Adhesively Bonded Joints Composed of Wooden Load-Bearing Elements

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Abstract

Joining timber structural elements using mechanical fasteners goes against the anisotropic and fibrous nature of the material. Adhesive bonding is by far better adapted, since it permits a smoother load transfer. However, due to the not yet fully understood behavior of wood-adhesive joints, there is still no generally recognized design method to predict the strength of such joints. As a contribution to help close this research gap, the authors have carried out experimental and analytical investigations on adhesively bonded double lap joints composed of timber. The paper addresses the question of the influence of the overlap length and the adhesive thickness on the strength of adhesively bonded joints and the corresponding stress distribution under the bonded splice.

1. Introduction

Mechanical connectors such as screws, bolts, nails, or pins are those mainly used to connect timber structural elements. However they weaken the cross section of the connected elements by cutting through the fibers. On the other hand, although adhesive joints are increasingly used for fibrous and anisotropic materials such as G-FRP, they are still not used for timber structural elements. Where wood was traditionally joined with carpenters' glue, the function of the glue was essentially gap-filling rather than load-bearing. The advantages of glued joints were first recognized by the airplane and automobile industries: besides the already mentioned advantages, there is a favorable behaviour under reversed loading, and adhesive joint offers a natural protection by sealing off environmental influences. One of the most prominent early examples of adhesive joints was the de Havilland Mosquito fighter-aircraft, which essentially consisted of plywood with an intermediate layer of balsa and the substantial parts were glued together. Adhesive joints exhibit higher efficiencies in many aspects. They are stiffer than bolted joints. This is particularly important when stiffness is the governing factor for the structural design.

Before adhesive bonding can gain larger acceptance for use in the design of load-carrying structures, methods should be developed to predict the joint strength as a function of the material properties, the joint geometry and the type of loading. A prerequisite for the successful prediction of strength is the understanding of the stress-strain state in the joint. The stress–strain state can be determined either analytically, by solving the differential equations describing the mechanics of the joint, or numerically with the use of Finite Element Analysis (FEA). Contrary to analytical solutions, mostly restricted to idealized situations [1–2], FEA permits the consideration of important geometrical details as well as non-linear and anisotropic material behavior of bonded joints [3,5]. Research for the application of adhesive-bonded connections has been performed mainly in aircraft and automobile applications and the development of adhesive bonding for civil infrastructure applications is still at an early stage [6].

The objective of the investigations presented in this paper was to investigate the influence of major geometrical parameters on the joint strength and the stress-strain state inside the joint. Besides this, it is aimed to provide data to benchmark a design method for adhesive bonded lap joints for timber members [7].

2. Experimental investigation

2.1. Materials

Symmetrical double-lap joints were fabricated using rectangular sections. The timber used was Spruce (*Picea abies*) conditioned to 12% moisture content. The double lap joints consisted of two outer and two inner adherends connected by a layer of adhesive; Fig. 1 details the used nomenclature. The inner profiles were always twice as thick as the outer ones to keep the cumulative cross-section constant.

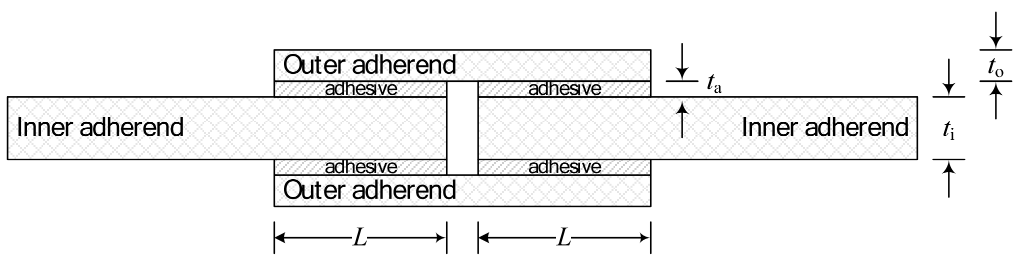

Figure 1: Geometry of lap joint specimens (not to scale)

Regarding the mechanical properties of the considered timber, the longitudinal modulus of elasticity was assumed to be 10 MPa; the transverse modulus of elasticity and the shear modulus as 0.6 MPa (all values according to generally recognized literature [8]). A two component-epoxy adhesive (SikaDur330) was used. Previous work had shown that the tensile strength is 38.1 MPa, the corresponding failure strain 0.97% and the E-Modulus 3.55 GPa [3]. The behavior in tension was linear-elastic up to brittle failure.

