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Compression failure mechanism in small scale timber specimens

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HIGHLIGHTS

- Compression tests on small clear-wood specimens to better understand the kinkband initiation and propagation.
- Results show a clear correlation between compression modulus, strength, steady-state stress and silviculture method.
- Mature wood has higher compression mechanical properties than juvenile wood, irrespective of the silviculture method.
- The deformation data measured globally over the specimen can be used to describe the local plasticity/kinkband behavior.

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ABSTRACT

Understanding the failure mechanism of wood loaded in compression parallel to the grain has been shown to be an important parameter in the design of timber beams strengthened with fibre-reinforced plastics (FRP). In this paper, a constitutive relationship for wood under uniaxial compression load parallel to the grain was determined experimentally. Several parameters, such as silviculture, moisture content and radial position in the log in relation to the pith from where the specimen was sawn, were considered. Small clear-wood specimens were used. The strain localisation in the failure region (kinkband) was monitored using the digital image correlation method. The results show that silviculture and moisture content are two very important parameters which influence the compression failure mechanism. Furthermore, there is a significant difference in behaviour between specimens from the juvenile region of the log and specimens from mature wood. Based on experimental results, two numerical models were built, considering either a global or a local constitutive relationship. It was demonstrated that both numerical models yield accurate results and that, depending on the experimental equipment available, a constitutive relationship could be extracted and used as input in these numerical models.

1. Introduction

Strengthening timber beams loaded in bending requires knowledge of the failure mechanism of timber in compression, tension, shear and so on. In a recent state-of-the-art review carried out by the authors [1], it was reported that a large number of projects have investigated the effect of strengthening timber/glue-laminated timber (glulam) beams with fibre-reinforced plastics (FRP). It has been shown by Kliger et al. [2] that the optimal strengthening system for glulam beams loaded in bending is to use reinforcement on both the tensile and compression sides. Not only increases in stiffness and moment capacity were reported but also the greater utilisation of the ductile behaviour of timber in compression.

Fig. 1 shows a glulam beam, heavily reinforced with FRP on the tension side, which developed compression failure under four-point bending test carried out by the authors [3]. Compression failure was the first failure mode observed and it provided ductility to the global failure of the beam. Tension failure was prevented by the FRP bonded on the tension side of the beam. This global behaviour was clearly visible on the load–displacement curve shown in Fig. 1, which was characterised by linear elastic behaviour up to a load where a reduction in the stiffness due to failure on the compression side was observed.

Timber is often described as a brittle material, which is mostly true if tension or shear failures are the only failure modes that are considered. However, compression failure is a ductile failure mode in timber. Taking advantage of this ductile feature of timber is of great interest when designing timber structures. There are several reasons for this; they include increasing safety, predicting load and moment capacity more accurately, or making better use of the material used. Tomasi et al. [4] reported that the use of poorer

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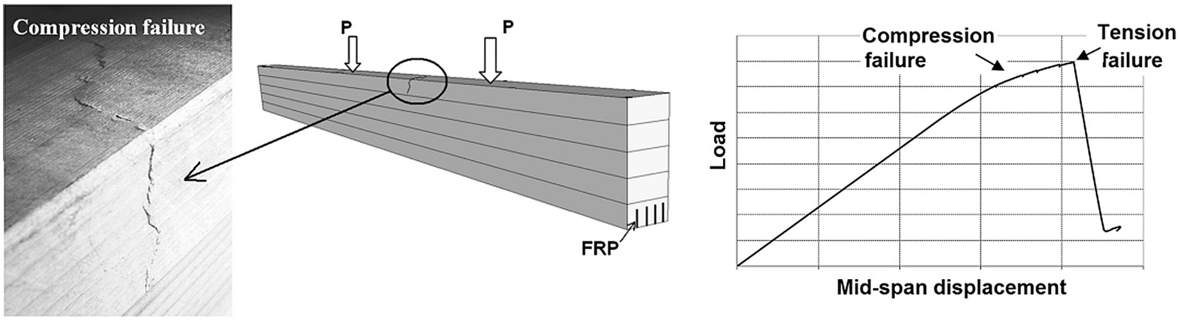

Fig. 1. Compression failure in a heavily tensile reinforced glulam beam loaded in bending [3].

wood quality on the compression side of a glulam beam increased its ductility.

For a simply supported glulam beam loaded in bending, the primary concern is to assure the resistance of the beam in tension. In Europe, the compression side of the glulam beam is usually made of the same material used for the tension side, in order to avoid assembly issues (a beam mounted upside down, for instance). However, reinforced concrete beams are usually manufactured with steel rebars in the tension side only and the appropriate marking is used to differentiate the two sides. No or only a few problems are reported due to human error during assembly. The use of unbalanced glulam beams, i.e. glulam beams with higher wood quality for the tension timber, has already been introduced in American standards [5]. A clear "TOP" mark on the top of the beam prevents assembly errors.

