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The influence of selected factors on the strength of angle joints of frame elements

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Abstract: *The influence of selected factors on the strength of angle joints of frame elements.* The research determined the impact of 5 types of adhesives (PVAc, EVA, PO, PO met., PUR) and the time elapsed since the moment of gluing (4, 8, 12, 24 and 72h) on the strength of the mitre joints of frame elements made of MDF. The elements of the frames were additionally connected with metal staples. As a reference option, joining elements without an adhesive, using only staples, was employed. The strength of the connections was determined as the maximum module when testing connections in two configurations: compression and tensile strength. For each variant, 10 repetitions were performed. It was demonstrated that regardless of the test system or the time elapsed since gluing, the highest values of the modules were recorded in the case of the EVA adhesive. In turn, the use of PO and PUR adhesives requires a long bonding time, while PO met. and PVAc adhesives are characterized by low suitability for gluing mitre joints made of MDF sheets (values of modules comparable to the values of modules having only stapled connections).

Keywords: mitre joint, connection strength, frame, MDF

INTRODUCTION

Joints are an important element of all wood and wood-based products, regardless of their function, complexity and purpose. A joint is defined as a structural node within which two or more components or sub-assemblies are joined together. The joints in constructions, depending on the arrangement of the elements to be joined, can be divided into parallel and angle ones. Angle joints are characterized by the fact that the joined elements are set at a certain angle in relation to one another, most often in one plane. Flat or wall corner joints, half-cross and cross joints can be distinguished here (Swaczyna and Swaczyna 1993, Spanngel 2002). In corner joints, the ends of the elements are joined at an angle, and the connected elements form a shape similar to the letter L. Depending on the angle of cutting the ends of the joined elements, perpendicular joints (90°cut angle) and mitre joints (generally 45°cut angle) can be distinguished. The latter ones are generally characterized by lower strength and often require additional reinforcement in the form of metal connectors (https://www.finepowertools.com). A typical example of the application of flat mitre butt joints are various types of frames, including photo frames.

Most of the research focused on corner joints is carried out in the context of furniture element joints, construction joinery or construction elements. The strains occurring in corner joints result both from the forces acting on the frame during its use and the unladen weight of the joined elements. The intensity of these loads is related to the purpose and place of using a given frame. It is important that the strength of the frame (including its corner joints) be able to carry the loads acting on it. Otherwise, cracks will occur initially in individual joints and then the entire frame will be damaged. The strength of the frame and its corner joints depends primarily on the materials used, the design of the joints and the connectors used, the type of adhesive used and the element placed in the empty space of the frame and the method of its attachment (Eckelman 1971, Hill and Eckelman 1973, Molain and Carroll 1990, Zahn 1991, Zhang and Eckelman 1993, Eckelman and Lin 1997, Kharaouf *et al.* 1999, Falk *et al.* 2001, Hwang and Komatsu 2002, Yadama *et al.* 2002, Sawata and Yasumura 2002, Erdil *et al.* 2003, Erdil *et al.* 2004, Kurt 2003, Kilic *et al.* 2009, Ozkaya *et al.* 2010, Imirzi and Efe 2013, Joščák *et al.* 2014, Podlena *et al.* 2015, Imirzi *et al.* 2016, Kaygin *et al.* 2016, Matwiej *et al.* 2018).

With regard to furniture pieces, it is generally believed that joints are generally the weakest part of the product and are the main cause of their failure (Erdil *et al.* 2004). The authors indicate the need to use appropriate connectors in joints. Rajak and Eckelman (1996) stated that the flexural strength of corner joints is in direct proportion to the number of connectors used. Taghiyari (2013), when examining the mitre connections of elements made of MDF sheets, demonstrated that the highest strength is achieved with the use of dovetail connectors in combination with an adhesive joint. Similar results were obtained by Ozkaya *et al.* (2010) as a result of the study of mitre connections made of OSB. The authors indicated that it is more efficient to use reinforcements with single rather than double dovetail connectors. In addition, the authors stated that higher connection parameters are obtained with the use of PVAc adhesive compared to polyurethane or cyanoacrylate adhesive.