2.2. Parameters

The influences of, firstly in series S1, the overlap length (80, 120 and 160 mm), and, secondly in series S2, the thickness of the adhesive layer (0.5, 1.0 and 1.5 mm) were investigated. The labeling, e.g. F.160.15 represents a specimen with 160 mm overlap length and 1.5 mm adhesive layer thickness. The length, width and thickness of the central timber members were kept constant at 350 mm, 50 mm and 38 mm, respectively. Table 1 shows the parameter combinations.

2.3. Methods

A Schenck Trebel testing machine with a capacity of 250 kN was used. The quasi-static axial tension experiments were performed under displacement-control at a constant loading rate of 10 mm/min. The study was conducted within a laboratory environment without the consideration of temperature and moisture effects. Figure 2 shows a specimen clamped in the testing machine.

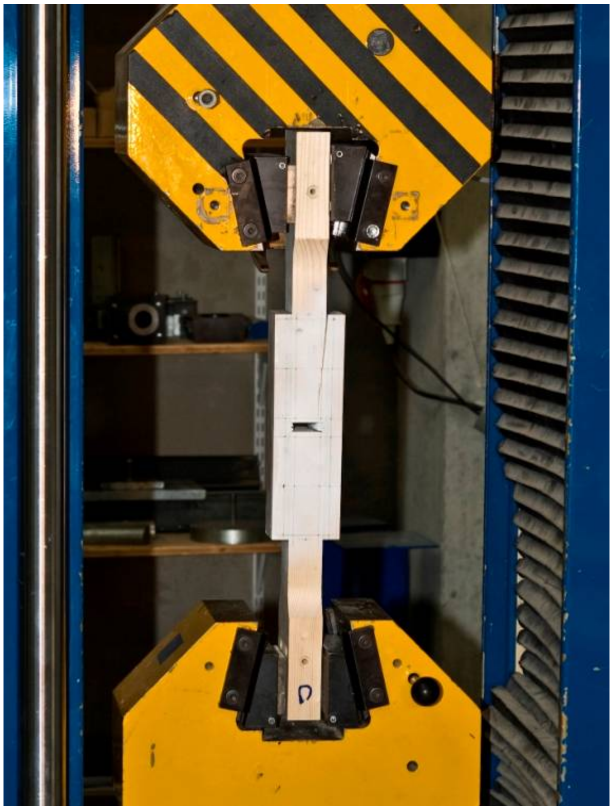

Figure 2: Double lap specimen clamped into testing machine

2.4. Experimental results

Figure 3 shows a typical specimen after failure, which usually occurred in the timber, just below the end of the overlap length, inside the inner adherend. In no case did the adhesive layer fail.

Table 1 shows the ultimate failure loads measured for the double lap specimens. The test results can be summarized as follows:

- The overall scattering of the strengths amounts for around 7%, and is comparable for both investigated series, see Tab. 1.

- Joint strength is related to the overlap length: both are positively correlated, as shows Fig 4.

- Joint strength is almost independent on the adhesive thickness, at least within the range of investigated data, as indicated by Fig. 5.

Table 1: Overview of lap joint configuration and experimental results

Specimen designation	Overlap length [mm]	Adhesive layer thickness [mm]	F_{ult} (kN) Mean	F_{ult} (kN) Std.-Dev.
F.080.10	80	1.0	23.2	2.4
F.120.10	120	1.0	31.3	0.5
F.160.10	160	1.0	38.3	6.2
F.160.05	160	0.5	41.9	2.8
F.160.15	160	1.5	40.3	5.1

Figure 3: Double-lap specimens after testing: general view (left), close-up at the locus of failure initiation (right)