It becomes obvious, based on previous experience and literature studies, that an understanding of the wood compression failure mechanism and the determination of complete material models are fundamental when designing reinforced timber beams. As the first step in this study, the compression failure mechanisms of unreinforced wood specimens is considered and reported in the present paper. In the accompanying paper [6], the compression failure mechanism of wood specimens reinforced with carbon fibre-reinforced plastics (CFRP) has been investigated.

Several studies have been conducted in order to derive models which describe the compression failure mechanism in wood [7,8,15,17], and in FRP [9–13,16], separately, in particular the phenomenon of kinkband (terminology commonly used to describe plastic microbuckling of fibres in FRP). Other terms, such as slip planes or gross shear bands, have been used to describe this phenomenon in timber on different scales, but the overall behaviour is based on a similar theoretical approach, see Fig. 2a. Substantial differences exist between the natural composite material, timber, and man-made FRP; they include the size of the defects and the density (high density for FRP vs. high wood porosity). In addition, fibre failure is observed in the kinkband region of FRP, while fibres buckle in wood. However, Poulsen [8] observed that compression failure processes in wood and in FRP present several similarities, see Fig. 2b and c.

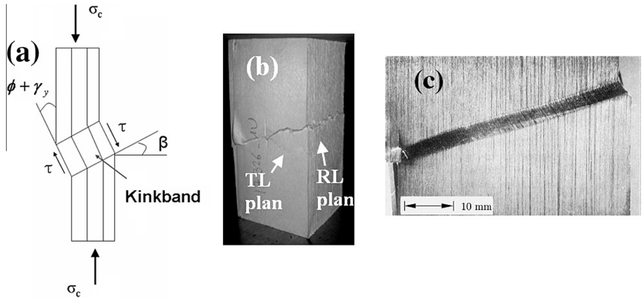

Fig. 2. General kinematics of a kinkband (a); kinkband as a result of compression failure, (b) in wood (André) and (c) in FRP [9].

An early attempt to theoretically determine the compressive strength of FRP (σ_c) was presented by Rosen [10]. The proposed model was based on the assumption that the bending of the fibres and the shear of the matrix are elastic. Furthermore, the inevitable misalignment of the fibre, which is assumed in further studies as a driving parameter controlling the compression strength of FRP [8,11–15], is ignored, i.e. the fibres are assumed to be perfectly aligned. The compressive strength is determined by the longitudinal elastic shear modulus G of the composite, see Table 1. However, it was reported by Budiansky and Fleck [16] that these assumptions yield unconservative results.

The influence of fibre misalignment on the compressive strength of FRP has been reported by Argon [11]. The formulation for the peak stress has been derived for a rigid, ideally plastic composite. It is a function of the plastic shear strength of the matrix, k, and the angle of misalignment of the fibres, ϕ. The longitudinal shear yield strain, γ_y was subsequently taken into account in the model presented in Budiansky [12].

Many studies based on the first models introduced by Poulsen [11] and Budiansky [12] have been carried out for both wood and FRP. The original objective of these studies was to determine the compression strength, σ_c. The understanding and analytical description of the post-peak process were not included. In a detailed study of the compression failure mechanism in wood carried out by Poulsen [8], an analytical modelling, supported by experimental testing, was reported. To understand this mechanism, some basic knowledge of wood anatomy at the fibre level is highlighted (Fig. 3). The annual rings are divided into early wood fibres, with thin cell walls, and latewood fibres, with thick cell walls, running in the longitudinal direction. These fibres, called tracheids, perform both a support and a conduction function in the tree. Resin canals or rays are visible in the radial direction and are mostly responsible for the initial misalignment of the fibres (15° for spruce). As shown in Fig. 2b, the behaviour of wood under compression parallel to the grain is different in the radial-longitudinal (RL) plane and in the tangential-longitudinal (TL) plane. In the TL plane, the kinkband develops with a certain angle β function of the wood species (typically 23° for spruce ([8])). It is perpendicular to the fibres in the RL plane.

Under a compression load parallel to the grain, small clear-wood specimens undergo four main deformation steps (Fig. 4): linear elastic (a), incipient kinking (b), transient kinking (c) and steady-state kinking (d). The incipient kinking is the plastic shearing and buckling of the fibres, localised close to the resin canal region

Table 1
Different analytical models to determine the compressive strength σ_c of FRP.

$\sigma_c = G$	$\sigma_c = \frac{k}{\phi}$	$\sigma_c = \frac{k}{\phi+\gamma_y}$
Rosen [10]	Argon [11]	Budiansky [12]