International Journal of New Technology and Research (IJNTR)
ISSN:2454-4116, Volume-4, Issue-6, June 2018 Pages 16-20

Optimization of Welding Frictional Parameters by Inserting the Dowels of Beech in Douglas-Fir Wood Substrate

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***Abstract*— The wood welding technique has been developed as a new technique for joining wooden parts without the use of adhesives, and with the help of heat developing due to friction and pressure on the joint. The friction may be realized by vibration or rotation. Wood welding is a process in which chemical-physical reactions occur. During the welding process, the surface layers in the wood elements (lignin) were broken into mutual contact, which was initiated because of the influence of pressure and heat which is most often achieved under the influence of the friction of the elements we are interfering with. The paper presents the results of our own exploration of the impact of the penetration of the beech dowels into the substrate of Douglas/fir on the basis of pulling force. Within the experimental investigation we have observed differences between the direction of penetration of the dowel in the hole with (and without) changing the profile of the pre-drilled hole for insertion and the impact of the bond withdrawal strength in relation to the angle between axes of penetration and the line of tree rings.**

***Index Terms*— wood welding, rotational welding, joint strength, wooden assemblage, Douglas-fir wood weld.**

I. Introduction

Even today, wood as a material with low impact on ecology and its high mechanical properties makes it an alternative to polymer or metal materials. As such, wood plays a major role in the design of furniture, joinery and various applications in construction structures.

One of the most widely used woodworking technologies is the wood joining technology. This technology is applied in order to assembly several wood pieces, to increase the size and to adjust the shape of the workpiece etc. For joining wooden elements in the wood industry, adhesive technology is most commonly used. The same application of the adhesive must be carried out carefully both in the adhesive application stage and in the drying process, which requires time and space. Also, industrial adhesives are often based on by-products from the petroleum industry and as such have a negative impact on the life of wood products and have a negative impact on the environment.

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Welding technology involves the coupling of two or more, odd or varied materials, by melting or pressing, with or without the addition of an additional material, in order to obtain a homogeneous welded joint. Welding technology is widespread in the mechanical engineering and construction industry, while wood welding technology is relatively young and is still in the process of technological upgrading. These bonding processes are fast and have high resistance, and their great advantage lies in the fact that the process itself is taking place very quickly and is a process that does not require the use of additional material for joining (mechanical elements or synthetic adhesives)[1]- [2].

The aim of this research is to prove the technological and environmental justification of the use of rotary welding technology for wooden joints for the purpose of joining the wood and to determine the need to replace the use of adhesive based on polyvinyl acetate adhesives that are harmful to health and the environment. In this research we use Douglas-fir wood as a substrate and inserting dowels of beech. The different models are studied treating especially the content of moisture and grain orientation of wood. For this reasons the pulling force and withdrawal strength are measured aiming to explain the phenomena of wood welding.

II. The Principle of Wood Welding Technology

The welded wooden joint is very similar to the glued joint in which the adhesive function is used by thermoplastic materials. Such a compound is realized as a result of the formation of a mixture of melted wood fibers during the thermo mechanical effect produced under the friction effect and which is then stimulated in the pressure-retaining phase. The linkage is mechanical, where fixing with wood improves as a union of thermoplastic mass in porous wood cells, thereby increasing the adhesion surface and creating a kind of interwoven mesh.

Previous research and development of wood welding technology has been conducted through consideration of mechanically induced friction generated by vibration (vibration welding) [3].

III. Rotary Welding

The method of rotating welding of wood is characterized by the insertion of wooden dowels into the wooden substrate, for the purpose of joining two or more elements [4]-[5]. This method is a somewhat simpler way of joining two or more massive wood or slab elements as opposed to vibration welding. It is accomplished drilling the hole through the elements with slightly smaller diameter than the diameter of the dowel, and with the aid of a torque, it is pressed by a wooden dowel, while the elements that are welded together are tightly joined.

