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Adhesively bonded timber joints – Do defects matter?

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ABSTRACT

Although adhesively bonded timber joints have proven their suitability as a structural joining method, and often provide a better mechanical performance, practitioners remain reluctant to consider them as a substitute for traditional mechanical fasteners. Among the main reasons invoked, the quality control with regard to defects in the adhesive layer remains the most challenging. Little research effort, however, has been put into the evaluation of the effect of defects on the performance of adhesively bonded timber joints, respectively to which extent defects influence joint capacity. The experimental investigation of the influence of artificial defects on the capacity of adhesively bonded timber joints presented herein, completed by numerical calculations, demonstrated that joints with 50% amount of missing adhesion still achieve 70% amount of capacity of defect free joints. The investigation furthermore showed that it is possible to computationally estimate the influence of defects on joint capacity.

1. Introduction

1.1. Adhesively bonded timber joints

Timber as a structural material experiences a marked revival driven by aspects related to sustainability, its positive effect on interior building climate, and the increased architectural possibilities offered by engineered wood-products, adhesive systems and modern computer-numerically-controlled machining. With increasing structural complexity traditional mechanical timber joining techniques often limit the performance of timber members; alternative joining techniques are thus of interest. As one consequence, research on adhesively bonded timber joints has increased, as demonstrated by the growing numbers of related publications [1–16]. Nevertheless, the use of adhesive bonding is described as one of the most interesting fields of development, which holds the potential to trigger a paradigm change in timber engineering: "*just as adhesives have freed timber of its structural and size limitations, adhesives can free timber of the metal needed presently to make joints*" [1]. In fact, such a paradigm shift has been initiated as can be seen from adhesive joining techniques being used in highly demanding structural applications, as for example timber based tower structures [2] or large scale public structures in extreme climate conditions [3].

Adhesively bonded timber joints have been investigated as double-lap-joints (DLJ) composed of spruce bonded with epoxies [4,5], DLJ composed of beech bonded with epoxies [6], DLJ bonded with polyurethanes [7], connections between spruce and steel plates [8], glued-in steel rods [9,10], and glued-in G-FRP rods [11,12]. Timber has also been combined to other materials using adhesives, for example to form timber–concrete-composite beams and slabs [13,14] and to form timber–glass-composite beams and columns [15], besides applications of adhesive bonding used for repairing timber constructions in conjunction with carbon-fibre patches [16]. All these investigations show the potential of adhesively bonded connections involving timber and other materials, and the fact that they are clearly shifting into the focus of practical applications.

Predicting the capacity of adhesively bonded timber joints, however, is not trivial, mostly because of the complex multi-axial stress state generated inside them. Additional issues arise from the anisotropic and brittle nature of timber under shear and tension loading, and finally the uncertainties regarding the associated material resistance [17]. Since failure of bonded timber-joints is commonly triggered by a combination of shear and transverse tensile stresses acting in conjunction with axial tensile stresses, it is paramount to quantitatively address the question of timber strength in the form of a material failure criterion. Practitioners generally consider simplified multi-axial failure criteria, such as the one provided by Norris [18]; see Eq. (1) for the two-dimensional stress state.

$$\phi^2{}_F = \left(\frac{\sigma_X}{f_X}\right)^2 - \left(\frac{\sigma_X \sigma_Y}{f_X f_Y}\right) + \left(\frac{\sigma_Y}{f_Y}\right)^2 + \left(\frac{\tau_{XY}}{f_{XY}}\right)^2 \qquad (1)$$

where $\phi_F^2 = 1$ defines failure, σ_X, σ_Y and τ_{XY} are the normal and shear stresses, respectively, f_X, f_Y, f_{XY} are the material strength parameters, and the subscripts X and Y denote the material directions of the

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orthotropic wood, X being the longitudinal direction and Y the transverse direction.

The brittle failure of timber with regard to shear and transverse tensile stresses has been accurately described by statistical size effects [5,7,17]. Weibull [19] first hypothesised that the probability to encounter a randomly distributed defects increases with component size. The cumulative survival probability, P_S, of any material samples is related to its volume, V, subjected to any stress distribution, $\phi_{F,i}$, is then given by Eq. (2)

$$P_S = \exp\left[-\int_V \left(\frac{\phi_{F,i}}{m}\right)^k dV\right] \tag{2}$$

For a statistical description, two parameters are needed: m, the characteristic stress or scale parameter, and k, the shape parameter that gives a measure of the strength variability. The shape parameter k gives a measure of the strength variability, with low values of k corresponding to a high variability in material properties and large size effects. It has been shown that for timber, k can be approximated based on the coefficient of variation (COV) using $k = \mathrm{COV}^{-1.085}$ [20]. The characteristic stress m corresponds to the mean stress acting on a particular volume, and has, assuming the Weibull distribution, a probability of survival $P_S = 0.368$ $(= e^{-1})$. The Weibull distribution parameters can be estimated using either the maximum likelihood methods or least squares/rank regression etc. [21].

