Effect of Moisture Content on the Load Carrying Capacity and Stiffness of Corner Wood-based and Plastic Joints

Eliška Máchová,[a] Nadežda Langová,[b] Roman Réh,[b] Pavol Joščák,[b] Ľuboš Krišťák,[b,]* Zdeněk Holouš,[a] Rastislav Igaz,[b] and Miloš Hitka [b]

The effect of moisture content on mechanical properties of corner furniture joints was evaluated for when different joining methods and materials were used. Results included statistical processing of the measured and calculated data and evaluation of the effect of selected factors on mechanical properties of joints caused by using mechanical fasteners and glue. The load-carrying capacity and stiffness of corner joints were investigated in two environments, humid and dry, with standard conditions for temperature and pressure, *i.e.*, dry environment had a temperature of 23 °C ± 2 °C and relative humidity of 45% ± 5%, and the humid environment had a temperature of 23 °C ± 2 °C and relative humidity of 90% ± 5%. The two types of materials used were particleboard (PB) with a thickness of 12 mm and artificial stone (plastic) with a thickness of 12 mm. Both materials were tested individually as well as their combination. Epoxy and polyurethane (PUR) adhesives were used for the glued dowel joints. When the same materials were bonded, maximum load carrying capacity was achieved with PUR adhesive, material combination of plastic-plastic, and moisture content of 90%. The epoxy adhesive was most suitable for bonding materials with different properties.

Keywords: Load carrying capacity; Stiffness; Corner furniture joints; Moisture content; Particleboard; Artificial stone (plastic)

Contact information: a: Faculty of Forestry and Wood Technology, Mendel University in Brno, Zemedelska 3 61300 Brno, Czech Republic; b: Faculty of Wood Sciences and Technology, Technical University in Zvolen, T. G. Masaryka 24 96001 Zvolen, Slovakia;
** Corresponding author: kristak@tuzvo.sk*

INTRODUCTION

The construction and design of furniture is constantly developing. The construction of furniture refers to the relationship between the materials and the manufacturing technology. As an example, computer numerical control (CNC) machining centers can be used to ensure greater product precision and to create connections between a non-traditional design and the joining method (Simeonova 2015; Grič *et al.* 2017; Kminiak and Banski 2017; Langová *et al.* 2017, 2019; Gejdoš *et al.* 2018; Tureková *et al*. 2019). The weakest element of furniture construction is the joint, and therefore it must receive focus and attention. This element slightly affects the behavior of the composition of the joined components (Eckelman 2003; Sydor 2009; Kasal *et al*. 2016; Hitka *et al.* 2018; Záborský *et al.* 2018). Selecting a joint type can be considered the most important aspect when designing furniture (Záborský *et al.* 2017a,b; Kuskun *et al*. 2018).

The most commonly used joints using mechanical fasteners are confirmations, eccentrics and bolts, whose shape and respectively thread shape have been developed for joining wood or wood-based materials. The number and dimensions of these mechanical fasteners depend on the stresses or screw withdrawal capacity of universal screw and confirmat screw (Jivkov *et al*. 2017). The holding strength of screws in plywood and wood – plastic composites has been studied (Bal 2017; Erdil *et al*. 2002; Haftkhani *et al*. 2011). Researchers (Guo *et al*. 2019) have examined the corner joint performance of corner joints from bamboo-oriented strand board (BOSB) under different failure modes and joint techniques. In study of Yerlikaya and Aktas (2012), the failure loads of L-type corner joints in case-type furniture were analyzed experimentally and statistically in laminated medium-density fiberboard material. The failure loads of five corner joints were analyzed experimentally under tension and compression moments; these joint types were glass-fiber composite layer (C), dowel (D), dowel + composite layer (DC), dowel + minifix (DM), and dowel + minifix + composite layer (DMC). Branowski *et al.* (2018) examined new furniture joints and evaluated the load limit capacity, stiffness, and failure mechanisms for bending the new types of furniture joints. The first one was a flat cross fastener bonded with an adhesive, and the second one was a fractional eccentric fastener. Both fasteners were more suitable for furniture joints with high durability compared to fasteners with a thread connection. Furniture elements are connected *via* fasteners ensuring unassisted assembly. Several experiments using native wood and wood composites, such as particleboard (PB), medium-density fibreboard, hardboard, or oriented strand board, were conducted to examine the mechanical properties of such joints (Altinok *et al.* 2009; Tankut and Tankut 2009; Malkoçoglu *et al.* 2013; Suchomel *et al.* 2014; Vilkovská *et al*. 2018; Klement *et al*. 2019), as well as traditional and new types of adhesives and connectors (Vassilios and Barboutis 2005; Yerlikaya 2012; Smardzewski *et al.* 2016; Gašparík *et al.* 2017; Danihelova *et al.* 2018). Climatic conditions, especially temperature and moisture content, have shown statistically significant effects on the product lifetime and functionality in any application (Klement *et al.* 2011; Kučerka and Očkajová 2018; Segovia *et al.* 2019; Danihelová et al. 2019; Očkajová *et al*. 2019; Orlowski *et al*. 2019). Both properties of the material and the joint are affected this way.

