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TESTS OF POLYMERIC ADHESIVE JOINTS IN ASPECT OF THEIR APPLICATION IN PREFABRICATED TIMBER STRUCTURES

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The article concerns modern, flexible adhesive joints, which might be used in timber construction. The article discusses the test results carried out for timber elements joints using polymeric adhesives produced by Sika®. The scope of the tests includes the analysis of strength criteria, tests of polymer adhesion to the timber with a pull-off method, tests of polymer layer shearing between timber elements as well as examination of bending of timber elements joined with polymer. The conclusions indicate the types of these polymers which are recommended for the creation of polymeric joints of timber-polymeric type in timber constructions.

Keywords: flexibility, flexible joint, adhesive joint, deformation, shear stresses, normal stresses, distribution of stresses

1. INTRODUCTION

Susceptibility is the relationship between the mutual displacement of elements (linear displacement for the analysed composite elements) and the load acting on the joint (element) [9]. The joint is called according to the standard [20] a structure formed by contiguous parts of two or more

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elements, juxtaposed together or connected. Such places are frequently referred to as nodes that are connected with each other indirectly, i.e. by means of additional fasteners, such as bolts, screws or pins in the case of dowel-type connections. The nodes are classified, among others, because of their stiffness [9]. A pinned node (in fact, does not exist) is a node that allows mutual rotation of elements, however, it does not allow their displacement. The rigid nodes have such a rotational rigidity which is sufficient to ensure the continuity of the elements arrangement, and therefore both the displacement and the rotation are not possible. A node that does not meet the criteria of both a rigid node and a pinned one is in turn called a susceptible node.

In timber structures, the susceptibility of a node is a consequence of the selection of a connector. The smallest displacements generate adhesive joints, i.e. those made by the use of acrylic, polyurethane and polymer adhesives as well as epoxy resins and silicones [22]. The largest displacements generate the most commonly used connections on stem connectors.

Thanks to the implementation of adhesive joints based on polymers, there is a possibility to eliminate or significantly reduce the occurrence of the stress concentration phenomenon, as it is in the case of dowel-type connections [12]. The elimination of this phenomenon in timber objects subjected to the influence of strong winds, earthquakes, or large temperature gradients and humidity is particularly important.

The main purpose of the article is discussing the results of the tests conducted for joining timber elements by the use of susceptible polymer adhesives produced by Sika®. The scope of the tests includes the analysis of strength criteria, tests of wood polymer adhesion to the timber with the pull-off method, tests of polymer layer shearing between timber elements as well as examination of bending of timber elements joined with a polymer.

2. ADHESIVES TESTS IN LITERATURE

The scope of adhesive joints tests depicted in literature sources is quite wide. The tests, which have been conducted so far both in Poland and all over the world, contained the study of the adhesive joints behaviour itself. Those joints were made of various types of adhesives, and they were used in the construction of many analytical-experimental mathematical models in order to estimate the distribution of stresses in overlapping joints.

In Polish conditions, Jasieńko [7] coped with experimental investigations of forces distribution in adhesive fasteners of a steel rod with timber when reinforcing structural elements. Zając [27] aimed at developing an analytical-experimental mathematical model to determine the amount of stress in an adhesive weld, made of polymer. Kwiecień [11] was observing polyurethane adhesive joints subjected to static and repeatedly variable loads in the uniaxial stretching test. Additionally, he dealt with the rheology of polymers, particularly those described by the hyperelastic material model, including the study of creeping and relaxation of polymers of Sika® PM series. Kwiecień et al. [13] made an attempt to build a rheological model for the PM polymer. However, Majda and Skrodzewicz [15] modified the model of creeping of epoxy adhesive at ambient temperature. The newest national research concerns the following:

- the possibility of using polyurethane adhesives in timber-glass composite beams [22], whereby in his tests the author included double lap joints of timber shelves with a glass web,
- reducing of stress concentration by the use of a flexible polymer joint in the seismic protection of masonry walls, filling reinforced concrete frame [12],
- the possibility of using mechanical polyurethane adhesives for timber joints in the aspect of mending historical timber structures [14],
- cutting of rigid and susceptible adhesive fasteners, which work at elevated temperature [28], and which are also used in historical timber structures [29].

