TENSILE SHEAR STRENGTH OF BEECH LAP JOINTS WITH THICK POLYMER MORTAR GLUE LINES

ZUGSCHERFESTIGKEIT VON BUCHENZUGSCHER-PRÜFKÖRPER MIT DICKEN POLYMERMÖRTEL-KLEBFUGEN

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SUMMARY

This paper is an initial step to investigate the potential of polymer mortars and polymer concrete as a reinforcement and repair material for timber structures with large cracks, where the applicability of conventional two-component epoxy resins is restricted by their highly exothermic curing reaction. The current limit (crack width < 8mm) prevents that two-component epoxy resin systems overheat, affecting their bonding properties. New polymer infill products exhibit reduced curing heat, improved compressive strength and stiffness, and reduced production costs in comparison with two-component epoxy systems. However, the effects of moisture and varying environmental conditions on thick polymer infill glue lines and wood are not thoroughly reported. In this work, tensile tests on polymer concrete mortars according to ISO 527-2 and tensile-shear tests according to DIN EN 302-1 were carried out on thick polymer glue lines with beech wood adherends. Specimens with two different polymer infills with 10-mm thick glue lines were selected for tensile-shear tests under three climatic pretreatments to evaluate their performance in normal conditions, saturated in cold water, and saturated in boiling water (A1, A2, and A4 treatments acc. to EN 302-1, respectively). The results confirmed that thicker adhesive joints exhibit lower apparent tensile-shear strength due to the effect of increased peeling stresses. Regarding the effect of pretreatments, a significant reduction of strength is observed, both for saturated in cold (A2) and boiling water (A4), with a stronger reduction for the latter. Numerical simulations were conducted to analyse distribution of stresses and damage initiation within the adhesive layer using a cohesive zone model for the bonding interface, which confirmed the effects of reduced tensile-shear strength for thicker glue lines and aligned well with the experimental fracture patterns.

ZUSAMMENFASSUNG

Diese Arbeit soll einen ersten Schritt darstellen, das Potenzial von Polymervergüssen als Sanierungs- und Verstärkungsmaterial für Holztragwerke mit breiten Rissen zu untersuchen, bei denen die Anwendbarkeit herkömmlicher Zwei-Komponenten-Epoxidharze (2K-EP) durch deren stark exotherme Aushärtereaktion eingeschränkt ist. Die derzeitige normative Grenze (Rissbreiten < 8 mm) soll verhindern, dass 2K-EP Systeme überhitzen, was ihre Haftungseigenschaften beeinträchtigen würde. Neuartige Polymermaterialien weisen im Vergleich zu 2K-EP eine geringere Aushärtungswärme, eine höhere Druckfestigkeit und Steifigkeit, sowie geringere Produktionskosten auf. Allerdings sind die Auswirkungen von Feuchtigkeit und wechselnden Umgebungsbedingungen auf die Polymermörtel-Klebschichten und das Holz bislang nicht ausreichend untersucht. In dieser Arbeit wurden Zugversuche an Polymermörtel gemäß ISO 527-2 sowie Zug-Scherversuche gemäß DIN EN 302-1 an breiten Polymermörtel-Klebschichten mit Buchenholz-Adhäsionspartnern durchgeführt. Für die Zug-Scherversuche wurden Proben mit zwei verschiedenen Polymermörteln mit je 10 mm Fugendickenausgewählt, die drei klimatischen Vorbehandlungen unterzogen wurden um ihre Leistung unter Normalbedingungen, gesättigten Bedingungen und Sättigung in kochendem Wasser (A1, A2, A4 Behandlungen gem. EN 302-1) zu bewerten. Die Ergebnisse bestätigten, dass dickere Klebfugen aufgrund erhöhter Schälspannungen eine geringere scheinbare Zug-Schubfestigkeit aufweisen. Hinsichtlich des Einflusses der Vorbehandlungen wurde sowohl bei Sättigung in kaltem (A2) als auch in kochendem Wasser (A4) eine deutliche Festigkeitsabnahme beobachtet, wobei letztere stärker ausgeprägt war. Numerische Simulationen wurden durchgeführt, um die Spannungsverteilung und die Schädigungsinitiierung innerhalb der Klebschicht mithilfe eines Kohäsivzonenmodells für die Haftfläche zu analysieren. Diese bestätigten die verringerte Zug-Schubfestigkeit bei dickeren Klebschichten und stimmten gut mit den experimentell beobachteten Bruchbildern überein.