Gluing processes are significant in wood processing and the furniture industry. The rigid joints of structural elements and new materials can be created, and the aesthetic value of the structural parts can be increased as well. However, the quality of the joint is affected by many factors. The moisture content of the bonded material is one of the most important factors because the life span of some adhesives is somewhat affected by the moisture content (Broughton and Hutchinson 2001). Primarily, the type of adhesive used is important, as mentioned by Tankut (2007). The best resistance to the effects typically is achieved with formaldehyde-based adhesives (Pizzi 1994; Rowell 2012; Igaz *et al*. 2015), but their main negative is the unwanted release of formaldehyde into the environment (Irle *et al*. 2013; Bekhta *et al.* 2016; Lyutyy *et al.* 2017; Réh *et al.* 2019). Therefore, formaldehyde-based adhesives can be replaced by other types with increased moisture resistance, such as polyvinyl acetate (PVAc), polyurethane (PUR), and epoxy adhesives (Cremonini *et al.* 1997; Bomba *et al.* 2014a).

The change in mechanical properties of the glued joints under varied climatic conditions was studied by many authors. Uysal (2005) showed that the impact of water and humid air on the adhesive can be observed and therefore results in reducing the bond strength of the joint over a long time. Bomba *et al.* (2014b) investigated the impact of the moisture content of wood on the strength of a glued joint when PVAc and PUR adhesives are used. It was found that in addition to the moisture content of the bonded wood, the quality of the glued joint is also affected by the environment. In a standard environment, the strength of tested joints using PVAc adhesive decreases because of an increase in the moisture content of the wood; however, the requirements as per ČSN EN 204 (2001) are still met. In a humid environment, the strength is below the limit value for the standard. In a standard environment, the strength of joints bonded with PUR adhesive is similar, but the decrease in strength is lower. In the humid environment, the highest strength is at the wood moisture content of 20%, and the requirements for specific standard minimum strength (4 MPa) are met (Bekhta *et al.* 2014). The objective of the study of Smardzewski *et al.* (2017) involved modelling and the laboratory determination of the impact of changes in humidity and temperature on the stiffness and strength of the corner joints of honeycomb panels manufactured from wood composites. An increase in humidity and temperature resulted in a decrease in joint stiffness by 25% and the strength by up to 40%. The aim of the study by Smardzewski and Kramski (2019) was to determine the effect of these changes on Young's modulus and on the stiffness of the furniture units subjected to torsional loads. Tests were performed using furniture units with elements manufactured in five structural design modifications. The quality of the furniture units remained high when the materials were tested at a temperature (T) of 26 °C and a relative humidity (RH) of 40%. Increasing the values of the climatic parameters to T = 28 °C and RH = 85% resulted in a drastic deterioration of the furniture quality. The study by Máchová *et al.* (2018) focused on the impact of the moisture content on the shear strength of the glued joints. Moreover, the suitability of bonding the PB and plastic materials at an increased moisture content was evaluated. The experimental results and their analysis show that PUR adhesives cured due to moisture content are more suitable for bonding the same materials in a humid environment as well as a dry environment. Epoxy adhesive is the most suitable for bonding different materials, *i.e.*, PB and plastic. The highest shear strength was achieved with a moisture content of 45%, but the shear strength decreased significantly when the moisture content increased. When the moisture content was 90%, the difference in the shear strength of the investigated adhesives was statistically insignificant (Máchová *et al.* 2018).

Both the joining of wood and the bonding of wood with other materials is currently important for when new materials are developed. The capabilities of modern adhesives have led to the growth of hybrid structures composed of timber - glass (Cruz and Pequeno 2008; Ber *et al.* 2013; Eriksson *et al.* 2013; Lorincová and Potkány 2015; Němec *et al.* 2015; Borůvka *et al.* 2019; Schlotzhauer *et al.* 2019), glass and steel (Wellershof and Sedlacek 2003; Abeln and Preckwinkel 2011; Barcik *et al.* 2013; Richet *et al.* 2014), and other reinforced materials. The properties of glued joints of non-wood materials can be evaluated following the results of the study by Machalická and Eliášová (2017).