In the world, the works of Blyberg et al. [2],da Silva et al. [4], Dorn et al. [5], Neto et al.[17] Valarinho et al. [24] included research of double overlapping joints of glass with timber as well as glass with GFRP tapes, in which polyurethane, acrylic and epoxy resins were applied. The authors of the study were observing the behavior of adhesives with different stiffness modulus and different thickness of their layer between joined elements in the context of the behavior of the joint subjected to quasi-static clean shear. Moussa et al. [16] carried out thermal tests of epoxy resins. The authors were observing the influence of cyclic heating of this type of adhesives above the glass transition temperature as well as cooling to room temperature in the context of a possible weakening of the adhesive joint. A separate area of world research constitute works, the bottom line of which is an attempt to match an existing analytical-experimental mathematical model or create a new one to estimate the distribution of stresses in overlapping joints single and double lap [1, 3, 4, 6, 8, 10, 23, 25, 26]. In the works of Apalak and Gunes [1], Kumar et al. [10] as well as Statford and Cadei [23] a large number of analyses concerning the behaviour of adhesives with differentiated stiffnesses (including polyurethane adhesives and epoxy resins) were made. Furthermore, the authors of the study present a review of analytical models for estimation of shear and pull-off stress in the middle plane of the adhesive joint depending on the location of the joint's means. Nevertheless, Statford and Cadei [23] undertook an analysis of the influence of inclusions and discontinuities that may occur during the construction of adhesive joints, for subsequent stress distribution. The tests and analyses of Vallee et al. [25] were in turn concentrated on searching the optimal thickness of an adhesive weld, for which the average destructive stress is the largest. Double lap joints were the object of the authors' research. Klamer et al. [8] performed an extensive observation of the impact of temperature on joints made of epoxy resins. In their study, they presented the temperature at which typical resins are characterized by the lack of load bearing capacity. In addition, they checked what percentage of capacity some resins have at elevated temperature +60 °C.

3. Tests of polymeric adhesive joints

3.1. Tested materials and adapted strength criteria

In the tests adhesives, manufactured on the basis of polyurethane by Sika® Poland, were used. Two-component Sika® polyurethane adhesives: PMM, PM, PSM and C24 spruce wood classified in accordance with the standard [18], were tested.

In order to select adhesives for making structural joints in prefabricated elements from timber, the following strength criteria were adopted:

- for the adhesion testing of layers by the pull-off method: reaching at least 1.0 MPa of nominal stress with acceptable destruction form of type: cohesive in timber (ct), cohesive in polymer (cp) or adhesive in timber-polymer joint (at-p), whereby the least of the stress value recorded for a given form of destruction was assumed in the tests,
- for testing the shearing of the adhesive layer in a tensile test: reaching at least 0.5 MPa of shear nominal stress, which according to Hencky's theory of hyperelasticity will be in consonance with the fulfillment of the condition with regard to the tensile stresses in the main axes in shearing,
- for testing of bent wood components joined with polymer: the deflection increase by 1 mm occurs with the growth of force by 10 N, which corresponds to stiffness while bending of not less than 2.88 Nm^2, whereby it was assumed that the joint in the bending test should not be delaminated in the timber-polymer joint.

3.2. Tests description

The pull-off test consisted in subjecting prepared samples to pull-off force across the grains (direction with the lowest pull-off timber strength). The methodology shown in [19] was adapted for the purpose of testing polymer joints in combinations with timber. To prepared samples (wooden boards drilled across the grains to a depth of 5 mm with 50 mm diameter), aluminum discs with a diameter of 50 mm (1,962.5 mm^2) were affixed by the use of polymer adhesives tested. The test was conducted at a constant speed of force increase of 20 N/s.