If structural members constituted of n such elements with volumes V_i are subjected to a value of the failure function $\phi_{F,i}$, the probability of survival of the whole joint member can be statistically “summed up” according to Eq. (3):

$$P_S = \prod_{i=1}^{n} \exp\left[-\frac{V_i}{V_0}\left(\frac{\phi_{F,i}}{m}\right)^k\right] = \exp\sum_{i=1}^{n}\left[-\frac{V_i}{V_0}\left(\frac{\phi_{F,i}}{m}\right)^k\right] \tag{3}$$

where V_0 is the reference volume. How to determine stresses in adhesively bonded joints, i.e. analytically or numerically, has been largely settled by a couple of recent review papers [22,23] in favour of finite element analysis; this is particularly true when the orthotropy of timber must be accounted for.

1.2. Bonded timber joints with defects

As discussed before, timber joints in which adhesives are considered substitutes for traditional mechanical fasteners are increasingly the focus of current research. Practitioners, however, often remain sceptical because of uncertainties related to the quality of the bonded joint. A major concern is the possible presence of defects, e.g., voids, porosity, micro-cracking in the adhesive, or worst, lack of adhesion generated by inadequate preparation of the joint or by environmental degradation of the interface. This issue is mostly addressed by trying to detect defects before servicing the corresponding joints. Due to the large variety of defects [24], non-destructive-tests (NDT) have been developed for that purpose, e.g. in the context of composite materials [25]. These techniques have proven to detect defects with different success [26]. Besides warranting the absence of defects using NDT, or at least aiming to do so, research was also devoted to investigate and quantify the effects of artificially included defects of known nature and size, on the capacity of bonded joints, analytically [27], numerically [28] and experimentally [29].

Early studies on the effect of bonding defects on the capacity of bonded joints pointed out a differentiated relationship between defects and joint capacity that depends on the brittleness or ductility of the adhesive. For single lap joints made of aluminium adherents bonded with a brittle adhesive in which artificial defects were introduced, the joint capacity was essentially governed by the leading edges of the joint and not by the bonded area. Thus, joint capacity was not very prone to reduction if defects were located sufficiently away from the ends of the overlaps, even if the size of the defects was significant (up to 60% loss) [30]. Another investigation, also on aluminium single lap joints and artificial defects, but involving a ductile adhesive, found that joint capacity is not governed by edge effects but rather almost proportional to the bonded area and comparatively insensitive to stress concentrations [31]. At this point, it must be reminded that both previously discussed results [30,31] were obtained considering aluminium adherents, which exhibit significant ductility. No research has yet investigated the effect of the size of adhesion defects on the capacity of adhesively bonded timber joints.

1.3. Objectives

The objective of this paper is to present experimental evidence followed by numerical investigations to shed light on the relationship between defects and capacity of adhesively bonded timber joints. For this purpose, artificial defects were inserted in adhesively bonded single lap joints; the effects of these defects on the stresses were numerically investigated and related to the corresponding experimentally determined joint capacities.

2. Experimental and numerical investigations

2.1. Timber characterization

All experimental work was performed on beech (*Fagus sylvatica*) cut from high quality defect-free boards stored in constant climate (25 °C) and conditioned to an approximate moisture content (MC) of 8%. The elastic properties, which were shown to have little influence on joint capacity [4,5], were assumed according to previous experiments [6]. For the subsequent joint capacity prediction, the failure criterion of beech was experimentally determined on off-axis tests according to Ref. [30], and in accordance with previous validated practice [4–8]. Since failure is triggered by a combination of axial stresses, σ_X, transverse tensile stresses, σ_Y, and shear stresses, τ_{XY}, see Eq. (1), a total of 107 dog-bone-shaped specimens (Fig. 1) were tested to determine the material strength components f_X, f_Y, and f_{XY}. Four different angles of the specimens' longitudinal axis to the grain (0°, 10°, 45° and 90°) were considered; the specimen dimensions were: overall length = 35 mm, width of the grip section = 5 mm leaving a gauge length = 25 mm with a corresponding cross section $A = 5\ \mathrm{mm} \times 5\ \mathrm{mm}$, resulting in a reference volume $V_0 = 625\ \mathrm{mm}^2$.

A two-component epoxy adhesive (Henkel Hysol 9492) was used. The mechanical properties of the cured adhesive was characterized as $E = 5400$ MPa; based on the failure behaviour of the cured adhesive, it can be considered as brittle.

2.2. Specimen description and methods

All tests were performed on single lap shear specimens consisting of beech pieces 100 mm × 25 mm × 5 mm. An overlap length of $L = 25$ mm was chosen, and an adhesive thickness of $t_a = 0.5$ mm was defined. Defects were simulated using precisely cut circular Teflon patches of different diameters. Two series were defined:

- S1, shown in Fig. 2, in which the size of the centrally placed defect was varied from 5 mm to 20 mm, in steps of 5 mm, corresponding to defects of 3–50% of the bonded surfaces; and
- S2, shown in Fig. 3, in which circular defects (5 mm) were arranged in different patterns (1 × 1, 2 × 2, and 3 × 3).

Testing was performed on a universal testing machine, load–displacements and joint capacities were recorded. Timber was