Storage furniture used in an environment with a higher humidity must be designed to meet not only requirements of anthropometrics, ergonomics, and aesthetics, but also especially those associated with safety and strength. The aim of this paper is to present the results of research on the effect of different humidity of the environments on the load carrying capacity and stiffness of the glued and demountable joints for various material combinations based on wood (*e.g.*, particleboard) and plastic. The research was performed using three combinations of joined materials air-conditioned in two environments with different humidity over a long period. Two types of joints commonly used in furniture manufacturing, *i.e.*, glued dowel joint and demountable joint with the eccentric cam, were analyzed.

EXPERIMENTAL

Materials

Two kinds of materials were selected to create the tested corner joints: particleboard (PB) (Bučina DDD, Zvolen, Slovakia) and a material based on plastic, commercially known as "artificial stone." The wooden product used in the experiment was a P5-grade particleboard with a thickness of 12 mm (E1) suitable for use as a load-bearing board. According to the standard EN 312 (2011), for the P5-grade, the board resistance to changes in humidity were also considered. Similar boards are commonly used in various applications. The amount of water-resistant phenol-formaldehyde adhesive used to bond the particles was 9%. The moisture content of the particleboard prior to joining was 6.1%. A material based on acrylic resin, a Staron Solid Surface (Quartz; Cheil Industries, Uiwang, Korea) with the thickness of 12 mm, is an example of a non-wooden product.

Three sets of test samples with the material combinations plastic + plastic, PB + PB, and plastic + PB were made. Each set consisted of 12 samples. The corner glued joints were made using wood grooved dowel pins with a diameter of 6 mm and a length of 30 mm using a PUR Leim 507.0 (Kleiberit, Weingarten, Germany) adhesive. For demountable joints, a Rastex 15 eccentric cam and a Twister DU 319 T pin (Hettich, Kirchlengern, Germany) were used. The joint was supplemented with dry-guided wooden dowel pins (diameter of 6 mm and length of 30 mm). The shape and dimensions of the corner joints are shown in Fig. 1.

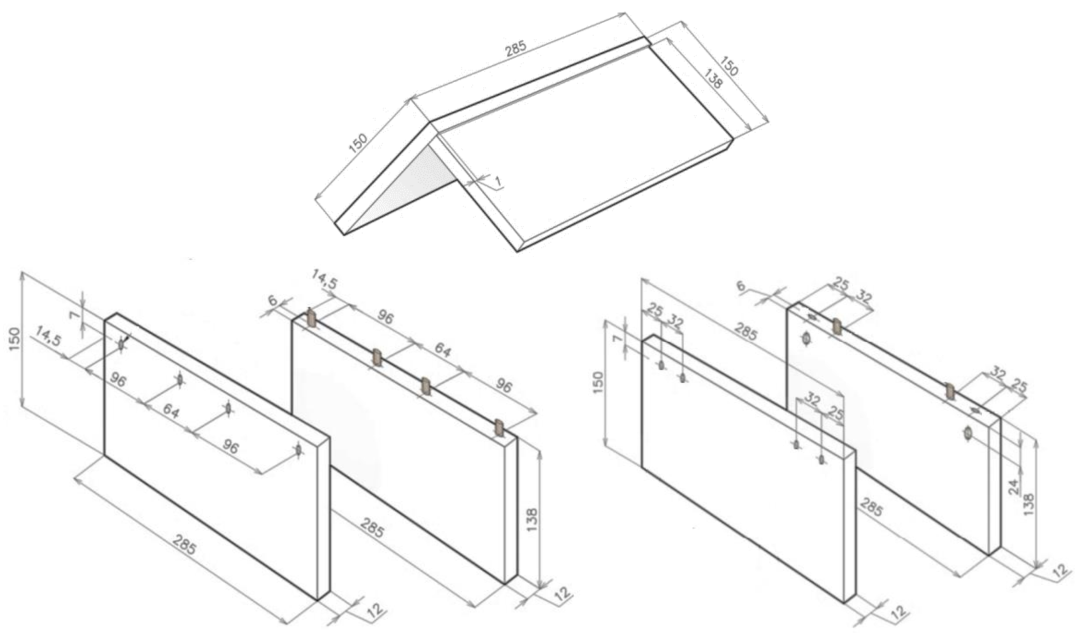


Fig. 1. The shape and dimensions (mm) of the corner joints

The mechanical properties of the corner joints were determined using the samples under laboratory conditions associated with having been assembled after equilibration of the materials in a dry environment (*i.e.*, T = 23 °C ± 2 °C, H = 45% ± 5%) and a humid environment (T = 23 °C ± 2 °C, H = 90% ± 5%) according to the standard EN 13986 + A1 (2015). The air conditioning of samples took 28 d. Samples were marked as follows: rigid glued joints (LR), demountable joints (DR), dry environment (D), humid environment (W), plastic-plastic joint (I), PB-PB (II), and plastic-PB (III).