In the attempt to shear the polymer layer between the timber elements, other timber samples connected with a 3 mm thick polymer layer were sheared. The affixed joint had a width of 20 mm and different lengths of the weld (10, 20, 40, 80, 160 and 320 mm). Fig. 1 depicts a scheme of the test bench as well as the geometry of an exemplary adhesive joint for a polymer weld, which is 10 mm long.

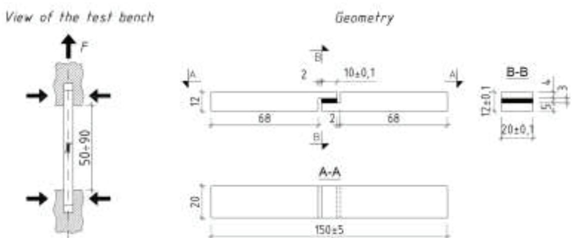

Fig. 1. Test bench scheme and adhesive joint geometry in the shear test

The last test consisted in the three-point samples bending with a bench scheme shown in Fig. 2. The samples were placed in a strength machine in such a way that the timber element of the sample, which was 5 mm thick, was placed in the compression zone. Thereby, the timber part of the sample, which was 4 mm thick, was located in the tensile zone, and the polymer adhesive layer was placed in the ratio of 1 mm in the compression zone and 2 mm in the tensile zone. Samples with a total length of 320 mm were used for that test. The spacing of struts was 240 mm, and the concentrated load was applied in the central section between the struts, thus adapting the guidelines of the standard [21] for the purpose of the test. The test was carried out with a constant speed of force increase equal to 100 N/s.

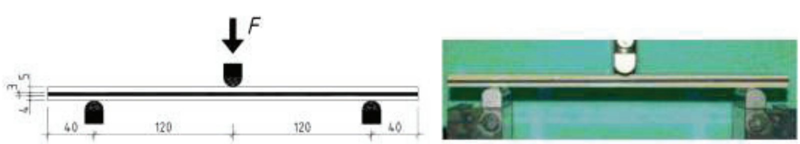

Fig. 2. Test bench scheme and the sample geometry in bending

3.3. TESTS RESULTS

The results of conducted pull-off adhesion tests are shown in Table 1. Table 1 depicts the quantities of nominal limit stresses in statistical terms. For each type of tested Sika® adhesive, the following values were calculated: mean value of tensile stress (m), standard deviation (s) and coefficient of variation (V). What is more, Table 1 contains information about the type of destruction form of the timber-polymer joint for each registered sample, whereby the following designations for damage forms were used: cohesive in timber (ct), cohesive in polymer (cp), adhesive in timber-polymer joint (at-p) as well as adhesive in the joint of polymer-aluminum disc (ap-ad). The samples showing the form of destruction (ap-ad) were excluded from the statistical analysis, also in the situation when the amount of recorded tensile stress exceeded 1.0 MPa.

Table 1. Tabulation of the quantities of the obtained stresses with an indication of the form of destruction

Type of glue	Peel strength in the pull-off test [MPa]						m [MPa]	s [MPa]	V [%]
Sample No.	1	2	3	4	5	6			
PMM	1.37	1.58	1.55	0.50	0.67	0.98	1.11	0.46	41.63%
	(cp)	(cp)	(cp)	(cp)	(cp)	(ct)			
PM	0.90	1.17	0.95	0.93	1.25	0.95	1.03	0.15	14.31%
	(cp)	(cp)	(cp)	(ct)	(cp)	(ct)			
PSM	rejected	rejected	rejected	0.98	1.18	1.22	1.13	0.13	11.41%
	(ap-ad)	(ap-ad)	(ap-ad)	(ct)	(ct)	(ct)			

Table 1 shows that the average quantity of the nominal limit stresses exceeds 1.0 MPa for each polymer. The smallest variability of the quantities of the limit stresses was achieved by the PSM polymer (V = 11.41%), whereas the largest one was achieved by PMM polymer (V = 41.63%). It is necessary to highlight that the results obtained did not decrease below 0.5 MPa. Fig.3. presents the received forms of damages of the tested samples, however.

