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Fracture in complex balsa cores of fiber-reinforced polymer sandwich structures

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HIGHLIGHTS

- Balsa wood mechanical properties in sandwich core panels vary significantly.
- Cracks initiated and propagated in the low-density balsa blocks.
- Crack locations could be predicted using the Tsai–Wu failure criterion.
- Cracks were not able to propagate through adhesive block joints if bonding was perfect.

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ABSTRACT

Fracture in the complex balsa cores of fiber-reinforced polymer (FRP) sandwich beams was analyzed. The cores were composed of high- and low-density balsa layers separated by a circular adhesive interface or FRP arch. The balsa layers were cut from panels which consisted of balsa blocks adhesively bonded together. Failure in the beams was initiated by cracks propagating through the balsa core thickness. The crack locations could be predicted using the Tsai–Wu failure criterion. Cracks initiated in the lowest density blocks due to their low fracture toughness. In mixed-mode fracture, crack propagation in the radial–longitudinal (RL) plane prevailed due to the low fracture toughness in RL fracture of Mode I. In pure Mode II, propagation occurred in the RL and TL (transverse–longitudinal) planes to the same extent since the toughness in RL and TL fracture is similar. Cracks were not able to propagate through the transverse adhesive joints between blocks if the bonding was good. If however the bonding was poor, interface failure occurred and cracks could propagate through the adhesive layer.

1. Introduction

Fiber-reinforced polymer (FRP) sandwich structures are composed of FRP face sheets and honeycomb, foam or balsa cores [1]. Basically, the face sheets bear the bending and the core the shear loads. Depending on the span-to-depth ratio and constituent material properties, several distinct failure modes may occur in sandwich structures when loaded in bending: compressive and tensile face sheet failure, face sheet wrinkling, core shear failure, core indentation failure or compressive or tensile core failure [2]. Wrinkling or compressive face sheet failure normally occurs in long sandwich beams while short span beams are sensitive to core shear failure [3]. Corresponding failure mode maps have been developed for foam and honeycomb cores [4,5]. Meanwhile, end-grain balsa cores, which comprise balsa wood fibers orientated perpendicularly to the face sheets, are increasingly used as core materials in sandwich structures due to their superior out-of-plane properties. The lightweight 11.45-m FRP-balsa sandwich bridge deck of the new Avançon Bridge in Switzerland [6], for instance, allowed widening of the bridge from one to two lanes without additionally loading the substructure of the former concrete bridge that it replaced.

End-grain balsa panels are heterogeneous materials composed of similar sized blocks with a cross section of approximately 90 × 110-mm, as shown in Fig. 1, which are selected within a limited density range [7]. The balsa blocks of both higher and lower density are randomly assembled to avoid concentrations of softer blocks in the final panel. Assembly is performed by adhesive bonding using the frequently used thermoplastic polyvinyl acetate adhesive PVAc. Furthermore, inside a balsa block, density may significantly vary due to the cyclical changes of early and late wood [8]. Nevertheless, most of the few available studies on failure analysis of these materials assume the material as being homogenous [9,10]. The effects of the balsa block composition of the panels on the location, initiation and propagation of the cracks were not

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Fig. 1. Balsa panel composed of adhesively-bonded balsa blocks (dimensions 1200 × 1200 × 60 mm).

taken into account. Other studies considered the block structure to some extent. In [11], the location of the shear failure was assumed to occur in the low-density balsa blocks, without experimental evidence however. In [12], crack propagation was observed at less dense and hence less stiff locations in the balsa core, where peak shear strain measurements varied between 0.15% and 0.5%; the crack propagation mechanisms, however, were not investigated. In [13], crack initiation in an FRP-balsa sandwich core interface bond was observed. The crack subsequently propagated in the balsa-adhesive interface and then deviated into the balsa and interface parallel to the adhesive block joint. This was exclusively attributed to the low tensile strength of balsa in the transverse direction to the fibers and contributions of potential flaws to the interface failure at the adhesive block joint were not investigated.

As an extension of these studies, the effects of assemblies of blocks of different densities and orientations and adhesive bonding between the blocks on the crack propagation and failure mode of balsa panels are investigated in this paper. The failure modes in the core of GFRP (glass fiber-reinforced polymer) – balsa sandwich beams with complex core assemblies are analyzed. The investigation of this type of beams was performed with a view to further optimization of the GFRP-balsa sandwich bridge deck used in the Avançon Bridge described above.

