

INVESTIGATION OF STRUCTURAL WOOD ADHESIVE JOINTS SUBJECTED TO ARTIFICIAL AGING PROCESSES USING NUCLEAR MAGNETIC RESONANCE (NMR) RELAXOMETRY

UNTERSUCHUNGEN AN TRAGENDEN HOLZLEIMVERBINDUNGEN MITTELS NMR-RELAXOMETRIE VOR UND NACH KÜNSTLICHER ALTERUNG

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SUMMARY

Within a master thesis [1], NMR relaxometry was examined as a non-destructive method for assessing wood adhesive joints before and after artificial aging. Preliminary tests showed that urea-formaldehyde (UF) adhesives gave distinct NMR signals, leading to their selection for main testing. Samples bonded with UF were partially exposed to hydrothermal treatment. NMR depth profiles and mechanical tests showed strength reductions up to 84 %. A correlation between NMR amplitude differences and joint strength could be shown. The study confirms that NMR relaxometry can effectively detect adhesive degradation in timber joints. Further work should explore additional aging conditions and adhesive types.

ZUSAMMENFASSUNG

Im Rahmen einer Masterarbeit [1] wurde der Einsatz von NMR-Relaxometrie als zerstörungsfreie Methode zur Bewertung von Holzleimverbindungen vor und nach künstlicher Alterung untersucht. In Vorversuchen wurden verschiedene Klebstoffe mit Fichte und Buche getestet. Urea-Formaldehyd (UF) zeigte dabei deutliche NMR-Signale und wurde für die Hauptuntersuchung ausgewählt. Die Proben wurden nach DIN EN 302-1 [2] verklebt und teils einer hydrothermalen Alterung unterzogen. NMR-Messungen sowie mechanische Prüfungen zeigten

signifikante Festigkeitsverluste von bis zu 84 %. Es bestand eine Korrelation zwischen der NMR-Amplitudendifferenz und der Klebfestigkeit. Die Ergebnisse zeigen das Potenzial der NMR-Relaxometrie als zerstörungsfreies Prüfverfahren für gealterte Klebefugen im Holzbau. Weitere Forschung sollte zusätzliche Alterungsszenarien und Klebstoffe einbeziehen.

1. INTRODUCTION

The use of timber as a sustainable material is increasingly important in modern construction. Laminated timber, often joined with structural adhesives, is a central element in engineered wood design. However, the re-use potential or the long-term durability of these adhesive joints is a critical concern, particularly when exposed to environmental influences over decades. This study investigates the potential of nuclear magnetic resonance (NMR) relaxometry as a new non-invasive technique to assess the condition of adhesive joints in wood structures, both in their original state and after undergoing artificial aging processes.

2. PRELIMINARY INVESTIGATIONS

An extensive series of pre-tests was carried out to evaluate the feasibility of NMR relaxometry for identifying adhesive interfaces and tracking moisture distribution. Seven different adhesives were examined, representing both polycondensation (e.g., UF, MUF, PRF) and polyaddition (e.g., PUR, EPI, EP) polymer hardening mechanisms. These adhesives were applied to spruce and beech samples, forming adhesive layers with a controlled thickness of 0.5 mm, using cardboard spacers. The specimens measured 55 mm by 55 mm in width and 10.5 mm in thickness.

Measurements were performed using a MOUSE PM25 (Fa. Magritek) device, applying the Carr-Purcell-Meiboom-Gill (CPMG) sequence to gather depth profile data. NMR imaging and optical microscopy were employed to validate layer structure and adhesive geometry. Results indicated that polycondensation adhesives, particularly UF and MUF, produced distinct amplitude increases at the adhesive interface. In contrast, polyaddition adhesives often showed minimal signal contrast between the adhesive and surrounding wood. Furthermore, moisture content and wood species had a significant effect on signal amplitude. Microscopy confirmed variations in adhesive layer thickness and helped correlate physical and NMR-observed characteristics.