Fig. 3. Damages forms of the tested samples: 1 (cp), 2 (ct), 3 (ap-ad)

The shear test was conducted for all 3 polymers in 5 samples for each adopted weld length (10, 20, 40, 80, 160 and 320 mm). In total, 90 measurements were registered. Their results are depicted in a statistical form in Table 2.

Table 2. Tabulation of results for shearing sample

Type of glue		Shear stresses σ_M [MPa]						Deformation ε_M [%]					
Length of joint [mm]		10	20	40	80	160	320	10	20	40	80	160	320
PMM	m	0.78	0.20	0.57	0.78	0.70	0.55	300.50	346.10	242.90	346.80	328.60	231.80
	s	0.12	0.03	0.03	0.04	0.06	0.07	69.50	200.90	16.80	21.90	49.50	43.20
	V [%]	15.83	15.36	4.46	4.87	8.21	12.84	23.13	58.04	6.92	6.32	15.07	18.66
PM	m	0.82	0.93	0.97	0.97	0.91	0.53	133.20	125.30	143.30	147.60	146.00	113.70
	s	0.05	0.10	0.08	0.05	0.13	0.16	7.00	9.30	6.30	4.00	41.40	56.90
	V [%]	6.20	10.27	7.85	5.47	14.33	30.15	5.29	7.41	4.38	2.73	28.33	50.02
PSM	m	1.59	1.58	1.57	1.30	1.07	0.55	197.10	214.50	218.70	136.50	143.30	125.00
	s	0.20	0.01	0.08	0.24	0.26	0.22	27.10	38.90	6.60	45.70	60.70	71.40
	V [%]	12.67	6.18	4.75	18.50	24.56	39.91	13.74	18.13	3.04	33.50	42.37	57.08

As can be seen in Table 2, the PMM polymer did not achieve a size of at least 0.5 MPa of nominal shear stress for a weld length of 20 mm. The PMM polymer (V between 4.46% and 15.83%) appeared to have the lowest variability of quantities of nominal stresses. The highest differentiation in results was observed for PM and PSM polymers (V between 5.47% and 30.15% as well as 4.75% and 39.91%, respectively). Selected results of shear tests for PMM, PM and PSM polymers with a weld length of 40 mm are presented in Fig. 4.

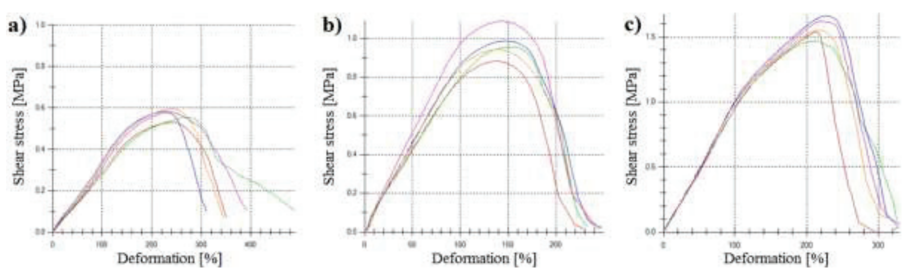

Fig. 4. Diagrams of shear stresses dependence on deformation with a weld length of 40mm for polymers: a) PMM, b) PM, c) PSM

In the bending test, the dependence of the force increment for displacement in the range from 0 mm to 10 mm was being observed. In this range, the course of dependence was close to a linear one. For PMM polymer, the climb in deflection by 1 mm appeared together with a force growth of approximately 14 N, whereas for PM by approximately 22 N. The highest value of force that was supposed to be applied to trigger a deflection increase by 1mm was noted for the PSM polymer. The value amounted to 24 N. For a deflection quantity of 10 mm, the average stiffness in bending (EI) was calculated with use of the formula (3.1), and it was for the PMM polymer 3.92 Nm^2, PM 5.82 Nm^2 and for the PSM 6.66 Nm^2, respectively. The results are depicted in Table 3.

$$EI = \frac{F \cdot L^3}{48 \cdot f} \tag{3.1}$$

where:

F – force [N], L – span of the element [m], f – deflection [m].

