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Ductile adhesively-bonded timber joints – Part 1: Experimental investigation

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HIGHLIGHTS

- Acrylic-bonded timber joints exhibited a ductile load-displacement response in tension.
- Acrylic joints showed much higher ultimate loads than epoxy joints in tension.
- Displacement- and energy-based ductility indexes of acrylic joints were high.
- A strain-based quadratic failure criterion allowed to estimate the ultimate loads.

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ABSTRACT

In the field of timber load-bearing structures, adhesive bonding is a promising joining technique that may increase the structural stiffness and capacity of timber joints and structures. The use of ductile adhesives may furthermore allow designing ductile joints, which can compensate for the material ductility that timber lacks. To demonstrate the potential of this approach, adhesively-bonded double-lap timber joints were manufactured using a ductile acrylic adhesive and then subjected to axial tension and compression loading. The load-displacement responses were measured and compared to those of the same joint configuration for which a brittle epoxy adhesive was used. The effect of the different adhesives on the joint capacity and ductility has been studied and quantified. Strain field measurements using the Digital Image Correlation (DIC) technique and a quadratic strain interaction criterion provided a better understanding of the mechanical behavior of the two different joint types.

1. Introduction

Joints are the most critical elements in the majority of timber structures; basically they can be designed as mechanical or adhesively-bonded joints. Although bonded joints may be sensitive to environmental conditions such as elevated temperatures and humidity, they can exhibit higher efficiency than doweled joints due to a more uniform stress distribution [1,2]; in the latter, high stress concentrations occur around the mechanical fasteners and the cross section is reduced [3]. In addition to this higher capacity of bonded joints, the stiffness is increased, the weight-to-strength ratio reduced, and fatigue strength and durability are improved, the latter due to the sealing by the adhesive [4]. Many different types of adhesives may be used, depending on the targeted application [5].

One of the most important requirements for load-bearing structures, especially in earthquake design, is ductility, i.e. the ability of a material or structure to sustain inelastic deformation prior to failure, without loss of resistance. The energy generated by the seismic action or any impact is dissipated and large deformations prior to failure provide sufficient warning [6]. In redundant systems, the internal forces may be redistributed and the structural safety thus increased. The provision of ductility is however made difficult when using brittle materials, such as fiber-reinforced polymers (FRPs) or wood. To overcome this difficulty in the field of FRP materials, ductile adhesives were proposed [7] and used [2] for developing ductile joints, thus compensating for the lacking material ductility [2].

The basic definition of ductility is expressed as the ratio between the total and yield deformations of a material or structural component [8]. However, ductile behavior cannot be derived based only on an observed non-linear load-displacement response. In an elastically buckling component, for example, the ascending non-linear loading and descending unloading paths overlap and

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no (permanent) yield deformation or related ductility are developed. Therefore, extended energy-based definitions of ductility, taking into account the inelastic energy dissipated during loading, were introduced. The total area under the load-displacement curve corresponds to the total energy, E_{tot}, which is composed of the elastic energy, E_{el}, which is released while unloading and the dissipated inelastic energy, E_{inel}, represented by the area between the loading and unloading paths respectively [9,10]. Such energy-based definitions usually consider different ratios of these energies: i.e. E_{inel}/E_{tot} [11,12] or E_{tot}/E_{el} [13].

Ductile adhesive joints to implement ductility in FRP composite structures have already been developed, as mentioned above. A systematic and comprehensive investigation of the application of such ductile adhesives for timber-timber joints, however, has not yet been performed; only an experimental study concerning their load capacity has been carried out [14]. The aim of this work is thus to design such ductile adhesive timber joints and compare their performance, if subjected to axial tension and compression loading, with similar joints comprising a brittle adhesive. Stiffness, capacity, failure modes and load transfer mechanisms based on strain field measurements are compared in detail and ductility is quantified. The comparison is based on experimental results obtained from large-scale joint investigations. The corresponding numerical modeling is subsequently developed and presented in Part 2 of this paper [15].