1. INTRODUCTION

Existing timber structures increasingly need to be renovated or reinforced to extend their service life or to adapt to new conditions, such as additional loads due to a change of use. This has led to a general increase in research and standardization of reinforcement methods in timber construction in recent years [1], including the injection of epoxy resins into cracked timber elements [2] and a number of cases where damaged structures have been successfully renovated or reinforced using composite materials such as polymer mortars or polymer concrete [3]. Polymer-concrete (PC) can be defined in this context, as a composite material with a two-component thermosetting epoxy matrix and the addition of fillers (graded sand, quartz, or similar smaller particles), that help in providing some variation on the mechanical and physical properties usually observed on pure epoxy resins. The addition of fillers helps to (1) reduce the effects of the highly exothermic curing process, (2) increase the compressive and shear stiffness moduli, and (3) reduce the cost of production of epoxy-based materials. Further investigation into the use of PC as reinforcement material for timber elements with large cracks is required.

This study focuses on examining the tensile-shear strength observed with the experimental methods usually applied to two-component epoxy resins, using in this case samples with thicker glue lines to allow for their fabrication and PC products with different matrix and fillers. The test programme is based on the requirements for two-component epoxy adhesives for approval by the German Institute for Building Technology (DIBt), which were introduced in DIN EN 17418:2021-06 [4]. According to this standard, adhesives for load-bearing purposes must have sufficient strength and durability to ensure that the functionality of the bond in the restored component is maintained over the intended service life of the structure. Preliminary experimental and numerical investigations of tensile shear strength testing in accordance with DIN EN 302-1:2023-5 [5] are performed on two different polymer-based mortar. Additionally, the effects of three different climatic pretreatments (A1, A2, A4) is applied to samples with glue joints made of two-component epoxy and PC. One usual requirement for 2-component epoxy resins is to test samples of varying thicknesses that are glued to beech wood, comparing their tensile shear strength to predefined limits. The thickness of the glue lines covers a range from 0.1 mm to a maximum thickness of 4 mm, but this study increases the thickness to 10 mm.

2. STATE OF THE ART

Previous research into hybrid composite elements using polymer concrete and wood dates back to 1991, with positive results for the partial replacement of timber beams [6]. More recent studies have addressed issues such as reinforcement for compression perpendicular to the wood fibers [7], compression reinforcement in bending [8], load transfer between steel bars and wood [9], and the development of sophisticated connections for wood beams [10, 11] and longitudinal connections [12]. In general, these studies show a significant improvement, particularly in the shear adhesion between polymer concrete and wood, compared to epoxy resins, mineral-bound mortar, or UHPC. Polymer concrete grouts could represent a promising approach for further research as an additional renovation or reinforcement option in timber construction.

The current state of technology in Germany does not yet allow all practical cases to be effectively covered by conventional means of renovation and reinforcement using resin injection. In the context of crack repair, only relatively thin cracks (< 8 mm) in timber structures may be repaired with epoxy resin adhesives [2]. This limitation of the crack width is due to the strongly exothermic curing reaction of conventional epoxy resin adhesives that could potentially damage the adhesive properties. However, common climate-induced cracks mostly due to the geometrically restricted swelling and shrinkage of solid timber, can have widths larger than 8 mm and therefore cannot be repaired or cannot be repaired optimally (e.g. no gluing of wedges possible) and must be completely replaced.

Thanks to additives and the technical possibility of reducing the exothermic curing reaction, polymer concrete grouting represents an apparent and a priori attractive solution to the problem. The usual requirements for the adhesive or grout (e.g. no additional pressure can be applied on site to the joined parts, no shrinkage is desired, filling of thin ‘hairline cracks’ is necessary, etc.) could also be met a priori, but must first be verified by means of suitable tests. More importantly, few results are found in the literature regarding the effects of moisture content on the strength of adhesive bonding of polymer-concrete and timber.

3. METHODS

3.1 Experimental tensile strength of polymer material

3.1.1 Tensile strength according to ISO 527-2:201

To determine the mechanical properties of different polymer materials, tensile tests were performed on dog-bone specimens, type 1A according to ISO 527-2:2012, as shown in Fig. 1. The dimensions of the cross section were 20mm of width and 10 mm of thickness. The tensile strength is defined as:

$$f_t = \frac{F_{t,max}}{A} \tag{1}$$

where f_t is the tensile strength of polymer-concrete (in N/mm²), $F_{t,max}$ is the maximum tensile load applied until failure of the sample (in N) and A is the area of the cross section (200 mm²). The elastic modulus is calculated using a linear regression of the engineering stress vs. engineering strain between 10% and 40% of the maximum stress for each sample.

3.1.2 Preparation of samples

Samples were prepared using different PC materials with a wide range of size for fillers and different two-component epoxy resins. Two of the products were provided in cartridges (SK-1, SK-4) and the rest in pails, in which case mixing of the epoxy resin and hardener was necessary. Immediately after mixing, PTFE molds with a thickness of 20 mm were filled in normal climatic conditions (20° ± 1°C, 65 ± 5% relative humidity). After 24 hours, the samples were removed from the molds using a press, and stored during two weeks before testing under normal climatic conditions. A total of five different PC materials were tested for the tensile tests (n=6 for each material).

