



Effects of mechanical and chemical surface preparation on adhesively bonded wooden joints



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ABSTRACT

Tensile shear tests according to EN 302-1 (2013) [4] for load bearing timber constructions were performed using a one-component polyurethane (PUR) and a phenol resorcinol formaldehyde adhesive. Prior to bonding, the adherends' surfaces were prepared with different machining techniques (planing, face-milling, and sanding). Additionally, the surfaces of the PUR specimens were chemically treated with two different priming substances. The results indicate that the priming of the surfaces can improve both tensile shear strength (TSS) and wood failure percentage (WFP) of PUR bondings. However, no effect of the different mechanical surface preparation techniques could be found. Additionally, the suitability of the wood failure proved to be questionable, as the highest WFP was accompanied by the lowest TSS and vice versa, even though the same wood was used for all tests. The inspection of the fracture paths indicated that a failure of the bonding close to the bondline (creating a low WFP) might be even more advantageous than the traditionally favored failure in the adherend part, as the adhesive itself could help dissipate energy, resulting in a higher TSS.

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1. Introduction

The bonding of wood represents one of the main connection techniques in modern load bearing timber constructions, such as in glued-laminated timber. In order to be certified for usage in such structures, the adhesive has to fulfill requirements set by technical standards which are specific to each respective country. Usually, these standards cover the bonding strength determinations, resistance to delamination and investigation of the connection's creep behavior. The bonding strength is determined after different pretreatments at dry and wet stages. In North America (NA), standards like ASTM D2559-04 [1] and CSA 0112.9-04 [2] comprise compression shear tests and define corresponding thresholds for shear strength and wood failure percentage (WFP). The criteria for WFP represents the traditional concept of a high quality wood bonding, specifically it should fail in the adherend to ensure that the adhesive strength surpasses the wood strength. In Europe, these thresholds are defined in EN 301 [3] for phenolic and amino resin based adhesives, where the strength is determined via lap-shear tests according to EN 302-1 [4]. For one-component polyurethane (PUR) bondings, only the requirements for a minimum tensile shear strength (TSS) are given in EN 15425 [5], however, as this standard considers the typical failure behavior

of PUR, requirements for a minimum WFP are omitted. A reason for this adjustment might be the growing interest of construction engineers in a more holistic understanding of wood bonding and the ability to predict failure situations. Therefore it could even be favorable to locate the failure path in the adhesive layer itself, as the adhesive is a much more isotropic material than the wooden substrate. Hence the behavior of the adhesive polymer can be computationally modeled in a more reliable way than the behavior of wood. The adhesive's properties are easier to adjust and control [6]. However, to be able to operate in the NA markets, adhesives have to fulfill the WFP requirements, which are still compulsory there. For relatively new adhesive systems, like PUR adhesives, this proves to be a problem, as they achieve strength requirements but usually show significantly less WFP than traditional wood adhesives such as phenol-resorcinol-formaldehyde resins (PRF). PRF acts as a reference system in NA standards. Therefore, wood bondings with PUR have to be adjusted in such a way that the WFP is increased, especially under wet conditions.

Prior to any modifications of the adhesive itself, the properties of the adherends' surface are studied before adhesive application to gain a better understanding of surface properties that increase bonding quality. For example Singh et al. [7] investigated the influence of the knife condition on the bond quality of polyvinyl-acetate bondings. They found that the pre-damage done to the wood surface with dull knives reached deeper into the wood substance than with sharp ones. As other investigators assume, the adhesive has to cover the pre-damaged region and connect to the