The mechanical properties of the experimental corner joints were determined *via* compression bending (Fig. 2). The tests were conducted using an Instron 3365 testing machine (Instron, Norwood, MA, USA) at the Mendel University in Brno, Czech Republic. In the tests, the force magnitude (F_{max}) (N) and the displacement (c) (mm) were recorded. The recorded data were used to determine the load carrying capacity of M_u (N.m), and the stiffness t (N.m.rad^{-1}) of the individual types of joints.

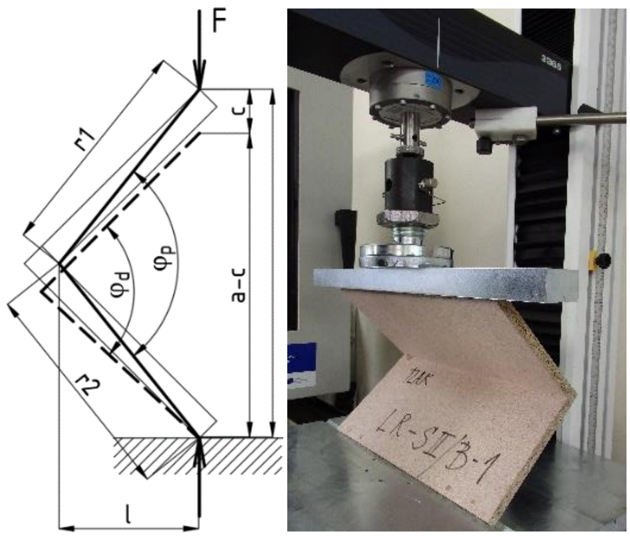


Fig. 2. The sizes and scheme of the test samples loaded with compression bending

The loading was continued until the joint samples were broken. The mechanical properties of the joints were determined following the dimensional parameters of the joint and the loading scheme. The recorded ultimate forces F_{max} were converted to the load carrying capacity using Eq. 1,

$$M_u = F_{max} \times l \tag{1}$$

where M_u is the load carrying capacity (N.m), F_{max} is the force size (N), and l is the length (mm). The stiffness was calculated according to Eq. 2,

$$t = \frac{\Delta M}{\Delta \varphi} \tag{2}$$

where t is the stiffness of the individual joint types (N.m.rad^{-1}). Compression bending was calculated using the following Eqs. 3, 4, and 5,

$$\Delta M = 0.3 M_{max} \tag{3}$$

$$\Delta \varphi = arccos \frac{r_1^2 + r_2^2 - (a - \Delta c)^2}{2 \times r_1 \times r_2} \tag{4}$$

$$\Delta c = c_{40} - c_{10} \tag{5}$$

where c_{40} and c_{10} are the displacements caused by the loading of 40% and 10%, respectively (mm).

RESULTS AND DISCUSSION

Glued Joints

The mean values of the load carrying capacity and the stiffness of the glued joints are shown in Table 1. The diagrams of force-deformation of the glued corner joints loaded in the dry and humid environment are shown in Fig. 3 (lines in diagrams show mean values of all conducted tests).

Table 1. Mean Values of Load Carrying Capacity and Stiffness of the Rigid Glued Corner Joints for Dry and Humid Environments

Joint Type	Rigid Glued Joints (LR)			
	Dry Environment (D)		Humid Environment (W)	
	Load Carrying Capacity (N.m)	Stiffness (N.m.rad^{-1})	Load Carrying Capacity (N.m)	Stiffness (N.m.rad^{-1})
Plastic-Plastic (I)	2.46 ± 0.19	147.01 ± 12.63	3.09 ± 0.28	184.60 ± 13.35
PB-PB (II)	2.40 ± 0.42	143.63 ± 23.89	3.88 ± 0.91	231.89 ± 46.75
Plastic-PB (III)	3.37 ± 0.36	201.33 ± 22.61	4.37 ± 0.49	261.04 ± 36.62