3.1.3 Experimental procedure

The experiments were conducted using a universal testing machine Zwick Roll Zmart.Pro under cross head displacement-based control and a testing speed of 1 mm/min using a load cell of 10 kN. The elongation of each sample was measured using a mechanical clip-on extensometer with initial length 50 mm.

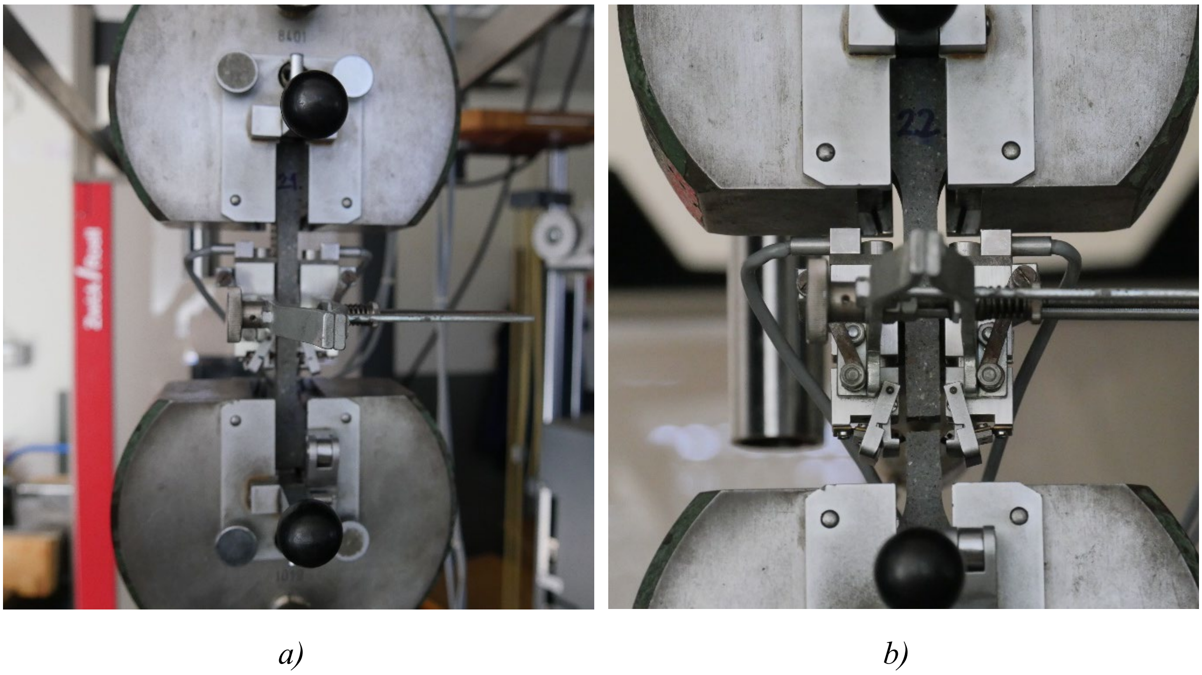

a) b)

Fig. 1: Tensile tests on polymer-concrete samples according to ISO 527-2:2012 (a) Test setup with mechanical clip-on extensometer (b) Failure of tensile test on PC

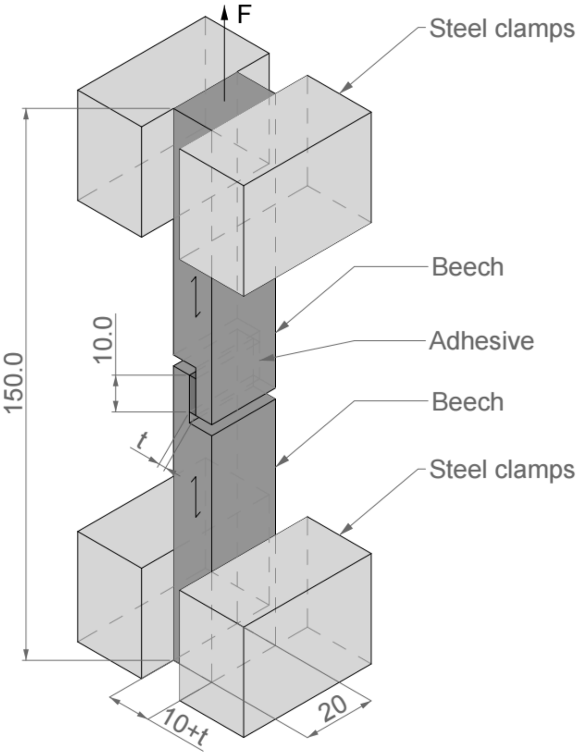


Fig. 2: Tensile shear specimens according to EN302-1: Isometric view of a specimen with glue lines thickness t (dimensions in mm)