Table 3.Tabulation of results for a bending test

Sample No. / Type of glue		1	2	3	4	5	m	s	V [%]
PMM	F [N]	139.00	122.00	152.00	129.00	138.00	136.00	11.34	8.34%
	EI [Nm^2]	4.00	3.51	4.38	3.72	3.97	3.92	0.33	8.34%
PM	F [N]	198.00	172.00	237.00	208.00	196.00	202.20	23.52	11.63%
	EI [Nm^2]	5.70	4.95	6.83	5.99	5.64	5.82	0.68	11.63%
PSM	F [N]	242.00	222.00	228.00	233.00	rejected	231.25	8.46	3.66%
	EI [Nm^2]	6.97	6.39	6.57	6.71	rejected	6.66	0.24	3.66%

Fig. 5. illustrates the results of bending tests for timber elements joined with PMM, PM and PSM polymers. The study results were compiled in the form of graphs showing the force dependence on deflection.

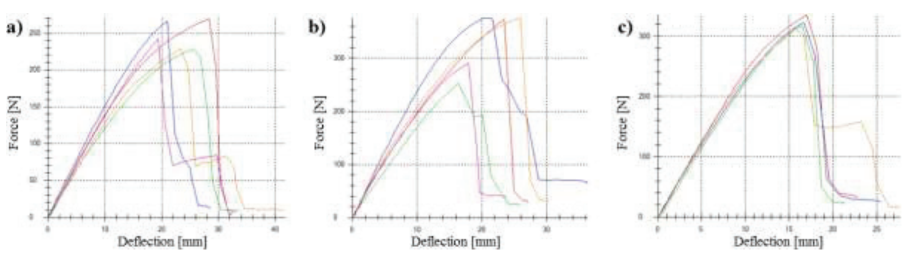

Fig. 5. Graphs of force dependencies on deflection obtained for polymers: a) PMM, b) PM, c)PSM

4. CONCLUSIONS

The results of the pull-off adhesion attempts (depicted in Table 1) indicate that all polymers (PMM, PM and PSM) met the assumption with a minimum pull-off strength of 1.0 MPa. The highest average quantity of the nominal limit stress in the pull-off test was obtained by PSM polymer (1.13 MPa).

In the case of shear tests of the polymer layer between timber elements, the assumed 0.5 MPa level of nominal shear strength in all shear tests was achieved by PM and PSM polymers. The highest average quantity of the nominal stress (1.59 MPa at a joint length of 10mm) was obtained by the PSM polymer. The fulfillment of the assumed criterion for shear strength is also ensured by the exceedance of the same 0.5 MPa quantity of tensile stresses in the main axes in shearing, which corresponds to the Hencky's hyporelasticity theory.

Examination of the timber-polymer joint during bending showed that all adhesives tested have very good adhesion to timber with large deformations. All samples with Sika® group polymers layers transported deflections higher than 10mm without being destroyed. The highest force value was noted in the case of PSM polymer (231.25 N). Furthermore, it was observed that none of the samples was delaminated in the timber-polymer joint.