These findings led to the selection of urea-formaldehyde (UF) adhesives for further analysis. This choice was driven by the adhesive's documented and well-known sensitivity to moisture-induced degradation and its clearly distinguishable NMR signal behavior.

3. MAIN EXPERIMENTS

The core testing phase focused on evaluating the effects of artificial aging on adhesive joints bonded with UF adhesives. Twenty test specimens as shown in Fig. 1 were prepared from spruce wood for representativity in accordance with glued-laminated timber members in practice being mostly limited to softwood (contrary to EN 302-1 recommending beech for guaranteed failure at adhesive interface in the frame of tensile-shear testing). The samples, which were made up of two wooden pieces that were 5 mm thick and a 0.5 mm thick adhesive joint, were each 150 mm long, 20 mm wide, and 10.5 mm thick. The bonding process adhered to the geometry specifications outlined in DIN EN 302-1. The bondlines of all 20 samples were initially measured by NMR after production. The red section in the middle of the adhesive joint is relevant to determine the tensile shear strength, whereas the light blue part with 4 cm by 4 cm is the NMR-sampled area. Half of the specimens ($n = 10$) underwent no artificial aging (treatment A1) and were directly mechanically tested.

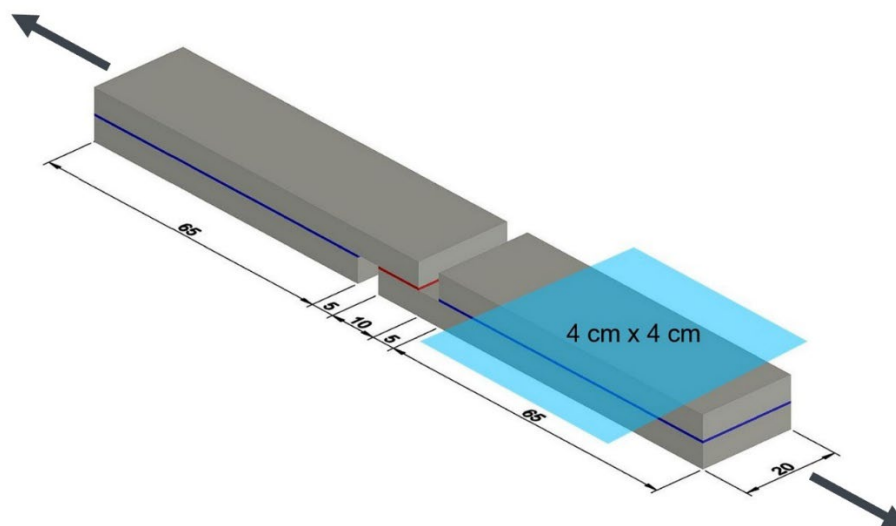


Fig. 1: Test specimen for tensile shear strength with tensile-shear (red) and NMR (light blue) measurement zones.

The other half of the specimens ($n = 10$) underwent an accelerated aging protocol labeled as treatment A5, involving submersion in boiling water for six hours followed by two hours in cold water, and subsequent drying to equilibrium moisture content (NMR depth profile measurements were taken both before and after this treatment on the same samples). In addition to NMR analysis, visual inspection of the specimens revealed clear signs of degradation, such as discoloration and crack patterns indicative of adhesive failure. Those depth profile measurements and the side view of the adhesive joint are shown in Fig. 2.