3.2 Experimental tensile shear strength test according to EN 302-1

3.2.1 Nominal Tensile-Shear Strength

The test specimens are shown schematically in Fig. 2. Tensile shear strength is defined in accordance with standard DIN EN 302-1 [5] by the straightforward equation (2):

$$f_v = \frac{F_{max}}{A} \tag{2}$$

where f_v is the tensile shear strength (in N/mm²), F_{max} is the maximum load applied at failure of the sample (in N) and A is the area of the bonded surface (200 mm²).

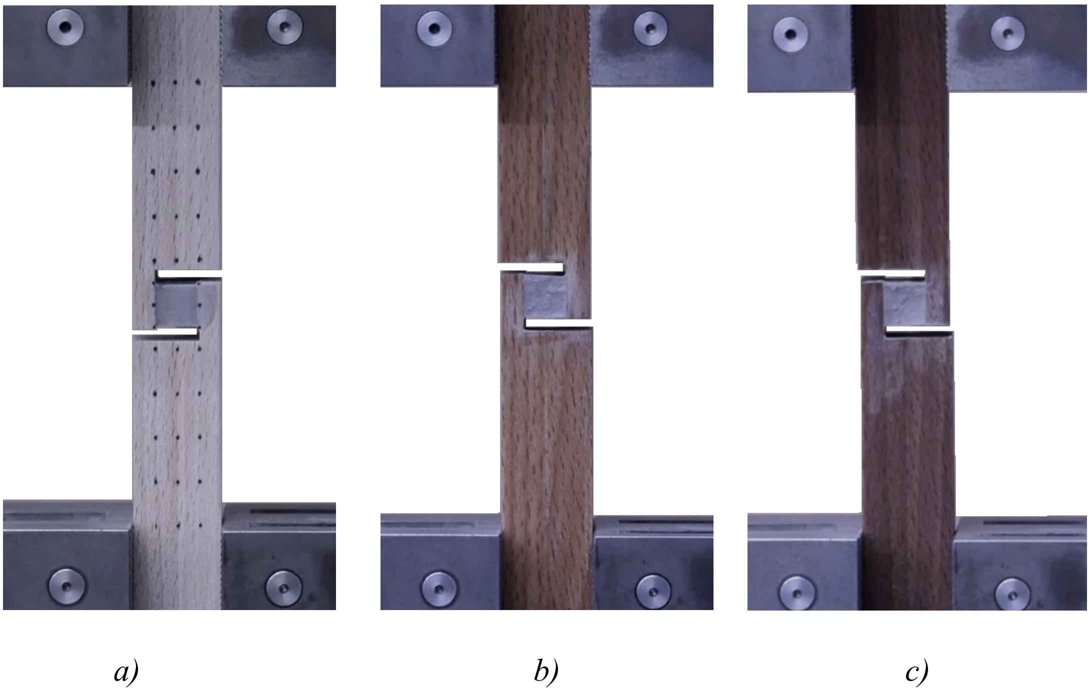
3.2.2 Preparation of samples

For the fabrication of tensile-shear samples, European beech (*Fagus sylvatica*) 10 mm-thick boards were glued using five different PC products. After being glued, the adherends were stored for at least 14 days in a climatic chamber Weiss SB1300 under normal conditions 20° ± 1°C and 65 ± 5% relative humidity. The adherends were then placed in plastic molds to constraint any movement during fabrication, using silicone molds to allow the PC to be placed in the central glue line without additional pressure until curing. After 14 days, the hardened excess of PC in each sample was mechanically sanded before testing to match the width of the adherend 20 ± 0.1 mm in dry conditions. For these experiments two PC materials were selected and one two-component epoxy resin as benchmark. For each of them, 10 samples were prepared and tested: Four samples were tested in normal conditions (A1, n=4) and the remaining samples were tested for the pretreatments A2 (n=3) and A4 (n=3).