ACKNOWNLEGDEMENTS

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BADANIA POLIMEROWYCH ZŁĄCZY PODATNYCH W ASPEKCIE ICH STOSOWANIA W PREFABRYKOWANYCH KONSTRUKCJACH DREWNIANYCH

Słowa kluczowe: podatność, złącze podatne, połączenie klejowe, odkształcenie, naprężenia ścinające, naprężenia normalne, dystrybucja naprężeń

STRESZCZENIE:

Dynamiczny rozwój połączeń klejowych, umożliwia ich zastosowanie już nie tylko w naprawach, czy wzmocnieniach głównie konstrukcji żelbetowych oraz murowych. Coraz częściej mówi się o zastąpieniu tradycyjnych łączników przez połączenia klejowe. Szczególnie interesujący jest rozwój połączeń na bazie polimerów w zastosowaniu w konstrukcjach drewnianych, który umożliwia eliminację lub znaczne ograniczenie występowania zjawiska koncentracji naprężeń, jak ma to miejsce w przypadku najbardziej powszechnych połączeń trzpieniowych. Szczególne znaczenie ma eliminacja tego zjawiska w obiektach drewnianych, poddanych oddziaływaniu silnych wiatrów, trzęsień ziemi, czy też dużych gradientów temperaturowych oraz wilgotności.

Głównym celem artykułu jest omówienie wyników badań przeprowadzonych dla połączeń elementów drewnianych przy wykorzystaniu podatnych klejów polimerowych produkcji Sika®. Zakres badań obejmuje analizę kryteriów wytrzymałościowych, badania przyczepności polimeru do drewna metodą pull-off (na odrywanie), badania ścinania warstwy polimeru pomiędzy elementami drewnianymi oraz badania zginania elementów drewnianych zespolonych polimerem.

W badaniach wykorzystano kleje wyprodukowane na bazie poliuretanu przez Sika® Poland. Badano dwuskładnikowe poliuretanowe kleje Sika®: PMM, PM, PSM oraz drewno świerkowe klasy C24, klasyfikowane zgodnie z normą PN-EN 338:2016-06 ”Drewno konstrukcyjne - Klasy wytrzymałości”.

Przy doborze klejów do wykonywania połączeń konstrukcyjnych w elementach prefabrykowanych z drewna, przyjęto następujące kryteria wytrzymałościowe dla:

- badania przyczepności warstw metoda pull-off: osiągnięcie wielkości co najmniej 1,0 MPa naprężenia nominalnego rozciągającego przy dopuszczalnej postaci zniszczenia typu: kohezyjne w drewnie (kd), kohezyjne w polimerze (kp) lub adhezyjne w styku drewno-polimer (ad-p), przy czym w badaniach przyjmowano najmniejszą z wartości naprężeń odnotowanych przy danej postaci zniszczenia,
- badania ścinania warstwy kleju w próbie rozciągania: osiągnięcie wielkości co najmniej 0,5 MPa naprężenia nominalnego ścinającego, co zgodnie z teorią hipersprężystości Hencky’ego odpowiadać będzie spełnieniu warunku w odniesieniu do naprężeń rozciągających w osiach głównych przy ścinaniu,
- badania zginanych elementów drewnianych zespolonych polimerem: przyrost ugięcia o 1 mm następuje przy wzroście siły o 10 N, co odpowiada sztywności przy zginaniu nie mniejszej niż 2,88 Nm^2, przy czym założono, że połączenie w próbie zginania nie powinno ulec zjawisku delaminacji w styku drewno-polimer.

Wyniki przeprowadzonych prób przyczepności pull-off przedstawiono w Tabeli 1, w której zawarto między innymi informacje o rodzaju postaci zniszczenia połączenia drewno-polimer dla każdej zarejestrowanej próby, przy czym zastosowano następujące oznaczenia dla postaci zniszczeń: kohezyjne w drewnie (kd), kohezyjne w polimerze (kp), adhezyjne w styku drewno-polimer (ad-p) oraz adhezyjne w styku polimer-aluminiowy krążek (ap-ak). Jak wynika z Tabeli 1, średnia wielkość granicznych naprężeń nominalnych przekracza 1,0 MPa dla każdego polimeru.

Tabela 1. Zestawienie wielkości uzyskanych naprężeń ze wskazaniem postaci zniszczenia.