2. Experimental set-up

2.1. Specimens and materials

The experimental program included 19 large-scale, adhesively-bonded dog-bone-shaped double-lap timber joint specimens, as shown in Fig. 1. Norway spruce (Picea abies) was used, as it is one of the most widely used types of wood for structural applications in the timber industry. The wooden adherends were cut from spruce wood logs, avoiding any obvious defects or knots. For the assembling of these adherends, two kinds of structural adhesives were used and two series of joints were manufactured: a reference series using a brittle epoxy adhesive, SikaDur330, and a series using a ductile acrylic adhesive, SikaFast5221NT; both adhesives were obtained from Sika AG, Switzerland [16,17]. The ductile behavior of this acrylic adhesive has already been investigated and quantified in a preceding work [18]. The basic mechanical properties of the materials used for the joints are summarized in Table 1. It has to be noted that the properties of the acrylic adhesive were highly strain rate-dependent, as shown in a preceding work [19].

The detailed specimen geometry, which resulted from preliminary studies to optimize the joint capacity [22], is shown in Figs. 1 and 2; the total length and width were 970 and 50 mm, the overlap length was 160 mm and the thickness of the adhesive layer was 2 and 3 mm, for epoxy- and acrylic-adhesive joints (denominated “epoxy joints” and “acrylic joints” in the following) respectively. In the latter case, subsequently to preliminary experiments exhibiting adhesion failure, a 0.5-mm (on average) layer of epoxy of SikaDur330 was added between the wood and acrylic adhesive to improve adhesion. The acrylic adhesive was applied on the cured epoxy adhesive. Before applying any adhesive, the joint surfaces were carefully smoothened with sandpaper and cleaned with acetone. The joints were fabricated under ambient laboratory conditions (21 ± 3 °C and 38 ± 10% relative humidity) and stored in a conditioning room (20 ± 2 °C and 60 ± 3% relative humidity) for at least one week to obtain a) a uniform moisture content (12%, as measured in Ref. [23]), and b) full cure of the adhesives (according to Ref. [18]).

2.2. Experimental procedure and instrumentation

The experimental program included both axial tensile and compressive experiments since the adhesive tensile and compression behavior was found to be different [18]. The joint specimens were loaded up to failure at a displacement rate of 2 mm/min. In the acrylic joint specimens an unloading-reloading cycle, at the same displacement rates, was implemented in the plateau region of the load-displacement response.

A universal Schenk machine of 600-kN capacity was used. Teeth-shaped steel plates were installed to prevent grip failure and specimen slip. The machine’s load-cell and two linear variable displacement transducers (LVDTs), symmetrically placed on both sides of the specimens with a gauge length of 330 mm, were used to measure the load and displacements applied to the joints respectively, see Fig. 2. In the following, average values of the two LVDT measurements divided by two are reported as “displacement”, assumed to correspond to the displacements of one of the

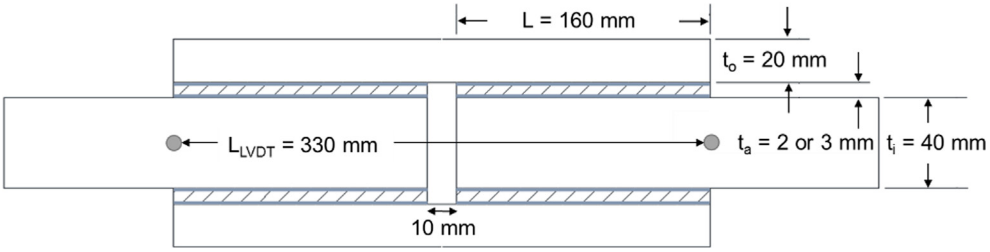

Fig. 1. Geometry of double-lap joint.

Table 1
Basic material mechanical properties.

Material	Mechanical properties			
	Tensile E-modulus (MPa)	Compressive E-modulus (MPa)	Poisson ratio (–)	Density (kg/m^3)
Epoxy	4500 [3]	3000 [3]	0.37 [3]	1300 [16]
Acrylics*	105 [18]	21 [18]	0.48 [18]	1200 [17]
Spruce (//fibers)	11,600 [20]	11,330 [21]	0.4 [20]	440**

* Values obtained at a strain rate of 0.17 min^{-1}.
** Measured.

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