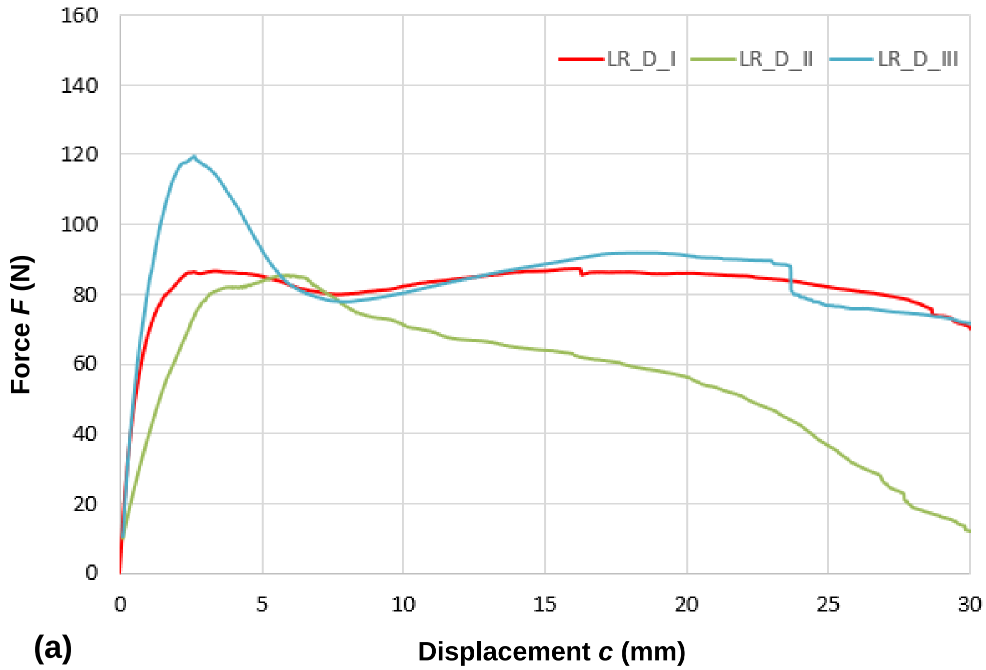
Following the statistical tests, the effect of the change in the humidity of the environment for glued joints was evaluated as statistically significant in all material combinations. In contrast, the effect of the type of bonded material was not considered statistically significant (Statistica 12, StatSoft, Palo Alto, CA, USA).

The values of the load carrying capacity and the stiffness of the glued joints mentioned in Table 1 show that an increase in the humidity of the environment resulted in an increase in the studied mechanical properties for all types of the tested glued joints. The most significant increase was observed in the PB-PB joint (approximately 61%). In the other two tested joints (*i.e.*, PB-plastic and plastic-plastic), an increase in both parameters of 25% to 30% was observed.

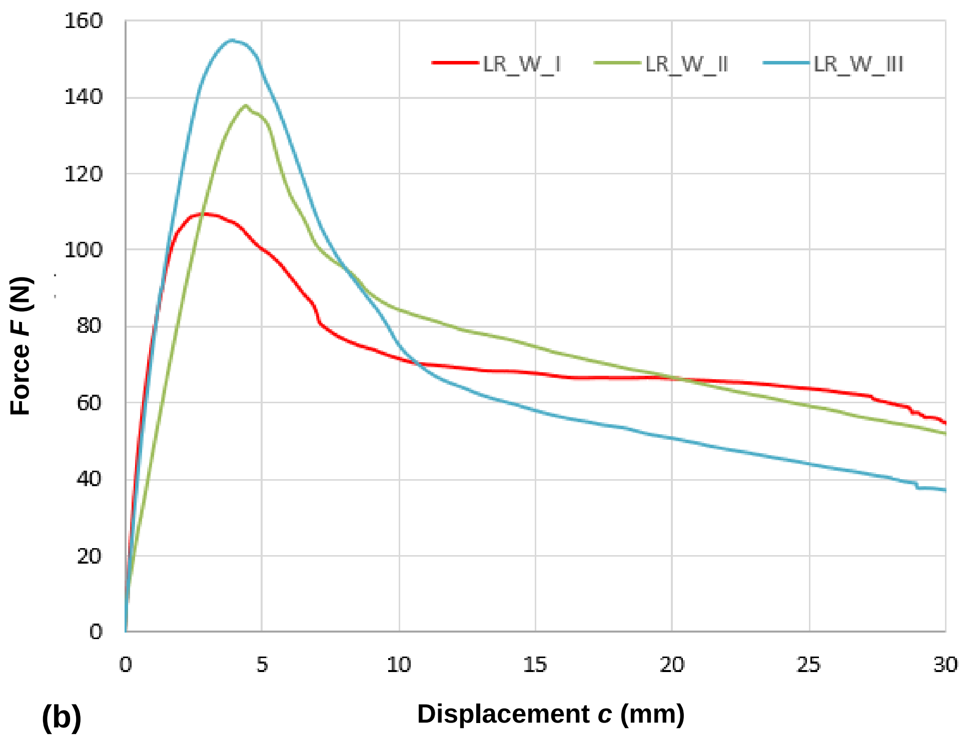
The diagram of the correlation between the force applied and the displacement (Fig. 3) shows that an increase in the humidity of the environment resulted in an increase in the recorded maximum force (F_{max}), corresponding with an increase in the load carrying capacity and stiffness of all tested samples. The quality of the glued elements was affected by the gluing technology (*e.g.*, type of glue, size of gluing area, glue line thickness, adhesion of glued surfaces, penetration grade, *etc*.). The glued joint could resist to the specific value of the loading force. The joint decreased because of the force being exceeded. Subsequently, the strength of the joint that depended on the strength of glued material and the type of joint was greatly improved.

