1% for five layer plywood with outer ply fibers oriented in longitudinal direction and by 2% for three layer plywood when outer ply fibers oriented in transversal direction to skin ply and added tension load direction. But when the bond pressure is increased to 1.0 N/mm^2 the ultimate strength increases respectively by 15%; 2% and 9%. To summarize these results, it could be concluded that the ultimate strength is dependent on the layer count in transversal direction of the bonded surface. It means when the more layers are oriented in transversal direction, the increase in bond pressure is required to achieve tighter connection. The bond pressure is dependent on the layers in transversal direction to surface. For three layer plywood connection and five layer plywood connection with outer ply fibers directed in longitudinal direction it is advisable to increase bond pressure from 0.3 to 0.5 N/mm^2, but further increase of bond pressure is not necessary. Although for plywood with outer ply fibers in transversal direction to skin ply it is recommended to increase bond pressure to 1.0 N/mm^2. Apparently, for 5 layer plywood this difference is not as large as it was for 3 layer plywood as the ratio between parallel and transversal layers smoothens.

Table 1. Comparison of pressure provided at the joint (comparison of bond pressure).

	Length of a glued joint mm	Thickness of a PW T mm	Pressure at joint kg/cm^2	Ultimate strength N/mm^2	F_{max} kN	$F_{max}/F_{max,teor}$	$F_{max}/F_{max3.0}$	Standard Deviation	Coeff. of var.	Range
PW II 4.0	25	4.0	3.0	7.14	1.43	-11%		0.17	12.12	0.54
PW II 4.0	25	4.0	5.0	7.92	1.58	-1%	11%	0.13	8.14	0.20
PW II 4.0	25	4.0	10.0	8.22	1.64	3%	15%	0.11	6.45	0.26
PW II 6.5	25	6.5	3.0	8.31	2.70	4%		0.10	3.67	0.24
PW II 6.5	25	6.5	5.0	8.40	2.73	5%	1%	0.16	5.59	0.42
PW II 6.5	25	6.5	10.0	8.51	2.77	6%	2%	0.14	5.19	0.20
PW ⊥ 4.0	25	4.0	3.0	6.70	1.34	-16%		0.21	15.26	0.49
PW ⊥ 4.0	25	4.0	5.0	6.82	1.36	-15%	2%	0.10	7.08	0.24
PW ⊥ 4.0	25	4.0	10.0	7.33	1.47	-8%	9%	0.17	11.03	0.44

The average strength was 7.76 N/mm^2 for PW II 4.0; 8.41 N/mm^2 for PW II 6.5 and 6.95 N/mm^2 for PW ⊥ 4.0. As it is seen, the average values are very similar to the values that were achieved with bond pressure 0.5 N/mm^2.

For most of the specimens the failure was in the plywood material. Delamination of the outer layer of skin plywood or of the longitudinal fibers of edge plywood was accompanied with glue abruption in transversal layer fibers was more common for lower pressure (0.3 N/mm^2) specimen (figure 15) it can be concluded that there is no need to change the glue for these applications because the strength of the glue is sufficient.

Figure 15. Different cases of failure mode.

4.2. Shear stiffness

Shear strength and stiffness at glued joints between core ribs forming plywood and skin forming plywood have been determined. As previously mentioned, this is the connection.

4.2.1. FEM results.

The plot of deformations in tension is shown in figure 16. The results show that deformations in the middle part are by 24% larger than they are in the parts close to the joint.
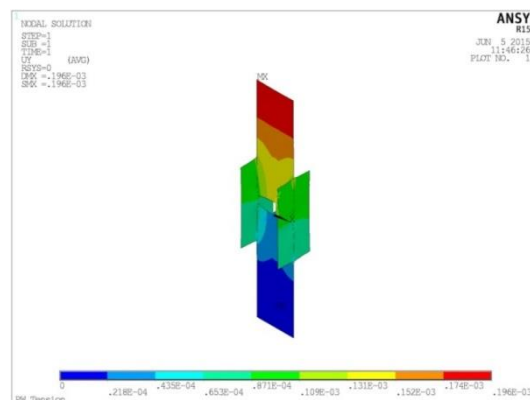

Figure 16. Shear specimen with dimensions.

