WAVEFORM ANALYSIS OF ACOUSTIC EMISSION MONITORING OF TENSILE TESTS ON WELDED WOOD-JOINTS

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Abstract

Wood welding is a relatively recent procedure for preparing joints between pieces of wood that shows promising potential for avoiding some of the problems related to conventional adhesive jointing of wood. As a first step towards more extensive characterization of their damage behavior and of the failure mechanisms, tensile tests on welded wood joints have been monitored with acoustic emission (AE). This contribution attempts a more detailed analysis of the AE signals from stair step-load tests on welded wood joints.

Keywords: Welded wood, tensile test, AE waveform analysis, failure mechanisms

Introduction

To connect load bearing timber structures, practitioners have at their disposal a series of methods; a first fraction of them rely on mechanical fasteners, a second type achieves load transmission by means of direct compressive contact between timber members, and a third increasingly considered option is adhesively bonding. It is less known that welding of wood also allows for load bearing connections of timber elements.

Wood-to-wood connections by means of welding are an innovative process, which holds high potential for development. To achieve joints by means of welding, the wooden parts are pressed against each other and a rapid vibration heats up and melts the material at the interface within few seconds. Once the motion stops, and after cooling down, a solid bond is formed [1]. Bonds are completed in less than a minute, and no further preparation of the surfaces is required. First reports related to welding of wood date back to Sutthoff et al. [2], welding of wood based on Linear Vibration Welding (LVW) greatly improves homogeneity and resistance of the resulting bonds [3]. Two sets of parameters proved to have an influence on the bond strength: firstly, parameters related to the wood [4-5], and secondly parameters related to the LVW device [6].

Since welding of wood is an alternative to adhesive bonding, it is also of interest to compare the mechanical properties and the AE behavior, i.e., the damage accumulation and failure with that of adhesively bonded joints made from the same type of wood [7]. The AE behavior (AE activity, AE intensity, Felicity-ratio, and linear AE source location) under stair step loading for both types of joints is compared and discussed in [8].

The objectives of this paper are (i) to compare AE waveforms recorded with the two types of sensors used in the experiments on welded wood joints, and (ii) to look for trends in the frequency content of the AE signals with increasing intensity (e.g., AE signal amplitudes observed with increasing loads).
Material and Experimental

In order to investigate the strength of wood welded joints, a series of single-lap welded timber joints was produced in which the sole varied parameter was the overlap length, L. The timber species used was spruce (Picea abies) cut from high quality almost defect-free boards. The material was conditioned to 12% moisture content prior to manufacturing of the specimens, and then again stored in constant climate before and after welding and until testing.

A total of 25 wood welded single lap joints were manufactured by welding two timber boards (700 mm long, 60 mm wide and 15 mm thick) by means of a Branson M-DT24L linear vibration-welding machine; Fig.1 details a specimen. Subsequently, a groove up to the wood weld was cut in each of the now connected boards, the distance between the two grooves defining the overlap length. The overlap length was varied from 100 mm to 400 mm in steps of 100 mm. Each of the welded lap joints was manufactured and subsequently tested five times. Five additional specimens with an overlap length of 100 mm were produced to study the AE behavior.

![Schematic geometry of single lap joint welded specimens](image)

Fig. 1: Schematic geometry of single lap joint welded specimens (not to scale).

Tensile tests with AE monitoring were performed on a servo-hydraulic test machine (type Instron 1251) with hydraulic grips (clamping pressure 30 bar) at 3 mm/min (first specimen) and 0.3 mm/min (all other), respectively. Specimens were stored and tested under laboratory conditions of +23°C and 50% relative humidity (differing from the standard conditions +22°C and 65% relative humidity for wood) after reducing the total thickness from 30 mm (Fig. 1) to 25 mm. Aluminum distance bars were used to prevent extensive compression of the specimens in the grips. A load cell with 200 kN (specimens 1 and 2) and 50 kN range (specimens 3-5) was used.

Acoustic Emission (AE) monitoring of the tensile tests was performed with commercial AE equipment (type AMSY-5 from Vallen Systeme GmbH) with a total of eight AE sensors (for type SE45-H, and four type SE150-M). Two sensors (SE150-M) were used as guard sensors on the hydraulic grips, the other six were mounted on the specimen with spring clamps using silicone-free vacuum grease as couplant. Threshold was set at 40 dB_{AE} and 50 dB_{AE} for specimens mounted near the top and bottom grip, respectively and at 55 dB_{AE} for the guard sensor on the bottom grip. Both, AE signal parameters and full AE waveforms were recorded, with 5 MHz sampling. Machine load and crosshead displacement was recorded simultaneously with sampling every 100 ms. Data analysis was performed with equipment specific software (VisualAE® and
VisualTR® from Vallen Systeme GmbH). Specifically, the Fast Fourier Transform (FFT) feature extractor routine (VisualTR®) has been extensively used in the AE waveform analysis.