Typ kleju	Wytrzymałość na odrywanie w próbie pull-off [MPa]						m [MPa]	s [MPa]	V [%]
Numer próbki	1	2	3	4	5	6			
PMM	1,37	1,58	1,55	0,5	0,67	0,98	1,11	0,46	41,63%
	(kp)	(kp)	(kp)	(kp)	(kp)	(kd)			
PM	0,90	1,17	0,95	0,93	1,25	0,95	1,03	0,15	14,31%
	(kp)	(kp)	(kp)	(kd)	(kp)	(kd)			
PSM	odrzucono	odrzucono	odrzucono	0,98	1,18	1,22	1,13	0,13	11,41%
	(ap-ak)	(ap-ak)	(ap-ak)	(kd)	(kd)	(kd)			

Badanie ścinania przeprowadzono dla wszystkich 3 polimerów w liczbie po 5 próbek dla każdej przyjętej długości spoiny (10, 20, 40, 80, 160 i 320 mm). Łącznie zarejestrowano 90 pomiarów. Najmniejszą zmiennością wielkości nominalnych naprężeń wykazał się polimer PMM (V pomiędzy 4,46 % i 15,83 %). Największe zróżnicowanie wyników zaobserwowano dla polimerów PM i PSM.

W próbie zginania, obserwacji poddano zależność przyrostu siły do przemieszczenia dla przedziału od 0 mm do 10 mm. Na podstawie zależności wielkości siły i ugięcia obliczono sztywność przy zginaniu (EI), która wynosiła odpowiednio dla polimeru PMM 3,92 Nm^2, PM 5,82 Nm^2 oraz dla PSM 6,66 Nm^2.

Wyniki przeprowadzonych prób przyczepności pull-off (przedstawione w Tabeli 1) wskazują, że wszystkie polimery PMM, PM i PSM spełniły założenie o minimalnej wytrzymałości na odrywanie wynoszącej 1,0 MPa. Najwyższą średnią wartość nominalnego naprężenia granicznego przy próbie odrywania pull-off osiągnął polimer PSM (1,13 MPa). Z uwagi na zaobserwowaną postać zniszczenia, tj. kohezja w drewnie (kd), polimer PSM wskazano jako rekomendowany w przeprowadzonej próbie.

W przypadku badań na ścinanie warstwy polimeru pomiędzy elementami drewnianymi, założony poziom 0,5 MPa nominalnej wytrzymałości na ścinanie we wszystkich próbach ścinania, osiągnęły polimery PM i PSM. Najwyższą, średnią wartość nominalnego naprężenia (1,59 MPa przy długości spoiny 10 mm), osiągnął polimer PSM. Spełnienie przyjętego kryterium dla wytrzymałości na ścinanie, zapewnia również przekroczenie tej samej wartości 0,5 MPa naprężeń rozciągających w osiach głównych przy ścinaniu, co odpowiada teorii hipersprężystości Hencky'ego. Powyższe kryterium wyklucza użycie polimeru PMM.

Badanie zespolenia drewno-polimer przy zginaniu wykazało, że wszystkie badane kleje wykazują bardzo dobrą przyczepność do drewna przy dużych przemieszczeniach. Wszystkie próbki z warstwami polimerów z grupy Sika® przeniosły bez ulegania zniszczeniu ugięcia większe od 10 mm. Największą wartość siły odnotowano w przypadku polimeru PSM (231,25 N). Ponadto zaobserwowano, że żadna z próbek nie uległa zjawisku delaminacji w styku drewno-polimer. Zniszczenie elementu następowało przez przekroczenie naprężeń rozciągających w dolnej warstwie drewna bez zniszczenia polimeru.

Biorąc pod uwagę wszystkie uzyskane wyniki, stwierdzono zasadność prowadzenia dalszych badań ukierunkowanych na tworzenie polimerowych złączy w konstrukcjach drewnianych z wykorzystaniem kleju PSM.

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