Following the diagrams illustrating the dependence of the joint air-conditioned in the dry environment, the size of the loading force was stabilized in two cases. At approximately 80 N to 90 N the glued dowel joint was damaged with a great extent of deformation. For the PB-PB joint (green line), the glued material was damaged, resulting in the decrease of the joint carrying load capacity.

The load-carrying capacity of glued joints that had been assembled after having been air-conditioned in the humid environment, in all combinations of the glued materials, was higher. The most significant increase (approximately 60%) was observed in the PB-PB joint (green line).



(a)



(b)

Fig. 3. The diagram of force deformation of the glued corner joints for: a - humid environment, b - dry environment

The mechanical properties of the glued joints air-conditioned just after bonding in the humid environment performed better. This finding corresponded with the results mentioned in other research studies (Rowell 2012, Máchová *et al.* 2018). This was due to the improved curing of the PUR adhesive used in the humid environment when the adhesive penetrated the glued material better and the strength of glued joint increased. The

PB and dowel that swelled in the humid environment resulted in an increase in joint strength. The amount of force applied without damaging the joint was greater in all the tested samples. These results are consistent with results of Omrani *et al*. (2008) and Rammer and Winistorfer (2001). A decrease in the loading after breaking the joint of the PB exhibited a linear decline in the force with the dependence upon deformation. This was caused by damaging the PB and extracting the dowel. For the plastic-plastic joint, the constant loading of approximately 70 N was applied up to the displacement by approximately 25 mm (red line).

Following the above-mentioned facts, a glued joint in the humid environment was resistant to the load, and the strength of the glued joint was greater. These findings are consistent with results of other research studies (Pizzi 1994; Rowell 2012). When the specific value of the loading was exceeded (much higher than in the case of loading in the dry environment), there was a significant decline in the joint strength.

The types of damage of the glued dowel joints are illustrated in Fig. 4. In both environments (*i.e.*, dry and humid), extraction of the joining element with the core of PB was observed. For the plastic-plastic glued joint, the place between the dowel and glued material was damaged, whereby the glued joint was not damaged and the extracted dowel ruptured due to the bending moment.

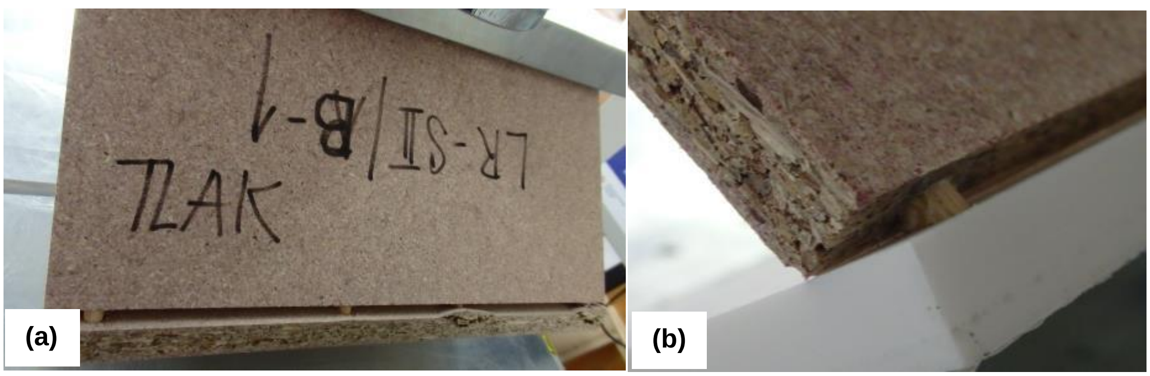


Fig. 4. Types of damage of glued joints loaded by compression bending: a - damage of PB structure and b - extraction of wood dowel

Demountable Joints

The mean values of the load carrying capacity and stiffness are shown in Table 2. The diagrams of the force-deformation of the demountable corner joints loaded in the dry and humid environments are shown in Fig. 5 (lines in diagrams show the mean values of all conducted tests).