Frames are a specific type of product, in which individual elements are usually joined with mitre joints. Their production process starts with the lengthwise cut of MDF sheets with a panel saw to a width 2 mm greater than the target width of the slat profile. Then, the processed elements are milled to the pre-set width and a specific profile is imparted to them. The elements prepared in this way are finished (covered) with finish foil using EVA hot-melt adhesive. Subsequently, the slats are cut at an angle of 45° to the target dimension using automatic bevel saws. The finished slats are joined together to form a frame using staples and adhesive. Electro-pneumatic staplers with an automatic staple feed cycle are used for this operation.

The machines are equipped with a gluing unit, operating in both cold and hot mode. Important technical parameters at this stage of frame production include the bonding force and application of the adhesive, its temperature and the driving force of the staple. The subsequent strength of the frame depends on them. The time necessary for the adhesive to set is also important, because after a few hours the frames end up on the line of automatic assembly and packaging. There, they are equipped with decorative elements such as passepartout, posters, pendants, as well as a rear wall made of HDF or glass, which are fixed by means of lamflexes driven pneumatically into the inner side surface of the frame. During this operation, the mitre joints of the slats must be characterized by high strength, as otherwise the frame structure could be damaged.

The aim of this study was to determine the possibility of using various types of adhesives for the industrial production of frames, taking into account the impact of time that has elapsed since the moment of gluing on the strength properties of mitre joints.

METHODS AND MATERIALS

To carry out the tests, slats with the profile of 16 x 35 mm were used (Fig. 1) made of MDF with a density of 690 kg/m^3. In order to produce samples for testing in the form of angled bars (Fig. 2), the slats were cut to size at an angle of 45^o, and then joined to each other at a right angle using one of the tested adhesives and metal staples No. 5 with a dimension of 12 x 5 mm (Fig. 3). An electropneumatic stapler by Brevetti Motta – model AUT 2112 (Italy) was used to make the samples.

5 types of adhesives were used for bonding the samples:

- dispersion adhesive based on poly(vinyl acetate) – PVAc (Unicol S.R.L, Italy)
- hot melt adhesive based on poly(ethylene-co-vinyl acetate) – EVA (Unicol S.R.L, Italy)
- hot melt adhesive based on polyolefins – PO (Unicol S.R.L, Italy)
- metallocene catalysed polyolefin hot melt adhesive - PO met. (Unicol S.R.L, Italy)
- hot melt adhesive based on hygroreactive polyurethane – PUR (Unicol S.R.L, Italy)

The characteristics of the adhesives are presented in Table 1. The application of the adhesive was equal to the value used in the industrial production of frames on this type of staplers and amounted to 0.25 g per corner.

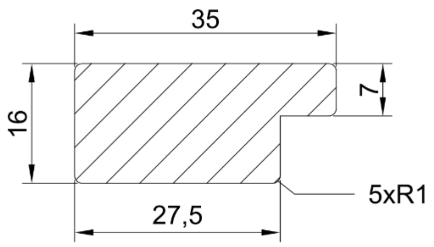

Fig 1. Profile of the slats used in the study.