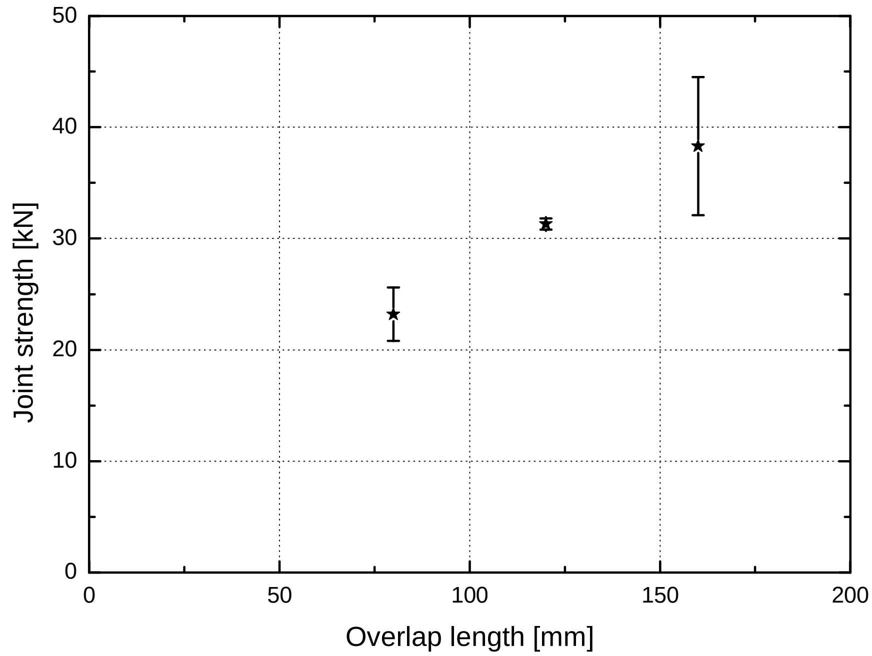

Figure 4: Experimentally determined joint strengths vs. overlap length (mean value ± standard deviation)

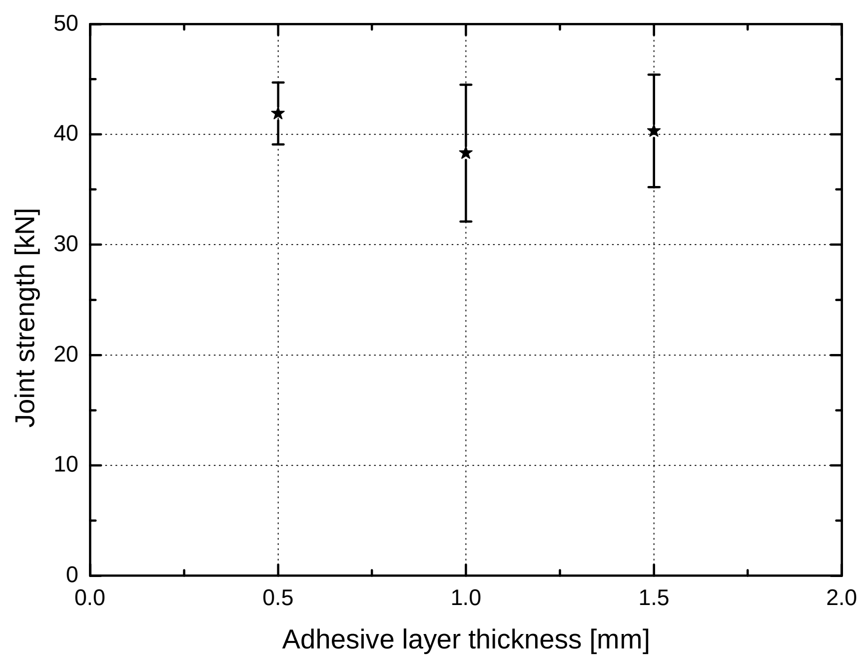

Figure 4: Experimentally determined joint strengths vs. adhesive layer thickness (mean value ± standard deviation)

3. Numerical investigation

3.1. Finite Element Model

To help the interpretation of the experimental results obtained, all joints were modeled using the finite element program ANSYS (v11). In preceding studies, it was shown that 2D instead of 3D modeling of adhesively bonded joints is accurate enough [6, 9]. Besides this, no adhesive fillets were modeled, since they were carefully avoided during the manufacturing of the specimen. The two-dimensional 8-node orthotropic element PLANE82 was used. The adhesive-adherend interface has been modeled as being rigid, this means without any interface- or contact elements. Symmetry conditions were used to reduce the modeling to one quarter, see Fig. 6. In the location were failure was experimentally observed, i.e. the inner adherend's region that lies just below the end of the overlaps, a very fine quadratic mesh (mesh size 0.25 mm) was applied to allow for an accurate modeling of the stresses in this critical region.