Table 2. Mean Values of Load Carrying Capacity and Stiffness of the Demountable Corner Joints for Dry and Humid Environments

Joint Type	Demountable Joints (DR)			
	Dry Environment (D)		Humid Environment (W)	
	Load Carrying Capacity (N.m)	Stiffness (N.m.rad^{-1})	Load Carrying Capacity (N.m)	Stiffness (N.m.rad^{-1})
Plastic-Plastic (I)	7.96 ± 0.45	435.22 ± 28.55	7.48 ± 0.45	446.83 ± 23.50
PB-PB (II)	2.13 ± 0.27	127.52 ± 13.56	2.26 ± 0.40	134.99 ± 24.61
Plastic-PB (III)	6.49 ± 0.67	287.85 ± 43.93	6.30 ± 0.94	360.35 ± 38.23

Using a statistical evaluation with Student´s t-test and F-test, the effect of the change in the humidity of the environment in a demountable joint was not regarded as statistically significant. Only for the stiffness of the plastic-PB joint was the result statistically significant. The effect of the properties of the bonded material was evaluated as statistically significant.

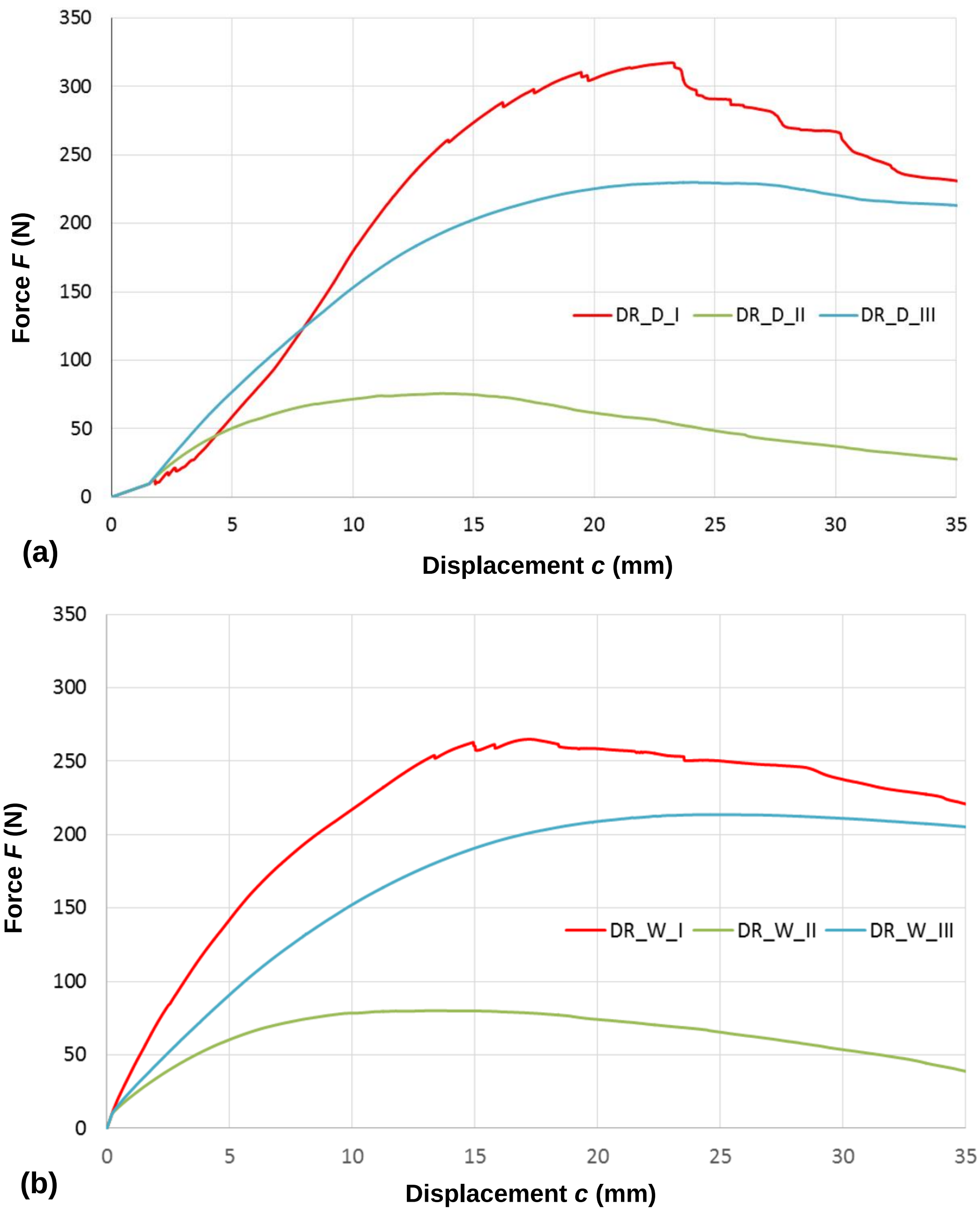


Fig. 5. The diagram of force-deformation of the demountable corner joints for a - dry environment and b - humid environment

The values of the monitored characteristics mentioned in Table 2 show that the changes in humidity resulted in insignificant changes to the load carrying capacity and stiffness of the demountable joint. In almost all combinations of the bonded materials and analyzed properties, the changes of 2% to 6% were observed. Only in the case of the plastic-PB joint was the change in stiffness larger, increasing approximately 25%.

The diagram in Fig. 5 illustrating the correlation between the load and the displacement shows that for the PB-PB joint and the plastic-PB joint, there were no significant changes due to the change in the humidity of the environment. During the loading and deformation processes, the structure of the PB was gradually damaged. The damage was presented by separating the material on the side and inserting the joining element into the face (Fig. 6a). Gradual compression of the PB structure where the bonded materials came into contact (Fig. 6b) was a typical feature of damaging the plastic-PB joint. In this place, the compression produced by the bending moment was the greatest.

Fig. 6. Types of damage of demountable joints loaded by compression bending: (a) PB-PB joints, and (b) plastic-PB joints

The change in the correlation between the load and the displacement was observed for the plastic-plastic joint. The elastic recovery and descending of the joint could be observed in the joint air-conditioned in the dry environment at the beginning of the loading. This phenomenon was observed in all tested samples of the plastic-plastic joint. After air-conditioning in the humid environment, this phenomenon was not