Results and Discussion

Mechanical Properties

The mechanical properties are reported in detail in [8] and only a few essential points are repeated here. All wood welded single lap joints tested with AE monitoring exhibited almost perfectly linear-elastic load-displacement behavior, and failed in a brittle and sudden manner. Failure load and displacement at failure show a fairly linear correlation for all specimens. One specimen was tested quasistatically with AE monitoring (displacement control at 3 mm/min). The remaining four specimens were then tested under quasistatic tensile loading with stepwise increase and unloading under displacement control (0.3 mm/min). The specimen tested quasistatically to failure yielded a failure load of 6.7 kN and a crosshead displacement at failure of 0.28 mm; those tested stepwise an average of 5.3 kN (coefficient of variation ± 2.4 kN or 38.1%) with an average crosshead displacement at failure of 0.24 mm (specimen deformation was not directly measured). A closer post-failure observation indicates that the welding process did not always yield in perfectly welded surface, see Fig. 2.

Fig. 2: Failure surfaces of two welded wood specimens tested with AE monitoring (left) and of two others including one specimen without separation of the two joint faces (right), on which the sensor positions are marked with pencil; note the light areas indicating poorly welded surfaces among the dark surface features.

The failure surfaces of the specimens after tensile failure showed a pattern of dark brown and light yellow color. Qualitatively, specimens 1 and 2 (Fig. 2, left) show a larger amount of light yellow color. This seems to correlate with lower failure loads (6.7 kN, but at higher strain rate, and 3.0 kN, respectively) than the other specimens. It can be noted that on the edges, the fracture surfaces indicate sufficient welding (dark brown areas). Visual inspection before testing hence did not reveal the difference in welding quality.

AE Signal Parameter Analysis

AE activities, AE intensity as a function of load, and linear as well as planar AE signal source location have also been discussed in detail in [8]. Again, the major conclusions are summarized here. AE activity and AE intensity both are increasing with increasing level of loads. Under stepwise loading, the joints show a clear Felicity effect with decreasing Felicity-ratio for
increasing load steps. Values of the Felicity-ratio around or below 0.90 are indicative of critical damage. Even though AE activity and AE intensity (e.g., measured by the AE signal amplitude) drop when holding the load constant, a surge in AE activity and AE intensity is observed upon unloading from each load level (even if the Felicity-ratio is still >1). This could indicate damage that occurred during loading, but also damage existing in the specimens from the welding process, such as, e.g., incomplete bonding evident as light yellow surface parts (Fig. 2).

Linear AE signal source location plots projected on the narrow (thickness) side of the specimens yield AE source location clusters (especially when filtered for events with amplitudes ≥60 dBAE), isolated in time roughly in the area of the weld or nearby. The times of occurrence correlate well with load changes, i.e., the AE activity and AE intensity surges. This highlights the weld zone as a weak area with significant damage accumulation. Damage starts quite early in the tests, i.e., at relatively low loads. This leads to failure by separation of the two adherends in a plane inside the weld-zone. The mechanisms contributing to failure can, however, not be identified with this type of analysis.

**AE Waveform Analysis**

Analysis of the recorded AE waveforms will be explored for providing more information on the events and mechanisms leading to failure. As a first step, Fast Fourier Transforms (FFT) calculated from the recorded AE waveforms are compared for both types of sensor and for different load levels. In a second step, two features of the FFT are compiled (using the FFT Feature Extractor routine provided in the Transient. Recording data analysis package of Vallen Systeme GmbH). This routine determines the frequency at which the peak amplitude in the FFT occurs, as well as that of the center of gravity of the FFT spectrum. These features are compared for the different sensors types and for the different stages of the tests.

From a visual inspection of the FFT calculated from the AE waveforms, there is a slight trend for a higher share of AE signals with relatively low frequency content, i.e., essentially below 100 kHz and 150 kHz, for the sensor type SE45-H and SE150-M, respectively (Fig. 3). It has to be noted that a high-pass frequency filter of 30 kHz has been used in all tests, and that a Hamming window was applied for calculating the FFT.

Visual inspection, therefore, roughly yields two classes of AE waveforms, one with relatively low frequency content and one with higher frequency contributions (above about 100 kHz and 150 kHz for the two sensor types, respectively). This hints at different AE signal source mechanisms, since signal attenuation in the specimens is relatively small and the effect is observed for sensors at comparable locations (near the top of the specimens).

As noted above, a software routine (FFT Feature Extractor, VisualTR® from Vallen Systeme GmbH) has yielded two features from the FFT of the recorded AE waveforms, namely two frequencies, i.e., that at which the maximum amplitude in the power spectrum and that at which the center of gravity of the FFT occur. Visual inspection of FFT calculated with different cut-off windows do, in some cases, show significant differences (e.g., between rectangular or Hamming), notably resulting in different values for the frequency at which the maximum amplitude of the FFT occurs. Further, in order to reduce the influence of noise at higher frequencies (above 250 to 300 kHz), a cutoff of 5% of the maximum amplitude has been applied. Calculation of the FFT features without a cut-off resulted in a significantly larger spread in the center-of-gravity frequencies, especially for low amplitude AE signals. Figure 5 shows plots of the FFT features for both types of sensors used in the test.
Fig. 3: Fast Fourier transforms (with Hamming window) of AE signals recorded in the early (below 3 kN), middle (below 7 kN) and late stage (below 9 kN) of a tensile test with stair step load pattern, (Left) Sensor type SE-45H, (Right) Sensor type SE-150M, showing relatively low frequency content (essentially below 150 kHz and 200 kHz, respectively).