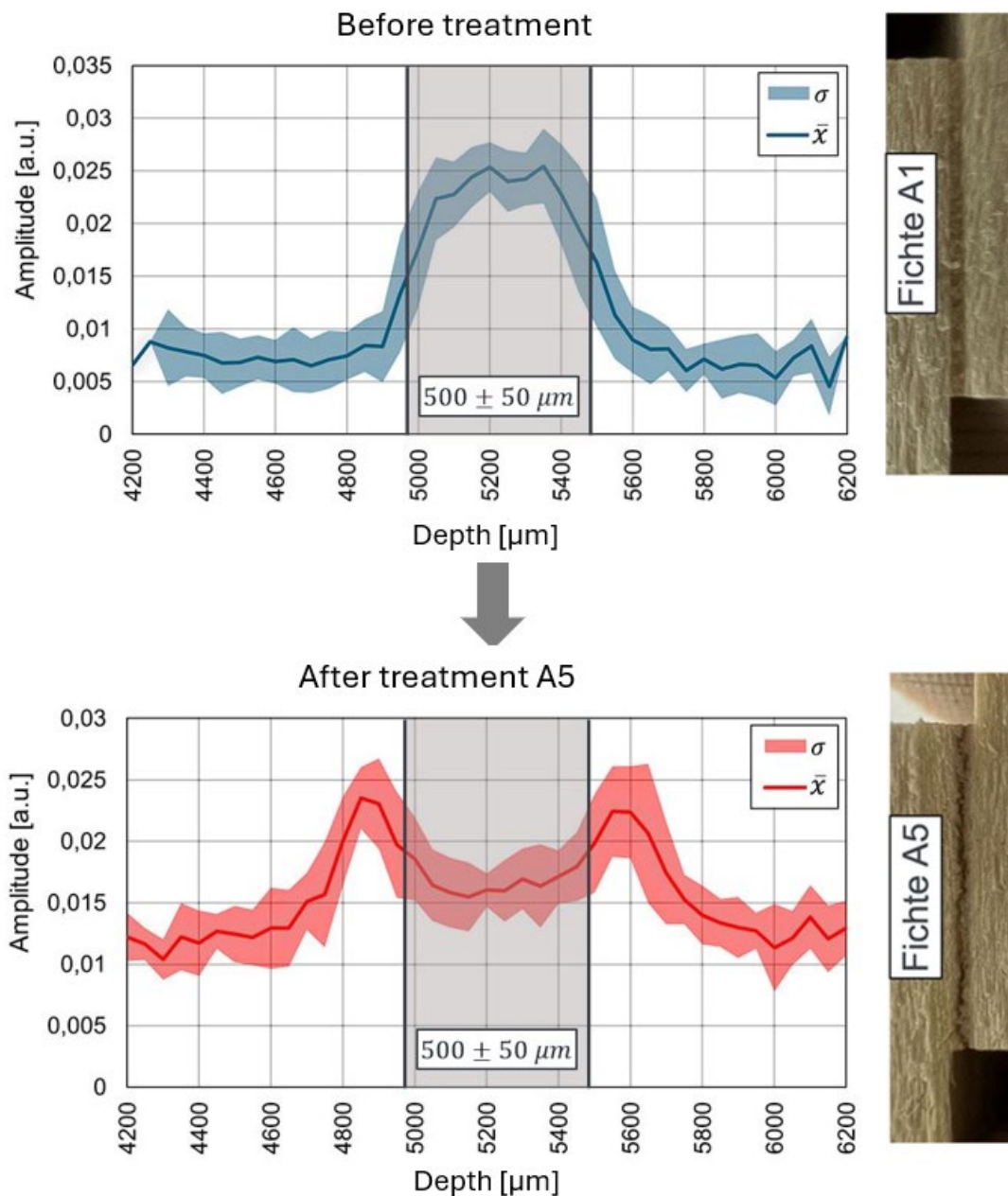


Fig. 2: NMR depth profile measurements with mean and standard deviation plus side view of the adhesive joint before and after treatment

Finally, tensile shear tests were conducted on the samples after the treatment A5. The results showed a considerable reduction in bond strength, with beech specimens experiencing an average loss of 84%, and spruce specimens 71%. Notably, the amplitude of profiles obtained from the NMR measurements demonstrated a evident statistical correlation with the mechanical performance of the joints. In particular, the difference and ratio of amplitudes between the adhesive and surrounding wood areas emerged as reliable indicators of joint degradation, yielding a correlation coefficient of approximately 0.96 as shown in Fig. 3.