2. Crack initiation and propagation in balsa sandwich cores

The relevant crack planes in end-grain balsa sandwich cores under flexural loads, i.e. if core shear failure is dominant, are the radial–longitudinal (RL) and tangential–longitudinal (TL) planes, see Fig. 2 (first and second letters indicate the direction normal to the crack plane and the direction of the crack respectively). Cracks in the longitudinal–radial (LR) or longitudinal–tangential (LT) planes are rare in practice since this would require fracture of the fibers [14]. In Mode I, the fracture toughness in RL fracture is lower than in TL fracture (e.g. for balsa of 260 kg/m^3 density, K_{Ic}(RL) = 0.14 MPa m$^{1/2}$ while K_{Ic}(TL) = 0.20 MPa m$^{1/2}$ [14]), because cracks propagate in the former case only in the early wood (see Fig. 2) while in the latter case, they propagate in both the early and the tougher late wood, where fiber bridging occurs [15]. In Mode II, toughness is similar in both RL and TL fracture (for the same balsa of 260 kg/m^3 density, K_{IIc}(RL) ≈ K_{IIc}(TL) = 0.26 MPa m$^{1/2}$ [14]) since no fiber bridging occurs in either fracture plane.

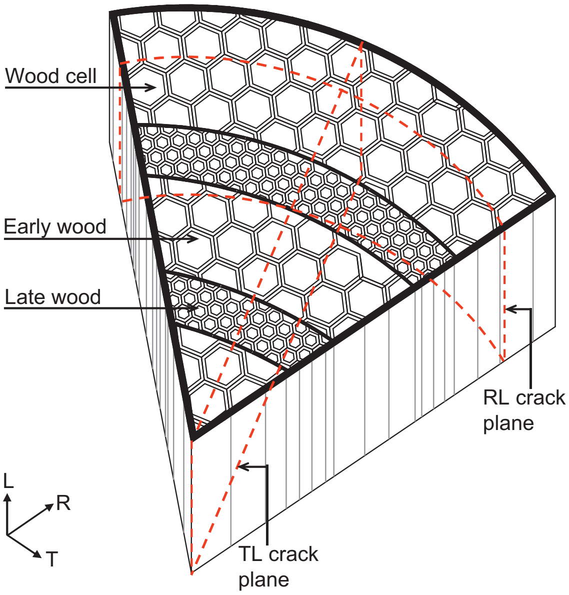

Fig. 2. Relevant planes of crack propagation in balsa wood.

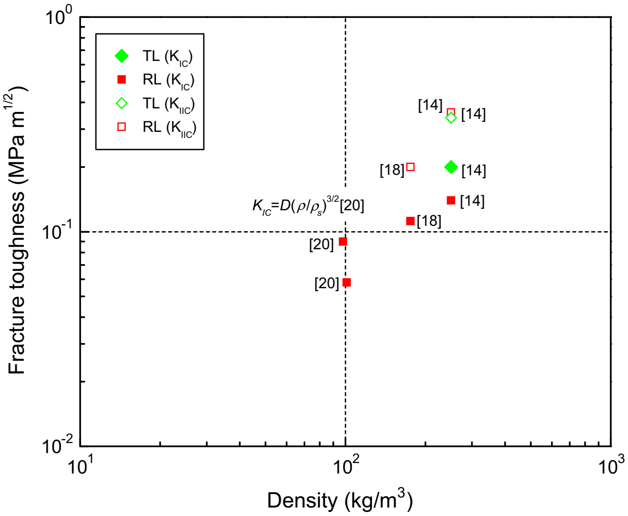

Fig. 3. Fracture toughness, K_c, as function of failure plane and mode, vs. density of balsa wood.

Interface failure (IF) in block joints, i.e. debonding between the balsa and the adhesive, is another prevalent failure type which is caused by voids in the adhesive layer or flaws at the wood-adhesive interface due to non-uniform or low penetration of the adhesive into the wood cells [16]. The crack propagating in the interface may then deviate into the balsa, but in most cases is not able to penetrate the adhesive layer since the Mode I fracture toughness, K_{Ic}, of PVAc is between 3.1 and 3.4 MPa m$^{1/2}$ [17] and thus much higher than that of balsa (see values above).

The fracture toughness in balsa fracture is mainly influenced by the wood density and fiber bridging. The fracture toughness vs. wood density shows a linear relationship in log-scale, as shown in Fig. 3, which summarizes data from different references [14,18–20]. Fracture energy values (G_{1c}) in [14] were converted into fracture toughness (K_{1c}) using $K_{1c} = \sqrt{G_{1c}E_z/(1-\nu^2)}$ according to [21], where E_z is the Young's modulus of wood in the transverse direction to the fibers and ν is the Poisson ratio of wood. A fracture toughness–density relationship was established in [20] for Mode I fracture as $K_{Ic} = D(\rho/\rho_s)^{3/2}$ with D = 0.18 MPa m$^{1/2}$ for propagation along the wood fibers (in the RL-plane), where ρ is the wood density and ρ_s is the density of the wood cell wall (assumed as being 1500 kg/m^3). In [22], Mode II fracture toughness was obtained as $K_{IIc} = 2.5K_{Ic}$.

Fiber bridging develops at the crack tip of the process zone during crack propagation. In [23], fiber bridging was quantified using a digital image correlation method. The results showed an increase in fiber bridging and thus fracture toughness with increasing balsa density. At the microstructure level, fracture toughness is influenced by the cell wall thickness, which determines the density of the wood. This was demonstrated in [20] where crack propagation