From the graphs in Fig. 5 it is clear that there are at least two distinct classes of AE signals that occur during the load tests to failure. This distinction is evident for both types of sensors, even though the separation between the two clouds is smaller for the sensor type SE-45H than for the resonant sensor type SE-150M. Clearly, there is a larger spread in the frequency at the center-of-gravity of the FFT for the AE signals recorded with the resonant sensor (type SE-150M). For sensor type SE-45H, the plot of frequency at maximum amplitude of the FFT may
even indicate a separation into three classes of signals, one ranging from about 30-50 kHz, one from about 70 to 85 kHz, and third from about 90 to 110 kHz.

Fig. 4: Fast Fourier transforms (with Hamming window) of AE signals recorded in the early (below 3 kN), middle (below 7 kN) and late stage (below 9 kN) of a tensile test with stair step load pattern, (Left) Sensor type SE-45H, (Right) Sensor type SE-150M, showing higher frequency content above 150 kHz and 200 kHz, respectively (bottom).

The data sets from both sensor types further indicate that higher amplitude AE signals (above about 60 dB$_{AE}$) tend to have a higher frequency at which the maximum amplitude in the FFT occurs. With respect to the frequency at which the center-of-gravity of the FFT occurs (data not
shown), the separation into two signal classes is not observed. Figure 6 shows a further analysis of the frequency at which the maximum amplitude of the FFT occurs. This time, the data are plotted as a function of time and the corresponding load signal is shown as well. It can be noted that the separation into two classes is observed almost from the start of the loading (except for the first load step, for which very few signals are recorded). If this separation is interpreted in terms of different AE signal source mechanisms, they are active throughout the test while load is applied (except for the Felicity-effect upon reloading). A closer inspection of the distributions shows a trend for signals with a higher frequency at maximum FFT amplitude to occur mainly during load increase (at least for the first few load steps), with fewer signals observed for increasing hold times at constant loads than those with lower frequencies. With increasing load steps, this difference becomes less obvious and at the last load level before failure, both types of signals are observed even during unloading.

![Fig. 5: Features of fast Fourier transforms of AE signals recorded in a tensile test with stair step load pattern, (Left) Sensor type SE-45H, (Right) Sensor type SE-150M, (top) frequency of center of gravity versus that of maximum amplitude, (bottom) frequency of maximum amplitude versus AE signal amplitude.](image)

Even with clear evidence for at least two, possibly three classes of AE waveforms that are recorded during the tests, a direct identification of the responsible AE signal source mechanisms is still not possible. Since mechanical properties of the wood from the welded zone (e.g., stiffness, hardness) are not available it is, however, not clear whether and possibly how much AE signal source mechanisms or AE signal propagation are affected by a possible variation in mechanical properties. The relatively low frequency content of one class of AE signals tentatively hints at
friction or friction-like effects. This would also be consistent with the effective shear load that is induced in the welding zone by the tensile load applied to the specimens. It is possible that the poorly welded areas and the observed roughness of the failure surfaces (see Fig. 2) provide a source of these friction-like signals. The AE signals with higher frequency content then quite likely reflect other damage mechanisms. The absence of AE signals with high amplitudes or high signal energy throughout the test (except at failure) would be consistent with defect formation on a “small” scale, excluding, e.g., large, sudden disbonding or delamination.

Fig. 6: Frequency of maximum amplitude of fast Fourier transforms of AE signals recorded in a tensile test with stair step load pattern versus time. (a) Sensor type SE-45H, (b) Sensor type SE-150M.
Conclusions

AE monitoring of load test on welded wood joints has indicated that AE activity and hence damage occurs mainly in the weld zone (around the center plane of the specimens). AE waveform analysis has provided evidence for two or three distinct classes of AE signals that occur throughout the test. AE signals with higher frequency content do appear more frequently during loading and less during hold at constant displacement (i.e., slight load decay). The AE signal amplitudes (mostly below 70 dB_{AE}) and the AE signal energies (mostly below 1x10^5 e.u. from time-integration of the squared voltage signal) hint at damage occurring at micro-or meso-scale, slowly accumulating to larger defects resulting in final failure. Friction or friction-like effects may also play a role, since there are a significant number of signals with "low" frequency content. Visual inspection of the failure surfaces after the test further shows that there is a certain percentage of unbonded or poorly bonded weld area. The size of that roughly correlates with the failure loads (low loads for larger unbonded area). This may provide a possible source of friction-like signals with low frequency content.

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References