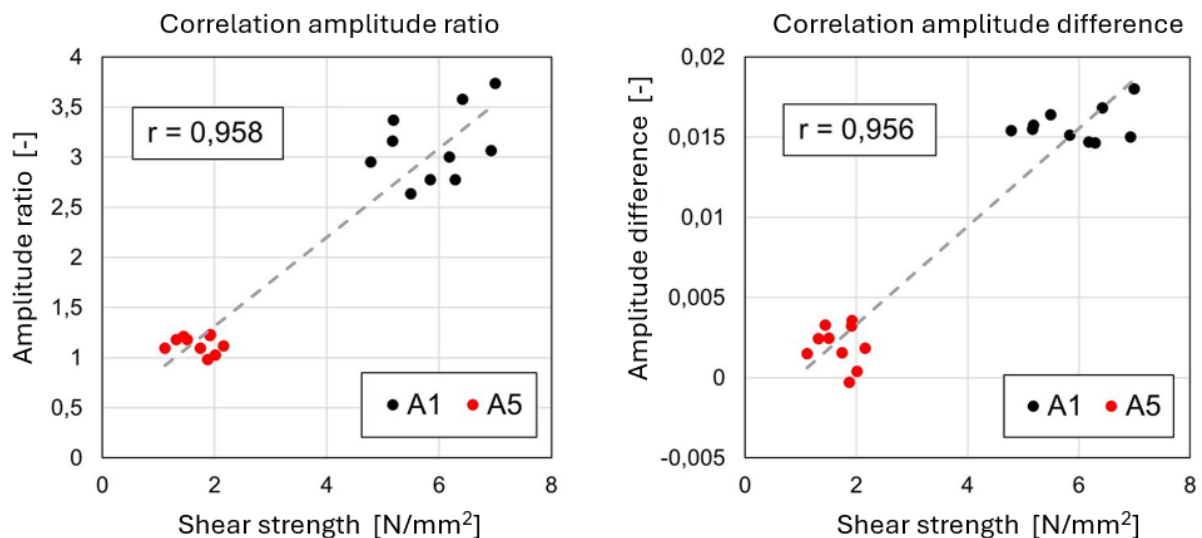


Fig. 3: Scatter plot correlating NMR amplitude characteristics with shear strength, indicating a linear relationship ($r = 0.96$)

4. SUMMARY

The study provided clear evidence that hydrothermal aging significantly impairs the structural integrity of UF-bonded wood joints. NMR relaxometry proved highly effective in detecting changes in moisture distribution and adhesive behavior resulting from such aging. Differences between beech and spruce samples were attributed to variations in wood anatomy and moisture absorption characteristics. The strong correlation between NMR signal data and mechanical performance supports the viability of relaxometry as a diagnostic tool for evaluating bond quality in glued timber structures.

5. FUTURE PERSPECTIVES

The findings of this research open several avenues for further investigation. Future studies could e.g. apply alternative aging scenarios, such as freeze-thaw cycles or prolonged UV exposure. This would simulate long-term environmental effects more realistically, and potentially provide additional data points in-between the closely clustered extreme (A5) and references (A1) scenarios; therefore, further validating the observed correlation. Expanding the range of tested adhesives and exploring thinner or more complex joint geometries would also enhance the practical relevance of the findings, as thinner adhesive joints are often found in practice. In addition, integrating NMR data with chemical analytics, such as the quantification of formaldehyde migration, could deepen the understanding of degradation mechanisms.

From an application standpoint, the development of portable, field-ready NMR devices would greatly enhance the feasibility of in-situ diagnostics for bonded timber components in existing structures. Such tools could help determine the residual service life of structural members and support more sustainable building practices by enabling reliable reuse of glued wood components.

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