3.2.3 Pretreatments

The standard DIN EN 302-1 defines eight pretreatments (A1 to A8) that shall be used to examine the effects of temperature and moisture content on the samples prior to testing. DIN EN 17418 specifies defined limit values for tensile strength for each pretreatment and for glue line thicknesses up to 4 mm. In this test phase, three pretreatments were applied (see Fig. 3):

- A1: Stored for 14 days at 20°C and 65% relative humidity after bonding and tested dry.
- A2: Stored for 14 days at 20°C and 65% relative humidity after bonding and tested wet after a further 4 days in water at 20°C.
- A4: Stored for 14 days at 20°C and 65% relative humidity after bonding and tested after 6 hours in boiling water and 2 hours of cooling in water at 20°C.



a) *b)* *c)*

Fig. 3: Front view of the test specimens with three different pretreatments and same polymer concrete, based on DIN EN 302-1: (a) A1, (b) A2, (c) A4

3.2.4 Experimental procedure

The experiments were conducted using a universal testing machine Zwick Z020 under cross head displacement-based control and a testing speed of 3 mm/min using a load cell of 10 kN. In this case, the elongation of the samples was not directly measured.

4. RESULTS AND DISCUSSION

4.1 Experimental results

4.1.1 Tensile tests on different polymer concrete mortars

The results of tensile strength for five PC products are shown in Fig. 4. The elastic moduli for these materials are presented in Fig. 5.

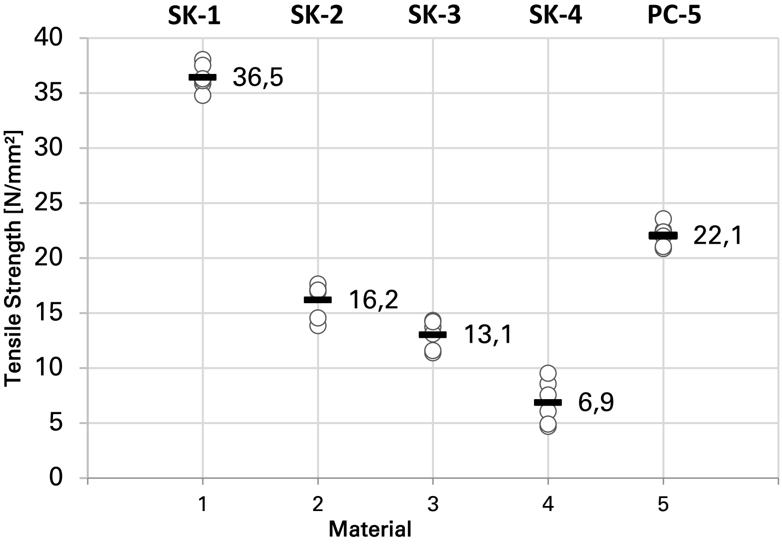


Fig. 4: Tensile strength for different polymer concrete samples (SK-1 – SK-4, PC-5) and their average values

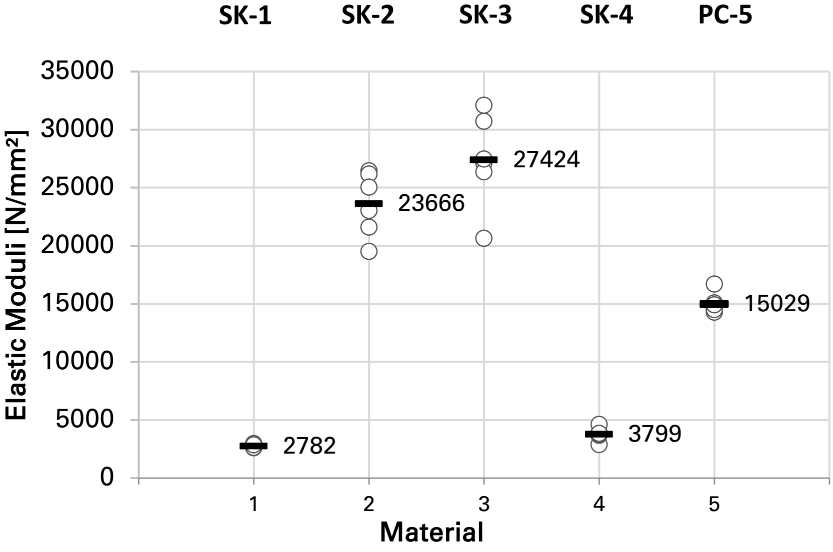


Fig. 5: Elastic moduli for different polymer concrete samples and their average values