apparent. Regardless of the humidity of the environment, a drop in the loading force resulting from the gradual separating and damaging of the bonded material was shown in the diagram associated with loading. The first drop happened regardless of the humidity of the environment when the size of the loading force was approximately 250 N and the displacement was approximately 13 mm. The properties of plastic material used were not affected by the change in humidity of the environment. The results are in agreement with (Yerlikaya and Aktas 2012 and Guo *et al*. 2019)

In all cases of tested demountable joints, the bonded materials were damaged. No metal fasteners were damaged during the testing.

CONCLUSIONS

1. Regardless of the humidity of the environment, a demountable joint with a material combination of PB-plastic and plastic-plastic could withstand higher loading.
2. The effect of higher humidity of the environment was significant for glued dowel joints in all combinations of the materials used. A significant increase in the load-carrying capacity and stiffness of the joint was observed in all tested combinations of the bonded materials.
3. An improvement of mechanical properties of the glued dowel joint in the humid environment was caused by the more effective penetration of PUR adhesive and the swelling of the dowel and the particleboard. The created joint was stronger in all tested samples.
4. For the PB-PB joint, a glued dowel joint that had been assembled in the humid environment was identified as the joint with the higher loading. In all other tested combinations, the changes in the tested mechanical properties of the PB-PB joint were not considered significant.
5. The change in the properties of the demountable joint with eccentric cam was due to the changes in the humidity of the environment and were significant only for the stiffness of the PB-plastic joint. In all other cases, the change in the tested properties of the demountable joint was not significant.
6. During the loading of the glued joint and the demountable joint with eccentric cam, the structure of the PB was damaged. For the PB-PB joint, separating the PB structure on the joint from the outside, due to the loading, was observed. For the PB-plastic joint, the structure of the PB was damaged due to compression on the joint from the inside.
7. The types of joints and combinations of materials considered in this work can be found in home furniture and in areas with high humidity, such as bathrooms, laundries, also in public furniture (non-domestic) in areas, *e.g.* wellness center, gym, in production areas using technology producing increased humidity and so on.

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