The increase in temperature causes partial decomposition and separation of wood cells, wood fibers, and the formation of fibers interwoven in a matrix of molten material which is then stoned. Thus, the wood fiber fibers are intertwined and with the molten lignin form a new structure. Due to the cooling of the hardening wood structure, a solid joint (disturbance) occurs.

It has been demonstrated that the process of mechanically induced wood welding is mainly due to the softening and melting of intercellular amorphous materials, coupled with the linkage of polymeric material from the wood structure, mainly lignin and some hemicelluloses [6]. This causes the partial separation of longer cellular wood and the formation of the interwoven network, forming a matrix of molten material, which is then edited.

Regardless of vibration or rotary welding, the process results in an increase in the volume density in the narrow zone of the weld line, approximately 0.6 mm in the line of disturbances, and in the narrow zone along the line of weld. By spectral analysis by X-ray microdensitometry, a transition between wood and molten material to the friction line can be observed.

Based on previous research, optimal welding parameters were adopted for the experiment: Tightness 2 mm for dowels having diameter 10 mm [3], the welding time is 3 to 4 seconds [1], [7] frequency, in the range of previous researches, which is conditioned by the parameters of drilling and pressure welding within 1.3 MPa [8].

IV. Experimental Study

Specimens have been made joining two elements of Douglas-fir wood, having dimensions 200x35x21 mm, with four rotationally welded beech dowels. Cylindrical beech dowels are commercially procured, having following features; material beech class 1, diameter 10 mm, length 100 mm, grain direction parallel to the length. Cylindrical beech dowels are commercially procured, having following features; material beech class 1, diameter 10 mm, length 100 mm, grain direction parallel to the length.

To test the strength of the weld, three models of test samples are made:

1) Model M1, having pre-drilled holes with a diameter of 8 mm and injecting dowels only from one side (Fig. 1)
2) Model M2, having pre-drilled holes with a diameter of 8 mm on the first transmission element and 6.7 mm at the second coupling means, with one-sided embossing of the dowel(Fig. 2),
3) Model M3, having pre-drilled holes with a diameter of 8 mm and with two-sided embossing of the dowel, two on each side of the sample (alternately) (Fig. 3).

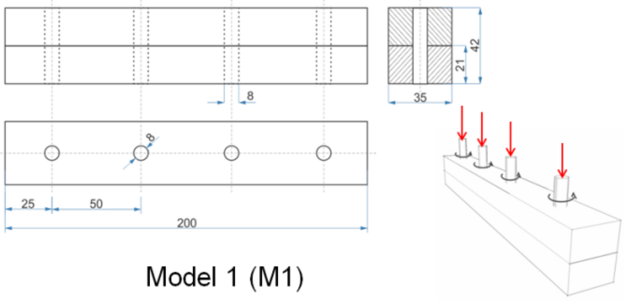


Fig. 1 Model M1

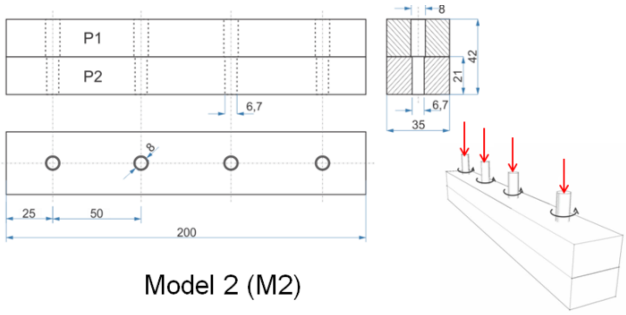


Fig. 2 Model M2

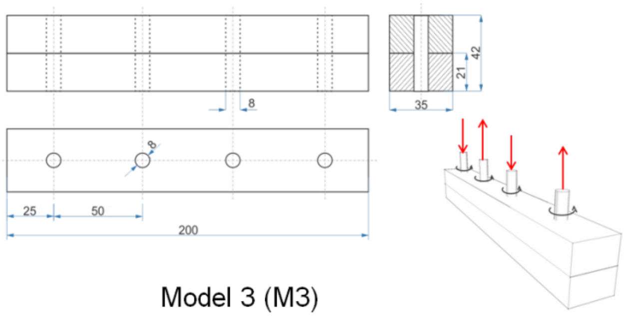


Fig. 3 Model M3

For model fixture in the receiving head according to EN 319:1996, it was necessary to develop special metal plates to replace the test blocks. Special backing head was designed and manufactured to place the test specimens in the receiving head Fig. 4 and Fig. 5.