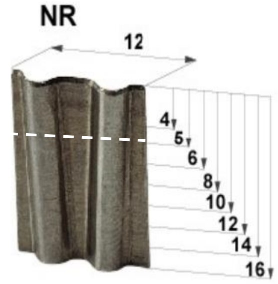

Figure 3. Staple No. 5 used for joining frame elements

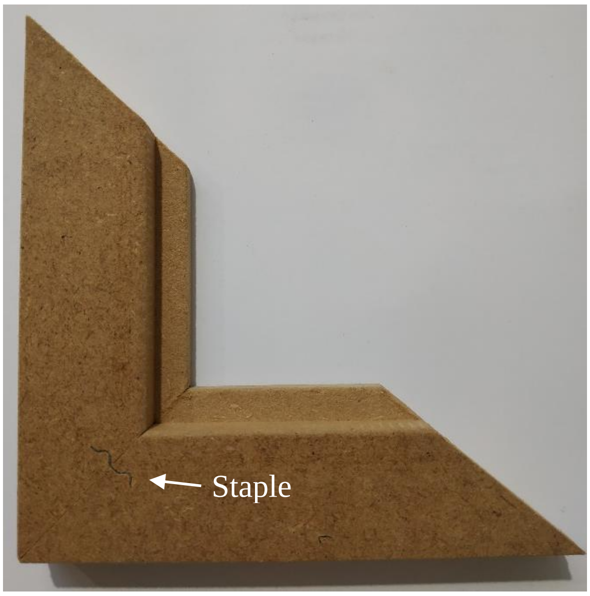

Figure 2. Samples for testing

Table 1. Selected technical parameters of the adhesives used for testing angle joints

Adhesive	Application temperature [°C]	Viscosity (Brookfield) [mPa*s]	Bonding time	Form	Density [g/cm^3]
PVA	>3	6000-10000	20-30 min.	white liquid	1,1-1,2
EVA	170-190	42000-56000	2-6 s	pellets	0,99-1,03
PO	180-200	12000-18000	10-25 s	pellets	0,9
PO met.	160-175	1200-1600	6-10 s	pellets	0,95-0,98
PUR	130-150	20000-35000	50-70 s[1] / 5-7 days[2]	glue block	1,1-1,15

[1]initial bonding, [2]according to the information given by the manufacturer, the initial bonding force is sufficient for the two substrates to be joined together. The final adhesion and resistance to temperature and chemical agents is achieved after curing the adhesive, which occurs thanks to the effect of moisture from the substrate and environment.

The gluing temperature depended on the type of adhesive and was respectively:
- PVAc – 20°C
- EVA – 185°C
- PO – 200°C
- PO met. – 165°C
- PUR – 150°C

When selecting the application temperature, particular attention was paid to obtaining the viscosity enabling the most effective application of the adhesive, while maintaining the values within the ranges declared by the manufacturers.

The manufactured samples were subjected to the test of glued joint strength in a system exposed to compression and tension (Fig. 4) (Joščák *et al.* 2014, Imirzi *et al.* 2016, Kaygin *et al.* 2016). The tests were carried out 4, 8, 12, 24 and 72 hours after the production (gluing) of the samples. In addition, the strength of joints without adhesive was also tested – elements joined by stapling alone. The produced samples, depending on the system during the test, had arm length of respectively:
- 130 mm with the compression system
- 150 mm with the tension system

The size of the samples was adapted to the technical capabilities of the materials test frame produced by OBRPPD in Czarna Woda (Poland), on which the strength tests were carried out. The tests were static, the load rate was 10 mm/min. For each variant, 10 repetitions were performed. The maximum moment of force during compression or tensile occurring at the time of joint rupture was determined as a parameter characterizing the strength of the joints. The maximum moment of force was calculated from the formula:

$$M_{S,R} = F_{max} \times L \text{ [Nm]}$$

where:
$M_{S,R}$ – maximum moment of force at compression (M_S) or tensioning (M_R) of the joint [Nm];
F_{max} – maximum destructive force [N];
L – length of the sample arm [m]