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sound wood substrate to form durable bonds [8]; this deeper pre-damage requires an adhesive that is able to penetrate deeper into the adherend. However, as this pre-damage entails a certain pre-compaction of the wood substrate it becomes more difficult for an adhesive to penetrate into the wood, as the major pathways for the adhesive penetration are blocked. Another recent work was conducted by Kläusler et al. [9], who investigated the bonding quality of PUR bonds on surfaces that were prepared using different machining techniques, including planing, face-milling and sanding. They concluded that a sound wood structure and good wettability of the wood surface are more important for good bonding than surface roughness. To improve surface properties, chemical pretreatments have also been investigated. One well-known solution is the application of a hydroxymethylated resorcinol (HMR) primer prior to the bonding process [10], which successfully improved the WFP in PUR bonds [11]. However, as this primer is formaldehyde-based, it lacks one major advantage of PUR, which is formaldehyde-free. The idea of a formaldehyde-free pretreatment has been considered by Kläusler et al. [12]. They investigated fracture surfaces of PUR bonded joints after shear testing at the wet stage by means of Environmental Scanning Electron Microscope (ESEM) imaging. Their results indicate that loss of adhesion is much more dominant at the wet stage than cohesion failures in the adhesive polymer or in the wooden adherend. Therefore they tried to find ways of using formaldehyde-free coupling agents. Two predominant approaches for a better connection between wood and adhesive were applied. In one, a substance capable of swelling the wood was used to increase the probability of adhesive molecules entering the wood cell wall, which is believed to have a positive effect on the bond quality. The other approach included substances that might be able to increase the number of possible linking points between the wood substrate and the adhesive. Ideally these additional connections should be stronger than the regular hydrogen bonds, which are believed to realize the connection between wood and PUR for the most part. However these hydrogen bonds tend to dissolve under high moisture exposure, which is assumed to be one reason for PUR's low WFP after water storage.

After the previous investigations where the focus laid either on the mechanical surface preparation [12] or the chemical surface priming [9], in the present work, the influence of a combination of mechanical and chemical surface preparations on the bonding quality was investigated in order to find a possible existing optimal combination of these two approaches.

2. Material and methods

2.1. Wood

In accordance with EN 302-1 [4], boards of European beech wood (*Fagus sylvatica* L.) were climatized at 20 °C/65% relative humidity (RH) until equilibrium moisture content was reached. All boards were derived from two logs and were chosen as required

by the above mentioned standard with respect to density (mean raw density of 718 kg/m³), growth ring angle and flawlessness, meaning that boards with very wavy grain direction, red heart wood formation or knots were discarded. Before surface treatments, the boards were mixed in order to evenly distribute any influences caused by the wood itself.

2.2. Surface treatment

Before bonding, adherend surfaces underwent different surface treatments. This included both mechanical preparation methods as well as priming of the surface with chemicals, all of which are described in detail below.

2.2.1. Mechanical surface treatments

2.2.1.1. *Planing (PL)*. For the planed surfaces, a thickness planing machine was used, which was equipped with a four-knife cutter head (knife alignment parallel to the heads' rotation axis) and freshly sharpened knives.

2.2.1.2. *Face-milling (FM)*. The face milling was carried out using a CNC-machine center with a three-knife cutting head. To ensure the knives had enough space for material removal, the head was tilted 0.2° in the feed direction.

2.2.1.3. *Sanding*. Sanding was performed in a commercial wide-belt sander equipped with two operational units using a fresh sanding belt with a grit of P100. The sanding procedure was executed either parallel (SL) or perpendicular (SC) to the grain direction.

Details of the machining parameters used for the mechanical surface treatment are summarized in Table 1 (also cf. [9]).

2.2.2. Chemical surface treatments (priming)

2.2.2.1. *N, N-Dimethylformamide (DMF)*. DMF is a polar solvent, which is able to swell the wood substance better than water. For example work by Ashton [13] and Mantanis et al. [14] showed the potential of DMF as a swelling agent for wood. The idea of using such a substance as a primer is that by swelling the adherend's surface, more functional hydroxyl groups could be available for interaction between substrate and adhesive. Additionally easier penetration of low molecular compounds of the adhesive into the wood cell-wall, which hence support mechanical interlocking, might be possible. It is believed that such effects might improve the bonding quality at the wet stage. Pure DMF was used as a primer in this study.

2.2.2.2. *Desmodur® VKS 20 (VKS)*. VKS represents a commercially available mixture of diphenylmethane-4,4'-diisocyanate with isomers and higher functional homologues (PMDI). It is usually applied in the production of adhesive systems as a hardening component. The idea for its application as a primer is that it penetrates into the wood structure and interacts with the hydroxyl

Table 1
Machining parameters for the mechanical surface treatment.

	Planing (PL)	Face milling (FM)	Sanding	
			Parallel to fiber (SL)	Perpendicular to fiber (SC)
Tool	Knife head	Knife head	Sanding-belt	
Number of cutting edges	4	3	P100	
Feed speed [m/min]	8	6	6	
Working engagement per work step [mm]	1	3	0.3	

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