Fig. 4 Receiving head -picture

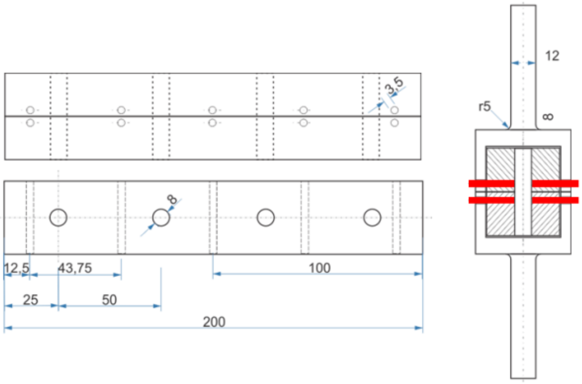


Fig. 5 Receiving head - asseblage

V. Statistical analysis of the results of withdrawal strength-Normality test of data distribution

As a first and basic step of any statistical data processing, it was carried out to check whether the distribution of the results obtained in the experimental section corresponds to the normal distribution.

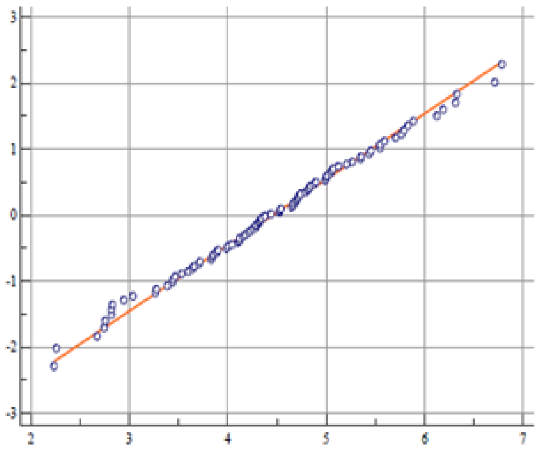


Fig. 6 Normal-plot diagrams for the results of withdrawal strength

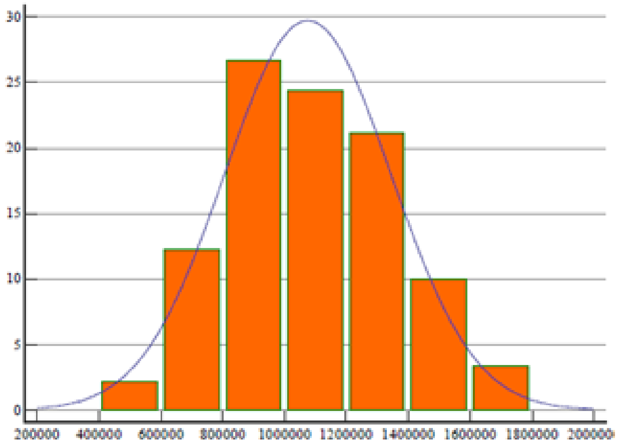


Fig. 7 Analysis of the distribution behavior of withdrawal strength data

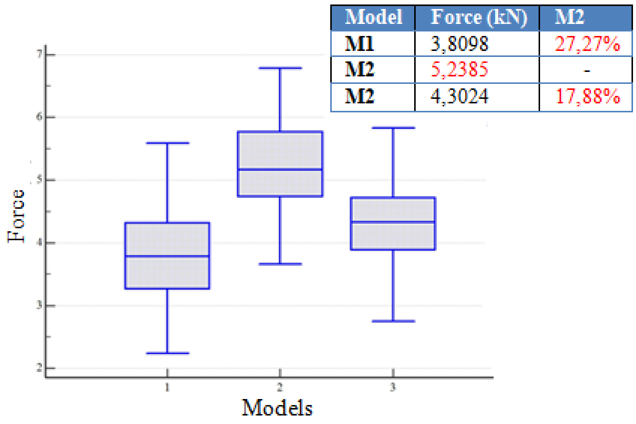
Normality checking was done on the basis of:

1) subjective estimates, based on the histogram graph (Fig. 6) and through visual checks how many results follow a normal distribution "normal - plot" (Fig. 6)
2) Check it with the help of K-S and SW tests

For results of embedded force and strain, analysis of variance (ANOVA) is applied, to analyze their results regarding to the penetration angle respecting the tree fibers. In Fig. 6 the histogram graph is shown and results obtained show that distribution of the results do not differ significantly and it follows a Gaussian curve of the interval estimation confidence. Analogous to Fig. 6, Fig. 7 shows the data analysis according to the calculated withdrawal strength.

VI. Pulling force

Test results based on measurement showed that the highest force generated in the model M2, with the use of the stepped profile of the bore for dowel embossing (Fig.8). The results of the variance analysis for the resulting force between the 3 groups (M1, M2, M3) show that a statistically significant difference in the force value between the experimental three models was obtained. Compared to the M1 model, the results showed a 27,27% higher force, while in relation to the M3 model, the pulling force of the M2 model is higher for 17,88%.



Model	Force (kN)	M2
M1	3,8098	27,27%
M2	5,2385	-
M2	4,3024	17,88%

Fig. 8 Pulling force analysis

VII. Strength on layering

Consideration of the obtained results only with the comparison of the measured displacement force for the M2 model is not fully justified. The reason for this is that in this model, the welding of the cap is performed through the step passage of the opening profile from 8 to 6.7 mm, which is the intensive wear of the cap, the volume decreases, ie the surface of the weld.

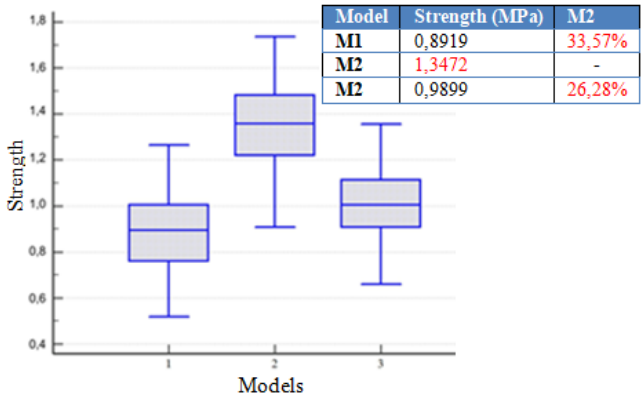


Fig.9 Withdrawal strength analysis

From a scientific point of view it is much more appropriate to compare this weld strength on layering. The surface of the welded joint with the dowel through the M1 and M3 models is about 9.4% higher in comparison with M2, and as the strength of the force per unit surface results for the same values of pulling force, the strength of the joint increases in favor of welding (Fig. 9).

VIII. THE RELATIONSHIP BETWEEN THE BOND STRENGTH AND MOISTURE CONTENT

As well as the results of the experimental study, the data on the moisture content were recorded at the moment of the pulling force test. Before testing, moisture measurement was performed for each sample. Despite the fact that after welding the samples are conditioned under certain climatic conditions (temperature 20 ° +/- 2 ° C, relative humidity of air 50 +/- 5%) the results of measuring moisture content in tree samples are ranged from 9,0 to 13,7%. The comparative relationship between the measurement arithmetic mean of the pulling force or the withdrawal strength at delamination was made grouped by classes of one percent difference in wood moisture (Table 1, Fig. 10 and Fig 11).