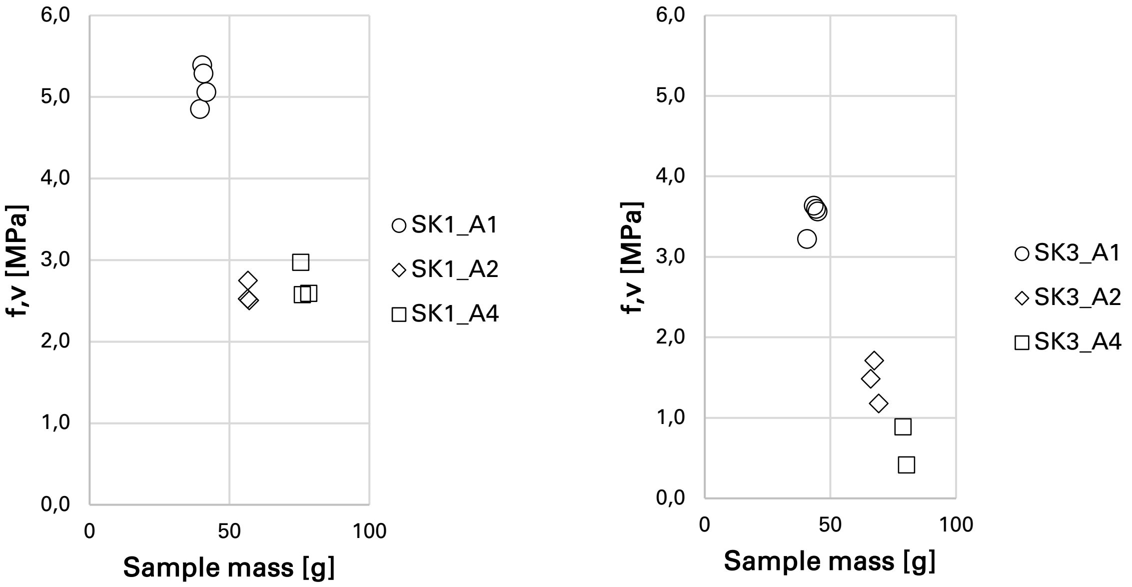
Two of these five materials were selected for tensile-shear tests: SK-1 which has the smallest fillers, highest tensile strength and smallest elastic modulus, and SK-3 which has the highest elastic modulus and relatively low tensile strength, in comparison with other PC materials.

4.1.2 Tensile Shear Tests on Beech and Polymer concrete

The following results correspond to the tensile-shear test specimens with a glue line thickness of 10 mm. Two different PC were selected to illustrate the comparison between a polymer with smaller fillers, which is more flexible and has higher strength (SK-1), and a second material with larger fillers, which exhibits stiffer and more brittle behavior (SK-3). As seen in Fig. 7, the tensile shear strength of pretreatments A2 and A4 is lower than that of pretreatment A1, which corresponds to a dry condition (see Fig. 3a). According to the standard [4], the shear strength of pretreatment A2 should be at least 80% and that of pretreatment A4 at least 60% of the strength under dry conditions (A1). Fracture surfaces after testing are shown in Fig. 6, where failure of the bond lines is mixed between beech fibers failure and adhesive failure. In the case of thinner glue lines, the expected result is that 100% of the failure is in the wood, and not on the adhesive interface. As benchmark, samples glued with a two-component epoxy resin exhibited comparable strength to SK-1 after pretreatments A2 and A4, and a lower strength in normal conditions A1 (see Fig. 8).

a) *b)*

Fig. 6: Damage on the bonding surface of samples: (a) Adhesive SK-1 tested after pretreatment A1. (b) Adhesive SK-3 tested after pretreatment A1



a) SK-1 *b) SK-3*

Fig. 7: Tensile shear strength of specimens with 10 mm glue line thickness for two PC materials, subjected to pretreatments A1, A2, and A4

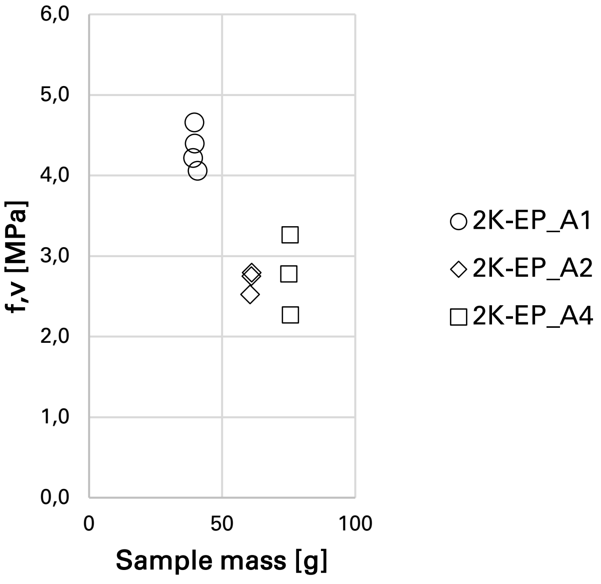


Fig. 8: Tensile shear strength of benchmark/reference specimens with 10 mm glue line thickness using a 2-component epoxy resin system, subjected to pretreatments A1, A2, and A4

