Wood Adhesives for Non-Destructive Structural Monitoring

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Abstract. Polymeric layers filled with electrically conductive particles can be used for measuring structural behaviour like deformations and crack growth. In glued-laminated timber the polymeric adhesive layers are theoretically best suited to evaluate the health state of the structure. It’s defined by deformations, damage growth in the adhesive joints and wood moisture by non-destructive measurements. Accordingly, the described investigations addressed the question, whether electrically conductive adhesives can be used to monitor the general health state of glued-laminated timber or not.

Glue-laminated timber was produced in laboratory scale by using a dispersion of carbon black into different for timber construction certified adhesives. In climate controlled conditions different influences on the signal has been investigated, including mechanical induced deformations and humidity changes. Other investigated aspects included the dynamic behaviour of the sensual adhesive layer, processing parameters and practical aspects like contacting the adhesive layer as well as the distinguishing of the signals.

Measurements of DC resistivity in the adhesive joint show a correlation between DC resistivity and deformation. Further, the signals also allow a separation among the different kinds of stress states. By varying the contact points of the resistivity measurement it was also possible to monitor the wood moisture.

The investigations show that electrically conductive wood adhesives are a promising alternative for integrated sensors in engineered timber, which can be used for non-destructive evaluation of different negative influences on the structure.

1 Introduction

Structural Monitoring usually uses non-destructive testing methods for evaluation of structural properties. For wood structures and adhesive failure following methods are in use [1,2]: visual inspection, stress wave, ultrasonic, resistance drilling and acoustic emission. While some techniques can be integrated with small sensors into the wooden structure or the bondline, embedded sensors are hard to repair or replace. The installation of embedded or attached sensors is expensive, similar to the regular inspection by experts. On the other side, if the structural material itself exhibits sensorial properties, monitoring becomes economic and less failure-prone.

Polymers, incorporated by electrical conductive fillers, can be used for measuring structural changes. The electrical properties of polymers, especially the resistance, change with rising strain or damage due to crack growing. Pressure sensitive properties are used in tactile robotic hands for example [3], while fiber reinforced plastics are monitored for damage by incorporating carbon fibers [4].
In engineered timber elements, the general health state can be evaluated with knowledge of the history of deformations, damage in the adhesive joints and wood moisture [5]. Additionally, wood adhesives exhibit imperfections due to curing in the adhesive bondline, which is shown by different works [6,7]. These imperfections can influence the durability of the bondline.

Based on the task of non-destructive monitoring and the possibilities of polymers, different approaches were used to examine the usability of electrical adhesives for non-destructive testing and monitoring of glued wood structures.

2 Electrical modification of wood adhesives

2.1 Background

The dispersion of electrical conductive fillers into the adhesive matrix leads to an increase of resistance by building a conducting network. The correlation of resistance and filler content is described by a percolation function with a specific threshold. At this threshold, the formation of a conductive network changes the resistance significantly, compared to the over- and under-percolation range [8]. This percolation model has been extended to the tunnel-percolation model (TPM) [9], where a small distance of insulating polymer can be bridged by quantum tunnelling. The percolation function itself can’t be calculated and has to be determined by experiments.

Influences on the percolation function are the properties of polymer (chemistry, morphology) and filler (wetting, surface chemistry) as well as the processing parameters, especially the induced shear forces [9,10]. Different techniques can be used for mixing and homogenization of conductive adhesives, including ultrasonication bath, ultrasound sonotrode, a dual asymmetric centrifuge, mechanical stirring, calendaring or a microfluidizer [11].

2.2 Experimental Approach

Different combinations of adhesives and conductive fillers have been processed. Two adhesive systems were used, a melamine-formaldehyde-resin (MUF 1251/7551, Akzonobel) and a 1K-PUR (JOWAPUR 686.60, Jowat). Used fillers were carbon fibres (Donacarbo S244, ASK Chemicals), graphite (Timrex KS75, TIMCAL), CNT’s (Baytubes C 150 P, Bayer) and carbon black (Ketchenblack EC-300J, Akzonobel). The used filler content was 5 wt%. The mixing and homogenization were done by a three roll calendar.

With these modified adhesives samples of layered wood (beech wood, Fagus sylvatica L.) were produced and the adhesive layer contacted with glued-in copper sheets. To calculate the specific resistance all but the thickness of the adhesive layer was measurable (see Figure 1). Due to the wooden structure, the adhesive layer differed in thickness in two dimensions. For calculations, the thickness has been assumed as 100 µm.

Figure 2 shows the specific resistance of all tested combinations. Based on the results, the 1K-PUR, filled with 5wt% carbon black has been used for most of the further investigations.
3 Deformation of electrical adhesive layers

3.1 Background

Theories regarding the resistance change due to deformation (sometimes called piezoresistive response) of conductive filled polymers have been covered by different authors. The change of particle-particle distance by compression of the polymer [12] is based on elastomer matrix polymers. Weiß showed an influence through the roughness of the polymer-electrode contact area, which is only valid for non-bonded polymers and if the compressive force is perpendicular to the contact area [13].
Overall, the electrical conductive polymer has a DC resistance, which is defined by its shape and dimensions. Change of the cross section through stretching or compression will change the metered bulk resistance.

3.2 Experimental Approach

First tests were realised with layered wooden samples, which were tested in 3-point bending [14].