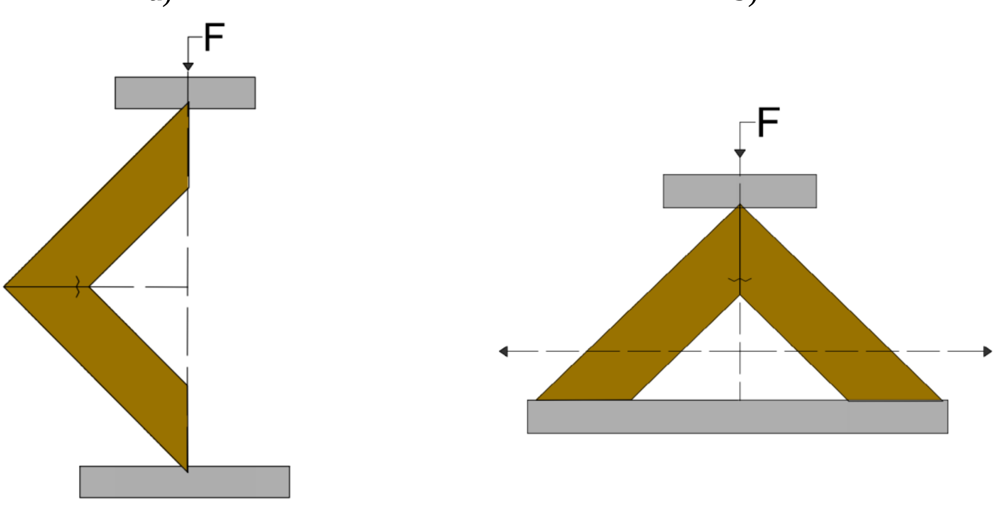

Fig. 4. The diagram of the adhesive bond strength test: a) in the compression system, b) in the tensioning system.

The statistical analysis of the results was carried out with the application Statistica version 13 (TIBCO Software Inc., CA, USA). Analysis of variance (ANOVA) was used to test (α=0.05) for significant differences between factors. A comparison of the mean values was performed using Tukey's test, with α=0.05.

RESULTS AND DISCUSSION

The results of testing the strength of mitre joints are presented in Tables 2 and 3. Regardless of the type of bond, the strength of the joints is lower in the compression system. In general, it should be stated that this relationship coincides with the data from the study of angle joints presented by other researchers (Joščák *et al.* 2014, Imirzi *et al.* 2016, Kaygin *et al.* 2016). In the case of elements joined by stapling alone (without adhesives), the decrease of joint strength in the compression system in relation to the tensioning system is 96%.

This is related to the beneficial "impact" of the staple during the test of the sample in the tensioning system. In this system, the staple is located in the maximum tensile stress zone. When the sample is tested in the compression system, the impact of the staple is definitely smaller. The maximum stress in this case occurs in the corner of the mitre joint. In the case of the elements joined with a staple and adhesive, depending on the type of adhesive and the time that had elapsed since gluing, the decrease in the strength of the joint in the compression system in relation to the tensioning system ranged from 94% to 13%. It is worth noting that regardless of the time elapsed since bonding, the smallest decrease was recorded in the case of the EVA adhesive (from 25% to 39%).

Among the analysed factors affecting the strength of the tested mitre joints (Table 4), the test system and the type of adhesive show the greatest impact in percentage points: 37.8% and 45.3%, respectively. The interaction between the type of adhesive and the test time since the moment of gluing also exhibits a considerable impact at the level of 10.7%. The impact of the other tested factors and the interaction between them (Table 4), although statistically significant, in practice did not exceed the error level of 2.5% (the impact of factors not included in the study).

Considering the durability of individual connection variants, it should be stated that regardless of the test system (compression or tension), the highest moment of force values were recorded in the case of the EVA adhesive – homogeneous groups *d*, *e*, *f* for the values of maximum modules in the tension system (Table 2) and *g*, *h*, *i* for the values of maximum modules in the compression system (Table 3). It should be noted here that the values of the maximum moments of force for the EVA adhesive decreased statistically significantly over time since the moment of gluing.

When tested after 72 hours, this decrease was 28% in the tension system and 38% in the compression system, respectively, in relation to the test conducted after 4 hours. This phenomenon could have been potentially caused by the stiffening of the adhesive bond, which in turn contributed to decreasing in its resistance to the effects of destructive force.

Table 2. The strength of adhesive joints (maximum moment of force) in the tension system.