Table 1: Results for force and withdrawal strength for different classes of humidity

Classes of humidity (number of samples)	Range of humidity	Force (diff %)	Withdrawal strength (diff %)
1 (16)	9-10%	4,2646 (11,47)	1,0523 (9,45)
2 (23)	10-11%	4,2148 (12,51)	1,0145 (12,70)
3 (24)	11-12%	4,6205 (4,08)	1,1058 (4,85)
4 (19)	12-13%	4,5219 (6,13)	1,0906 (6,15)
5 (8)	13-14%	4,8173	1,1621

Angle	Force (kN)	Difference in force (90°)	Strength	Difference in strength (90°)
0°	3,8416	17,53%	0,9534	14,46%
45°	4,6329	0,53%	1,1133	0,12%
90°	4,6577	-	1,1146	-

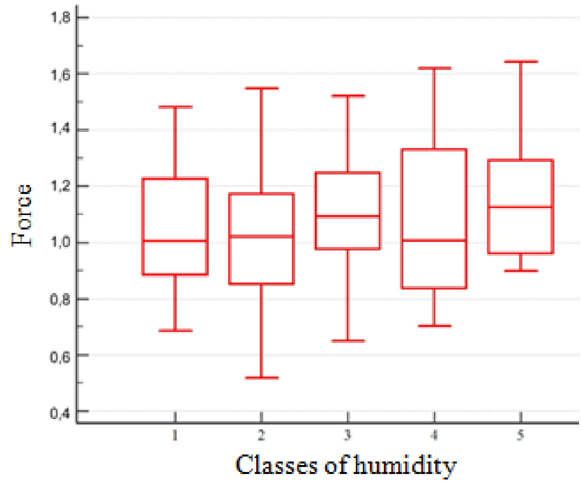


Fig. 10 Diagram for pulling forces in function of humidity

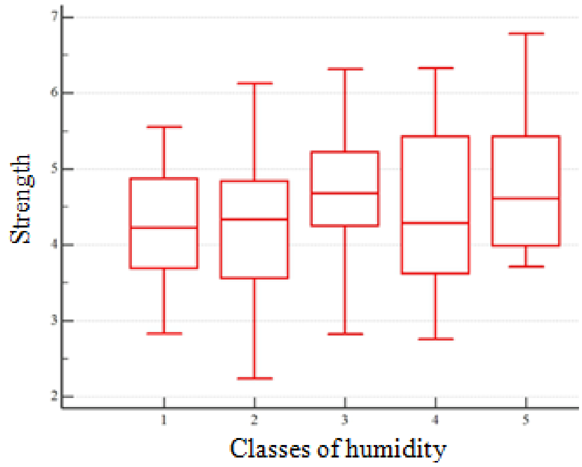


Fig.11 Diagram for strength in function of humidity

According to the results of the research, for almost all the compounds realized in wood with a higher percentage of humidity, the increase of the pulling force and strength was noted.

IX. THE DOWEL INSERTION DIRECTION IN RELATION TO THE ORIENTATION OF THE WOOD FIBERS

Douglas-fir wood is orthotropic material. Withdrawal strength in one direction is significantly greater than the strength in other directions. The withdrawal strength is highest parallel to the fiber, but in this direction the shear strength is smaller than the shear strength of the fibers.

The angle of the dowel insertion in relation to the line of rings results in a difference in the presence of early and late wood in the surface of the weld, thereby affecting the strength of the welded joint itself. The area with a larger proportion of early wood does theoretically realize a weaker connection than with a higher proportion of lateral wood of higher density.