4.2 Numerical Simulations

A numerical simulation was prepared using the commercial finite element software Abaqus 2023 to investigate the effects of various mechanical parameters on the total shear strength measured on EN 302-1 samples. The 2D model uses plane stresses with displacement-control and non-linear static steps. The materials are beech and polymer mortar, modelled as linearly elastic, while their bonding interface is modelled using cohesive elements with strength values corresponding to polymer material with smaller fillers. The specific mechanical properties used for beech are listed in Table 1, based on values provided in [14], modifying the longitudinal elastic modulus for a reduced value closer to the characteristic elastic modulus and using a uniform Poisson coefficient of 0.4. The parameters to represent polymer material and cohesive elements are defined in Table 2. The model was created using a uniform mesh with a maximum element size of 0.5 mm. The finite element type was plane stress CPS4 for beech and polymer concrete and cohesive elements COH2D4 to simulate the bonding interface with a thickness of 0.1 mm. The cohesive behavior is described using a bilinear traction separation cohesive zone model (CZM), with the parameters and fracture energy listed in Table 2.

Table 1: Selected properties to model beech (units in N, mm)

E,L	E,T	E,R	υ,LT	υ,LR	υ,RT	G,LT	G,LR	G,RT
11000	606	1900	0.4	0.4	0.4	1283	855	486

Table 2: Selected mechanical properties of polymer concrete and cohesive elements (units in N and mm)

E	υ	Knn	f,tk	f,vk	G,f
3000	0.4	2500	35	25	1.0

Three analyses were carried using different thickness for the polymer glue lines: 2 mm, 4 mm and 10 mm. All models were prepared using the same mesh size, cohesive elements thickness, and mechanical parameters.

As expected, and as supported by previous experimental results, greater thickness leads to lower tensile shear strength. However, at the point where maximum tensile shear strength is reached (see in Fig. 9), the reduced tensile shear strength is not primarily caused by shear stresses. Increasing the thickness leads to larger eccentricity and normal peeling stresses.

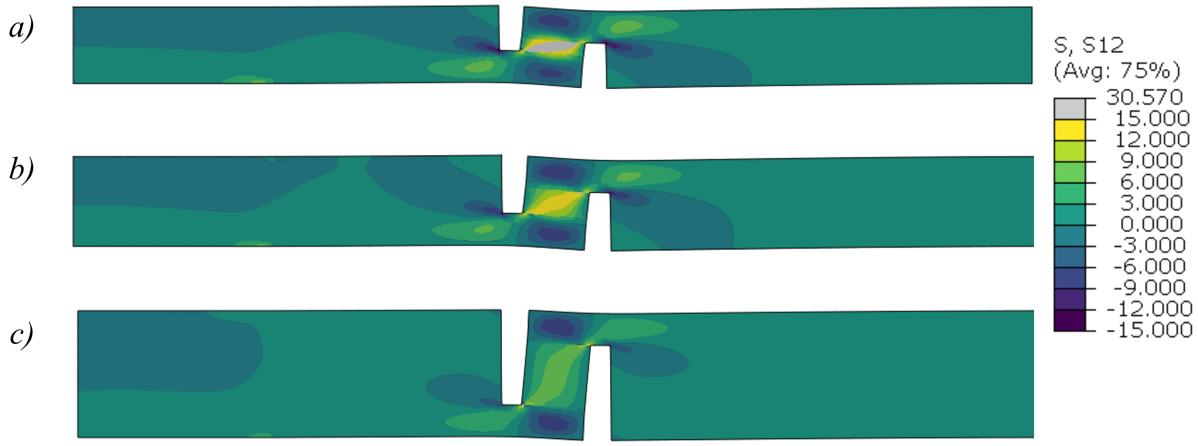


Fig. 9: Result of the numerical model comparing the stress distributions of the shear stresses (component S12); a smaller thickness leads to a stronger distribution of higher shear concentrations. This is compared for (a) thickness 2 mm (at the top), (b) thickness 4 mm, and (c) thickness 10 mm (at the bottom)

After the maximum load is reached, the typical crack onset appears with additional displacement (see Fig. 10).