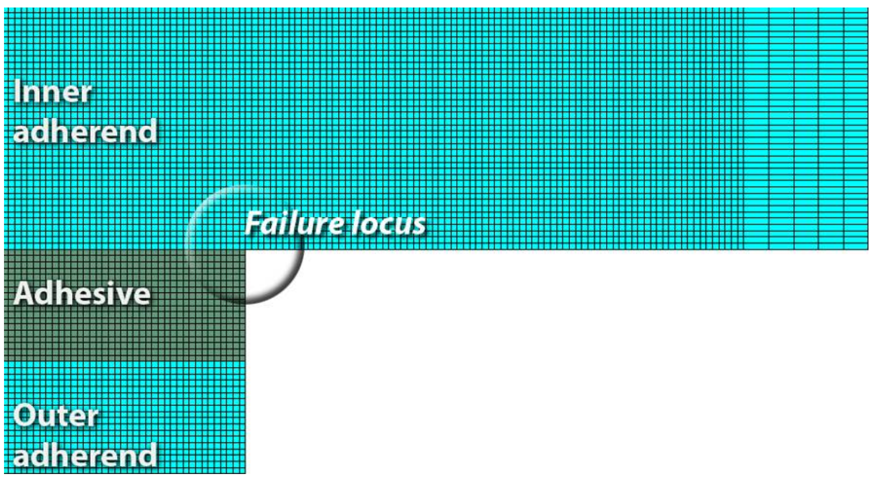

Figure 6: Finite element model of glued lap joint

The wood was modeled with linear-elastic and orthotropic material properties according to section 2.1; the epoxy adhesive was assumed to be linear-elastic and isotropic using the elastic properties also given in chapter 2.1.

All calculations were performed at the mean experimentally gathered strength value.

3.2. Numerical results

Failure of orthotropic and fibrous material is usually related to out-of-plane stresses (perpendicular to the grain), σ_z, and in-plane shear stresses, τ_{xz}, or failure criteria involving these values. Further, since failure clearly initiated in the inner adherend, it was decided to gather the profiles of these two stresses along the bonded splice of the inner adherend for all investigated geometrical configurations investigated herein. Fig. 7 shows the computed out-of-plane stresses, σ_z, and in-plane shear stresses, τ_{xz}, along the previously defined path.

The performed FEA indicates high stress concentrations at the ends of the adhesive interface (Fig. 7), which occur exactly at the locus where failure initiation was observed during the experiments (cf. also Fig. 3). As all calculations were performed at the averaged experimental failure loads, the generated out-of-plane stresses (perpendicular to the grain), σ_z, and in-plane shear stresses, τ_{xz}, indicate which stress levels trigger failure. It appears that for all investigated cases, the following stress combinations lead to failure: for series S1, $\sigma_{z,f}$ = 33.3±2.0 MPa and $\tau_{xz,f}$ = 25.1±1.9 MPa (mean ± stand. dev. of the three configurations); for series S2, $\sigma_{z,f}$ = 37.6±1.9 MPa and $\tau_{xz,f}$ = 28.7±1.5 MPa. Therefore there is no clear evidence that failure is triggered by a stress criterion.

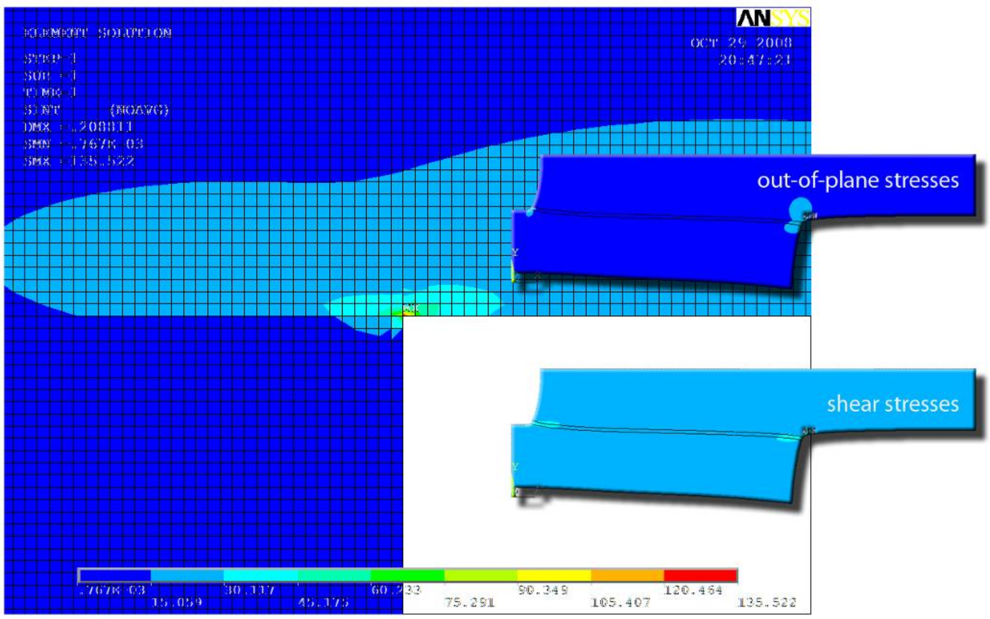

Figure 6: Zones of high stress concentration: stress intensity mapped on the elements; out-of-plane stresses (top) and shear stresses (bottom)