The investigations included a comparison of different adhesive systems regarding their piezoresistive response to deflection. The combinations included carbon black, carbon fibres, graphite and carbon nanotubes crosswise with a 2-componend melamine-formaldehyde resin (MUF) and a 1K-Polyurethane system (PUR) (see also 2.2). The results showed the most stable signal and best correlation between the electrical resistance and bending deformation for a carbon black/1K-PUR adhesive system (5wt% Ketchenblack EC300J in Jowapur 686.60), which is shown in Figure 3.

![Figure 3](image.png)

Figure 3: 3-point bending: relative change of deflection and DC resistance in both adhesive layers

The measurement shows a clear correlation of bondline resistance and deflection, while the different trends of resistance are reflecting the bondline position. While above the neutral phase the resistance decreases, the resistance below the neutral phase is increasing together with the increasing deflection.

The explanation for this effect can be found in the stress allocation of bending samples. The compression stress in the upper joint is followed by a shortening and perhaps a thickening of the adhesive layer, therefore the metered resistance decreases. The joint below the neutral phase is stressed in tension, which results in elongation and thinning of the adhesive layer and therefore an increase of resistance.
4 Humidity measurements by electrical adhesive layers

4.1 Background

The strength of wood depends on the wood moisture level and wet wood is threatened by decay through fungi. Therefore, the moisture content and their history is a strong indicator for the health state of wood. The mostly non-destructive method for moisture measurement of wood is made by driving nail electrodes into wood and measure the resistance between them. For a long term monitoring this method has been expanded be electrical conductive adhesive connection at the electrode tips [15]. This method helps to eliminate the resistance changes due to contact problems at the electrodes, especially through wood swelling.

4.2 Experimental Approach

The usability of the proposed electrical modified 1K-PUR (5wt% carbon black, see 2.2) as wood moisture sensing coupler has been investigated. The test setup used a similar simplified sample format like in the former investigations with glued in copper sheet electrodes and one bondline (compare to Figure 4). Control measurements were made by a moisture meter, the test material was from the same log with comparable annual ring sizes.

![Figure 4: sample geometry for moisture test setup](image)

Figure 5 displays the change of wood moisture and the change of resistance in respect of time. Referring only to the measurable section of the resistance measurement, the linear correlation coefficient r of both measurements was 0.6755.

The results show that the resistance measurements with the adhesive coupler and copper sheet electrodes can’t be used for reliable wood moisture measurements yet. Further improvements on the adhesive mixture and processing could possibly help to overcome these problems.
Figure 5: Resistance change between glued in copper sheet electrodes and wood moisture by a commercial moisture meter

5 Damage grow in electrical adhesive layers

5.1 Background

Damage in bondlines through opening and growing of cracks is based on deformation induced stress. During the curing process, shrinking stresses are caused due to emission of solvents and low solid content. After curing, the swelling and shrinking of wood causes stress in the bondline. Figure 6 displays two examples for damage in adhesive layers.

Figure 6: (A) cracks and imperfections in the bondline of UF [16], (B) curing cracks in electrically modified 1K-PUR, the scales correspond to 1 mm

With connection between the conductive particles and the polymeric matrix, the resistance will increase with growing number of cracks. The crossing of measurement range into
isolating resistance can be assumed as a failure criterion. In the case of a loose particle-polymer-bond, a decrease of resistance could be addressed to a migration of the particles in the polymer matrix due to metering voltage or matrix deformation. Then, the failure of electrical resistance doesn’t correlate with mechanical failure [17].

5.2 Experimental Approach

The in-situ evaluation of damage in the bondline was approached by fatigue tests with bending samples. The samples were made from beech wood (fagus sylvatica L.), 20 mm width, 12 mm height (3 wooden layers, 2 adhesive layers, each adhesive layer 3 mm away from the edge, and 225 mm long). The used conductive adhesive consisted of a dispersion of 5wt% carbon black (Ketchenblack EC300J) in 1K-Polyurethane (Jowapur 686.60), compliant to the former investigations. The adhesive has been contacted by glued-in copper tape and wired to the resistometer with contact clips and shielded cable.

The samples were loaded with a rising threshold level in one direction, increasing the threshold by 27.5 N and the amplitude by 22.5 N per level. The material reaction was recorded by resistography, extensometry and thermography. An exemplary result is shown in Figure 7.

![Figure 7](image)

**Figure 7:** Material reaction of layered beech wood under bending load, measured by extensometry, resistography and thermography (corresponds to [18])

The material reaction as function of the stress amplitude, recorded by thermography and resistography, show a clear leap at 36 N/mm. The extensometry, which was recorded by the traverse stroke, shows only a clear reaction at the second point of failing at around 14500 cycles. At this point, the tension area delaminates and the sample collapses. The results allow to guess, that resistography of an electrical conducting adhesive layer in wood can be used for non-destructive evaluation of the damage grow in the bondline.
6 Summary

The results show, how to use electrical modified bondlines as sensorial options to evaluate the condition of layered glued timber elements. The sensorial options can include information about the deformation as well as it can be used as coupling for wood moisture content measurements. The parallel thermography and resistigraphy of the bondline exhibit a promising opportunity to evaluate damage accumulation in the bondline under dynamic load. After all, there are still some drawbacks, which need further investigations.

7 References