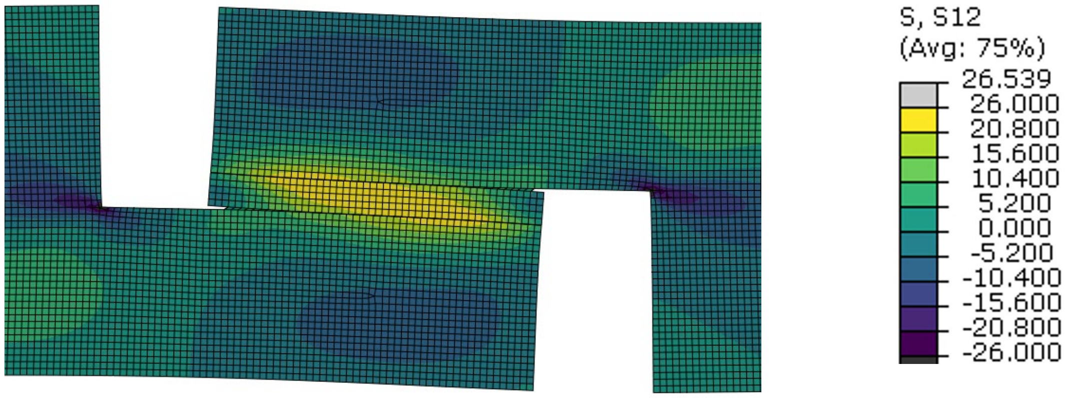


Fig. 10: Detailed view of cohesive damage formation at the edges of a specimen with an adhesive layer thickness of 2 mm. Representation of the shear stresses S12 in N/mm² after the initiation of the bond line failure

4.3 Parametric study

Although the calculation of tensile shear strength in the standard [4] is presented as an average stress per unit of bonded surface, the same standard clarifies that this is not a design value but rather a representative value that must be compared with predefined lower bounds. A closer look at the shear and tensile stress distribution perpendicular to the bonding surface shows that the failure is highly sensitive to the eccentricity of loads, which induce higher peeling stresses. In the case of this study, the eccentricity of loads is associated with higher glue line thickness and, in addition to this, several parameters influence the ability to accurately predict the strength of the adhesive joint, such as local strength, fracture energy, and the size and shape of the joint and the stiffness of both adherends and the adhesive [13].

A parametric analysis of the thickness effect on simulations is summarized in Fig. 11. It confirms that increasing the thickness of the adhesive joint reduces the apparent tensile shear strength by up to 62%. Although the distributed shear stresses are reduced on average, the increase in peel stresses leads to a lower F1 value for failure of samples with thickness of 10 mm.

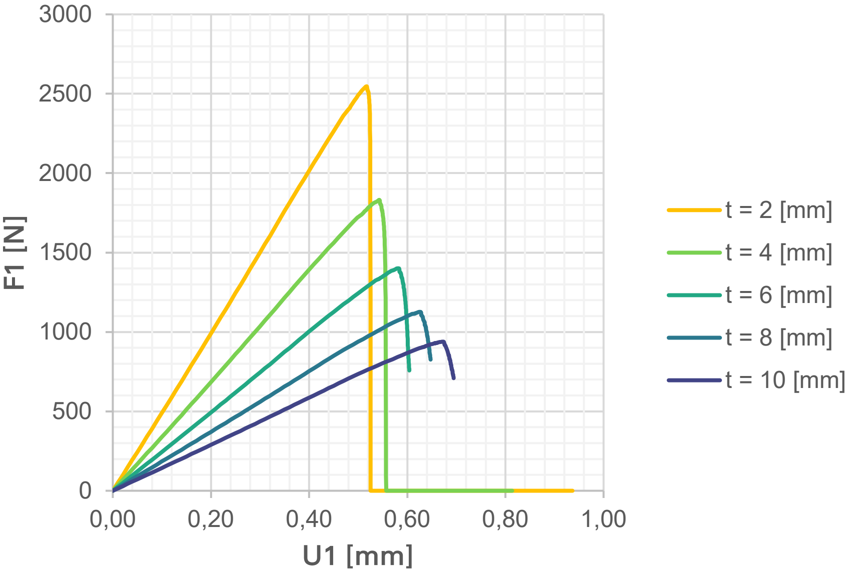


Fig. 11: Force-displacement curves for different glue line thicknesses of numerical tensile-shear tests. The maximum tensile load F1 is applied until failure of the bonding line

5. CONCLUSION AND OUTLOOK

Experimental results of tensile shear tests show comparable strength for a referential two-component epoxy resin and a selected polymer concrete with small size fillers (SK-1), which shows potential for further investigation as means of reinforcement in timber construction. Stiffer, more brittle materials tend to show a reduced performance in tensile shear tests, especially after the application of pretreatments A2 and A4.

The cohesive elements used in the numerical simulation provide acceptable agreement with the mechanical failure mode of the specimens. Further sensitivity analyses should be conducted to study the impact of different parameters on the apparent strength and failure of CZM models. The immediate outlook is to implement models to evaluate the effects of pretreatments A2 and A4. This would also include further development to three-dimensional models that take into account hygroscopic and temperature-related effects. Additionally, the development of predictive numerical models will help to (1) quantitatively assess and separate effects of normal peeling and shear stresses at the bondlines, thus increasing the applicability of the current tensile-shear strength results according to EN 302 for thick gluelines, and (2) evaluate and fit cohesive parameters also for different arbitrary geometrical test configurations.

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