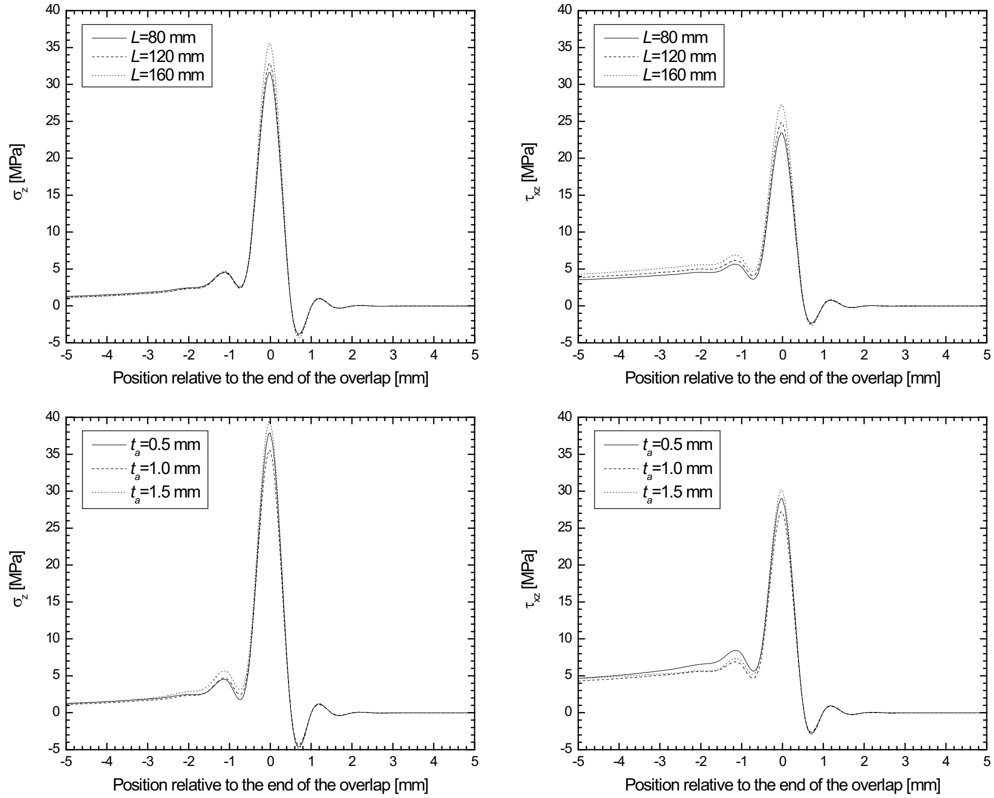

Figure 7: Stresses in the vicinity of the failure locus, in the inner adherend, at the end of the overlap: Series S1, (top left) out-of-plane stresses, (top right) shear stresses; Series S2, (bottom left) out-of-plane stresses, (bottom right) shear stresses

4. Discussion and Conclusions

The tests carried out on adhesively bonded joints composed of wooden adherends indicate that the scattering of the gathered strengths was reasonably small, by far lower than that what would have been expected considering the notorious scattering measured on timber strength data.

The experimental investigations further indicated that the glue line thickness has no influence on the strength of the lap joints, for the thickness range investigated. The joint strength increased proportionally to the overlap length for the overlap range investigated. Further experiments at the Bern University of Applied Sciences will investigate whether this relationship will still be valid when longer overlaps are used.

The experimental work, in conjunction with the corresponding numerical analysis strongly indicates that the joint failures were initiated by a combination of local tension perpendicular to the grain and shear stresses at the joint edges in the adhesive interface. The experiments did not allow to conclude on the form of this combination, i.e. which failure criterion describes failure. It appears that the joint strength is not directly correlated to the stress-state, so that simple stress-based dimensioning methods would probably fail.

The experimental and numerical work presented herein was also aimed to gather data to benchmark a dimensioning method, which, in conjunction with additional material specific tests on the considered wood, offers a dimensioning method [7].

5. References

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