Type of adhesive	Time elapsed since gluing	Moment of force value				Std. dev.	Coeff. of var.
		min.	max.	average			
	[h]	[Nm]					[%]
PVAc	4	32,3	44,6	38,9	*a*	3,5	9,1
	8	37,2	44,0	40,1	*a*	2,4	5,9
	12	34,2	42,9	37,7	*a*	3,0	7,9
	24	30,8	41,7	38,2	*a*	3,0	7,9
	72	31,2	45,8	40,5	*a*	3,9	9,6
EVA	4	80,3	102,2	89,2	*f*	7,0	7,8
	8	83,7	100,1	92,4	*f*	5,4	5,9
	12	82,8	95,4	88,9	*f*	4,9	5,5
	24	63,3	89,7	76,9	*e*	9,0	11,7
	72	51,2	85,1	63,8	*d*	10,7	16,7
PO	4	37,1	41,4	39,5	*a*	1,4	3,6
	8	22,8	44,1	38,2	*a*	5,9	15,5
	12	35,6	45,9	42,3	*a*	3,2	7,7
	24	32,4	50,7	39,5	*a*	5,3	13,4
	72	47,1	60,5	54,6	*b, c*	4,6	8,5
PO met.	4	38,1	41,6	39,6	*a*	1,1	2,8
	8	34,5	41,7	39,2	*a*	2,0	5,2
	12	37,2	42,9	40,3	*a*	2,2	5,4
	24	34,4	41,1	37,7	*a*	2,5	6,6
	72	37,2	51,5	42,3	*a*	3,9	9,3
PUR	4	33,8	42,8	38,7	*a*	2,9	7,6
	8	34,2	45,6	38,8	*a*	3,6	9,3
	12	31,8	50,0	41,4	*a*	4,5	10,8
	24	44,0	62,9	53,6	*b*	6,0	11,3
	72	53,0	79,7	62,1	*c, d*	8,8	14,1
Without adhesive	-	38,0	43,4	41,0	*a*	1,6	4,0

a, b, c, d, e, f – homogeneous groups in Tukey's test with $\alpha=0.05$

For other types of adhesives (PVAc, PO, PO met., PUR), especially within the period up to 12h from the moment of gluing, the durability of the joints is generally comparable to the durability of the connection produced on the basis of the staple itself – a homogeneous group *a* for the values of the modules (Tables 2 and 3). This is probably related to the lower viscosity of these adhesives in relation to the viscosity of the EVA adhesive, which could have resulted in their greater penetration into the transverse structure of the MDF at the place of making the mitre. With a low level of adhesive application, its penetration into the board structure makes it difficult to create a continuous bond. It should be added that greater variability in the results of maximum modules (more homogeneous groups) occurs when tests are performed in the compression system. In this case, too, a significant increase in the value of the maximum moment of force was recorded after 12 hours from the moment of gluing for PO, PO met. and PUR adhesives.

Table 3. The strength of adhesive joints (maximum moment of force) in the tension system.

Type of adhesive	Time elapsed since gluing	Value				Std. dev.	Coeff. of var.
		min.	max.	average			
	[h]	[Nm]					[%]
PVAc	4	3,8	5,5	4,6	*a, b, c*	0,6	13,9
	8	3,0	5,7	4,5	*a, b*	0,7	15,8
	12	4,6	7,5	5,4	*a, b, c*	0,9	17,2
	24	4,3	6,9	5,4	*a, b, c*	0,9	17,6
	72	4,2	7,4	5,5	*a, b, c*	1,2	21,1
EVA	4	45,4	72,4	62,7	*i*	8,4	13,3
	8	51,4	74,8	64,0	*i*	7,5	11,8
	12	61,8	71,2	66,5	*i*	3,2	4,8
	24	45,5	66,3	52,3	*h*	6,9	13,2
	72	31,9	47,7	39,2	*g*	5,5	14,1
PO	4	1,7	3,0	2,2	*a*	0,4	15,9
	8	2,1	3,4	2,7	*a, b*	0,5	18,3
	12	2,3	3,9	3,1	*a, b*	0,5	17,0
	24	6,5	10,9	8,5	*b, c, d*	1,4	16,8
	72	28,2	40,8	34,0	*g*	3,8	11,1
PO met.	4	7,5	12,7	10,6	*c, d, e*	1,8	16,9
	8	9,6	15,0	12,2	*d, e, f*	1,8	14,7
	12	8,6	12,5	10,6	*c, d, e*	1,4	12,8
	24	10,5	17,8	15,3	*e, f*	2,7	17,6
	72	13,3	21,6	17,8	*f*	3,0	16,9
PUR	4	2,1	3,3	2,8	*a, b*	0,3	12,1
	8	2,5	4,3	3,3	*a, b*	0,6	16,7
	12	2,6	4,0	3,4	*a, b*	0,5	15,1
	24	34,6	55,8	46,4	*h*	7,9	17,1
	72	41,5	62,7	49,8	*h*	7,6	15,3
Without adhesive	-	1,3	2,1	1,7	*a*	0,3	16,7