Table 2: Results for force and withdrawal strength for different angles of dowel insertion in regards to wood fibers

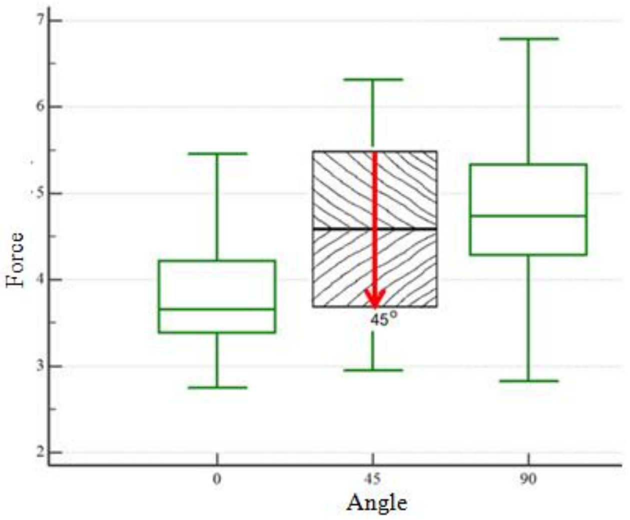


Fig. 12 Pulling forces in function of different grain direction of dowel insertion

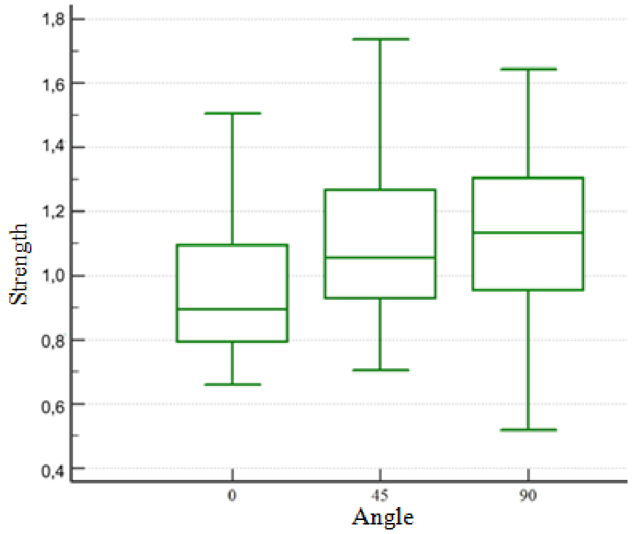


Fig. 13 Withdrawal strength in function of different direction of dowel insertion

The results (Table 2, Fig. 12 and Fig. 12) showed that the strongest joint, in relation to the pulling force, was reached at an angle of 90° in the direction of the rings, and the pulling force is 0,53% higher than at the angle of 45^{o} and 17,52% higher than at the angle of 0^{o} where the penetration is almost parallel to the line of rings.

Analysis by strength of delamination shows the same behavior that the strongest compound is achieved for insertion at an angle of 90°, it is 0,12% higher than at the angle of 45^{o}, or 14,46% higher than at the angle 0^{o}.

Here it is possible to conclude that with the increase of the angle between the line of the dowel insertion and the lines of rings, the strength of the compound is increased. The withdrawal strength increase is more significant in the range of 0-45^{o}, while in the range 45-90^{o} this difference is to slight.

X. Conclusion

Solid wood elements (Douglas-fir) can be successfully assembled using welding technology without any use of adhesives. The rotary welding of a wooden dowel (beech) at high speed is one of the forms of wood elements joining. Compounds made up of two solid wood elements are joined together by welding technology of wooden dowels provides satisfactory bond strength. The experimental part of this paper is based on the assumption that it is at the same parameters of speed welding, time welding and wood humidity, the welding direction of dowels is one of the factors, influencing welding of two wood elements, which is caused by the wear of the dowel during welding.

The angle of insertion of the dowel at rotational welding in relation to the line of ring, ie the direction of wood rings is also one of the important factors on the final strength of the compound. This can be explained by different percentage of early and late wood and the zone of welding. The influence of ambient humidity also has a significant influence on the rotary welded joint. The experimental results have shown that the bond strength increases with the moisture content of the wood. The reason for the increase of strength of a compound with a rise in humidity can be sought in the swelling. This results with dimensional disruption of the anatomical parts of the wood. In this case, shrinkage of bore (Douglas -fir) of its elements and swelling dowel (beech) reinforces the joint. To define the optimal set of welding parameters, consider the anatomical properties of wood, or at least for the given patterns, which implies their density, the width of the ring and the angle of penetration.

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