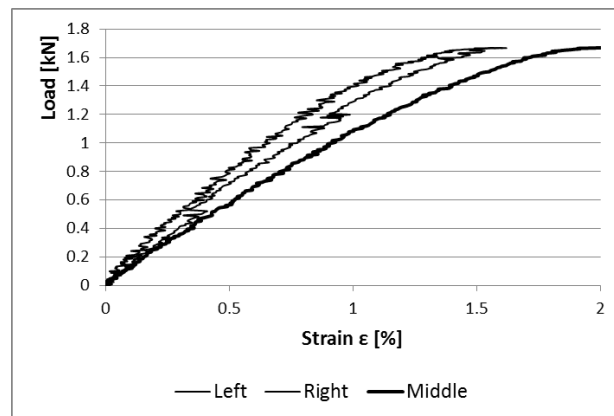*4.2.2. Experimental investigations.*

Shear stiffness was calculated from the measured load and deformations. For different bond pressure, the stiffness of the joint remains in 5 % level independent of bond pressure (table 2). The coefficient of variation is under 10% showing that these results are feasible to assume properties in modeling and determination of joints in design of composite ribbed cell type plates. The average stiffness is equal to 4.24 N/mm^2 for *PW II 4.0*; 3.25 N/mm^2 for *PW II 6.5* and 3.59 N/mm^2 for *PW $\perp$ 4.0*. In this case the stiffness properties are similar to strength properties, the average values are very similar to the values that were achieved with bond pressure 0.5 N/mm^2.

Table 2. Stiffness comparison of pressure provided at the joint.

	Pressure at joint kg/cm^2	Joint stiffness N/mm^2	Comparison to 0.3 N/mm^2	Standard Deviation	Coefficient of variation	Range	Average N/mm^2	Comparison to average
PW II 4.0	3,0	4.15		0.21	5.07	0.34		-2%
PW II 4.0	5,0	4.19	1%	0.25	5.91	0.76	4.24	-1%
PW II 4.0	10,0	4.38	6%	0.12	2.66	0.30		3%
PW II 6.5	3,0	3.15		0.09	2.62	0.26		-3%
PW II 6.5	5,0	3.28	4%	0.14	3.96	0.35	3.25	1%
PW II 6.5	10,0	3.32	5%	0.17	5.30	0.55		2%
PW ⊥ 4.0	3,0	3.53		0.13	3.72	0.36		-2%
PW ⊥ 4.0	5,0	3.60	2%	0.07	1.92	0.19	3.59	0%
PW ⊥ 4.0	10,0	3.65	3%	0.14	3.73	0.34		2%

4.2.3. DIC results.
Digital Image Correlation (DIC) tests were done for several experiment specimens to calibrate the load measurement and determine the deformation (and stress) distribution along the joint and its elements. It has been noticed that the strain in the middle part is by 24% on average (20-30%) larger than the strain in the parts close to joint. For one specimen of sample PWII4.0 0.5N/mm2 is shown in figure 17.

Figure 17. Deformations in the middle part of the joint and exactly at joint comparison.

5. Conclusions
In cases when more layers are oriented in transversal direction to longitudinal direction than other layers of the plywood surface that is glued, it is useful to increase the bond pressure comparing to traditionally used 5 kg/cm^2 (70 psi), although when more layers are oriented in longitudinal direction then it is practical enough to apply 5 kg/cm^2.

The obtained results from experimental investigations show that the achieved results for lower bond pressure less than (5 kg/cm^2) show approximately similar mean values of ultimate strength, although the dispersion of characteristic values increases.

6. References

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