a, b, c, d, e, f – homogeneous groups in Tukey's test with α=0.05

Table 4. ANOVA for selected factors influencing the tested adhesive joints

Source of variation	Sum of squares	Mean sum of squares	Fisher's F-test	Significance level	Percentage of contribution
	SS	MS	F	p	P [%]
test system[1] (a)	139677,6	139677,6	8122,29	0,000	37,8
adhesive (b)	167439,2	33487,8	1947,33	0,000	45,3
time[2] (c)	3782,0	945,5	54,98	0,000	1,0
a x b	3945,4	789,1	45,88	0,000	1,1
a x c	1975,0	493,7	28,71	0,000	0,5
b x c	39553,8	1977,7	115,00	0,000	10,7
a x b x c	3791,3	189,6	11,02	0,000	1,0
error	9234,7	17,2			2,5

[1]test system: compression or tension; [2]time elapsed since gluing

Considering the industrial conditions of frame manufacturing, where a few hours after the elements are joined, they are subject to further assembly, the best results are provided by the application (highest values of the maximum modules) of the EVA adhesive. The use of PO and PUR adhesives requires the application of a long binding time – the values of maximum modules similar to the EVA adhesive are obtained only after 24 hours. With regard to the industrial process, this would significantly disrupt it. On the other hand, PVAc and PO met. adhesives, due to the low durability of joints (values of modules comparable to the values of the modules for joints made by stapling alone), cannot be used in the proposed industrial conditions for the production of frames.

CONCLUSIONS

1. The highest strength of the mitre joints in frame elements made of MDF is ensured by the use of hot melt adhesives based on poly(ethylene-co-vinyl acetate) (EVA).
2. The use of polyolefins-based hot melt adhesive (PO) and hygroreactive polyurethane-based hot melt adhesive (PUR) for joining frame elements requires a long bonding time.
3. Poly(vinyl acetate) dispersion adhesives (PVAc) and metallocene catalysed hot melt adhesives based on polyolefins (PO met.) exhibit low adhesion of MDF frame elements.
4. Mitre joints are characterised by a higher durability when tested in the tension system compared to the compression system test.

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Streszczenie: *Wpływ wybranych czynników na wytrzymałość połączeń kątowych elementów ramek.* W ramach badań określono wpływ 5 rodzajów klejów (PVAc, EVA, PO, PO met., PUR) oraz czasu, który upłynął od momentu klejenia (4, 8, 12, 24 i 72h) na wytrzymałość połączeń uciosowych elementów ramek wykonanych z płyty MDF. Elementy ramek łączone były dodatkowo zszywkami metalowymi. Jako wariant odniesienia zastosowano połączenie elementów bez kleju tylko przy użyciu zszywki. Wytrzymałość połączeń określono jako moduł maksymalny podczas badania połaczeń w dwóch układach: na ściskanie i rozciąganie. Dla każdego wariantu wykonano po 10 powtórzeń. Wykazano, że nieżaleznie od zastosowanego układu badania czy też czasu, który upłynął od momentu klejenia najwyższe wartości modułów odnotowano w przypadku kleju EVA. Z kolei wykorzystanie klejów PO i PUR wymaga zastosowania długiego czasu wiązania, zaś kleje PO met. i PVAc charakteryzują się niską przydatnością do klejenia połączeń uciosowych z płyt MDF (wartości modułów porównywalne do wartości modułów połączeń tylko na zszywki).

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