COMPARING THE POTENTIAL OF ACOUSTIC PARAMETERS FOR THE ASSESSMENT OF THE STRENGTH OF TIMBER

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1. INTRODUCTION

Approximately 80% of Scotland's softwood is Sitka spruce (*Picea sitchensis*) of variable quality. The ability to improve post-felling segregation coupled with early identification of low stiffness standing timber are two key issues in Scottish forestry. There is also a need for non-destructive testing (NDT) methods which evaluate the quality of existing timber structures, particularly those identifying degradation or rot. Several NDT methods for timber quality investigation are available depending upon scale. These include: visual classification, static bending machines, resistance drilling, ring counting and density assessment, X-ray tomography, microwave and near infra-red scanning. Acoustic techniques are however, cheap and portable.

The authors conducted a three year study into the relationship between acoustic NDT techniques and the mechanical properties of wood. Low frequency (LF) and ultrasonic time of flight (TOF) velocity harmonic resonant frequencies f_0, and damping ratio ζ were examined with regard to their influence on dynamic modulus of elasticity E_d, their dependence on static modulus of elasticity E_s, modulus of rupture E_r, and knot area ratio (KAR) among other parameters. In addition to recommendations on the improved use of acoustic NDT, this provided the first large-scale derivation of reference values for E_s and other acoustic properties for 35 year old Sitka spruce logs and beams in Scotland (Mackenzie, 2009).

2. BACKGROUND

Many commercial devices measuring acoustic and ultrasonic velocities cover macro-, meso-, and micro-scale specimens. Questions remain: at what scale are the acoustic methods used applicable, what type of waveform deviation is used for detection and grading, and what are the specimens' material properties that can mislead the user? Using $v_c = \sqrt{\dfrac{E_d}{\rho}}$ the derived dynamic modulus E_d is typically an over-estimate due to the high strain rate. Nevertheless it remains well correlated ($R^2 > 0.99$) to E_s for small, clear, defect-free specimens (Andrews, 2000). Using the assumed correlation ($R^2 \approx 0.7$) between E_s and E_r from traditional machine grading; acoustic estimates of strength classifications become possible (Green *et al.*, 2006). Given the natural overestimation in E_d (5% to 30% depending on species, specimen size and test method), strength classifications should only be assigned after measuring this overestimate. Previously, there were no relevant data for Scottish Sitka Spruce, or reference velocities for either wet or dry C16 (general grade) or C24 (structural grade) timber.

The strength is only part-influenced by stiffness and knot content: more importantly, knot location can account for up to 50% of the variability in strength (Johansson & Kliger, 2000). A method quantifying and locating knot content may produce a better E_d:E_r correlation. Also, if (Ouis, 2005) was correct in the assertion that reverberation time acts as an indicator of rot, then ζ may also correlate with condition.

3. METHODS

The three test phases used Brüel & Kjær's PULSE™ 3703-B 4-channel analyser (with Fourier transform module), glue-coupled Type 5308-B uniaxial accelerometers and a PUNDIT™ 54 kHz ultrasonic tester.

3.1. Phase 1: acoustic method assessment

Acoustic NDT parameters were evaluated during tests on 33 controlled-homogeneity beam specimens cut from 12-layer laminated veneer panels and three solid wood beams. They were tested to determine f and ζ (Q-factor method used for best repeatability) at the first eight harmonic frequencies. The LF and ultrasonic TOF velocities were also measured. Holes were then drilled (6 mm dia.) through the beams and filled with dowels to simulate knots. These holes were then re-drilled (in steps to 32 mm dia.) and larger dowels inserted. After acoustic testing, the beams were mechanically strength graded to determine E_s.

3.2. Phase 2: log testing

150 logs cut from 36 felled trees were tested by both PUNDIT™ (measuring v_c) and PULSE systems (for f_0 to f_4, LF TOF, and ζ_0 to ζ_4), the latter using the set-up in Figure 1.

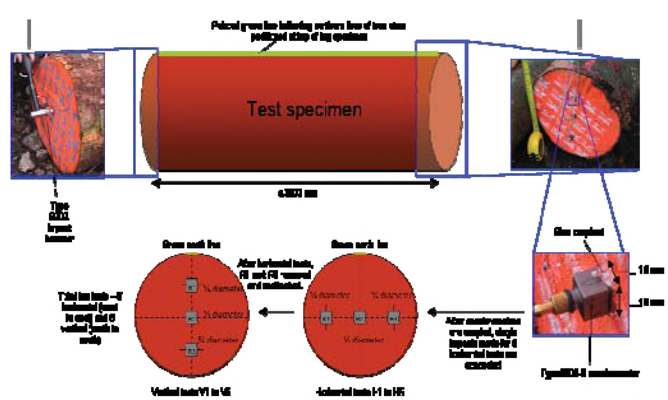

Figure 1 Phase 2 test set-up

3.3 Phase 3: beam testing

650 battens were cut from the logs and tested in the laboratory using the same method as the log tests. The beams were then mechanically strength graded to determine E_s: KAR and grain angle were visually assessed.

4. RESULTS AND DISCUSSION

4.1. Phase 1: acoustic method assessment

Those beams without simulated knots had the highest v_c, hence the highest E_d and E_s. The usual overestimate nevertheless left good correlation between moduli ($R^2 > 0.8$) with clear wood showing the best correlation ($R^2 = 0.85$). The position of the inserted dowels (simulating knots) affected E_d. For a simulated mid-span knot (the anti-nodal position for the fundamental frequency), the first and third harmonic frequencies (hence E_d) reduced significantly (see Figure 2). The second harmonic, unaffected as its nodal point lay at this location, remained unchanged despite increasing knot size. The opposite was true for knots at ¼- and ¾- span. The damping ratio increased from 0.4% to over 0.9% as the simulated KAR increased. Resonant peak bifurcation arose with increasing KAR.

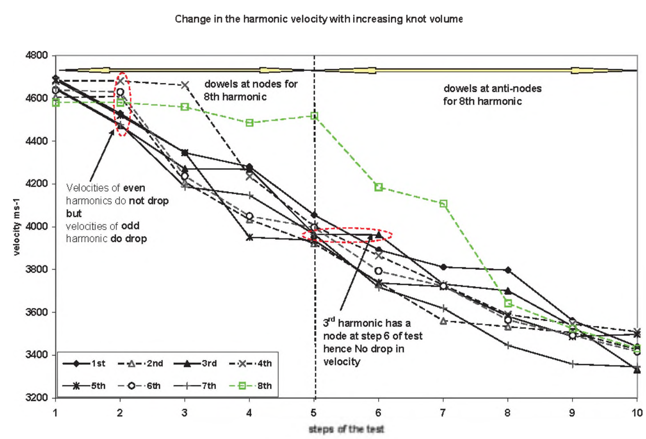

Figure 2 Influence of 25 mm knots: Beam 33

The number of 25 mm simulated knots was progressively increased along the beam while avoiding drilling at the anti-nodal positions of the eigth harmonic. The eigth harmonic underwent little change until holes were drilled at its anti-nodal points because harmonic frequencies are derived, not from a measurement of the whole specimen, but from discrete points along it. The fundamental frequency's waveform was weighted to the mid-span stiffness. Subsequent (η^{th}) harmonics were weighted to parts of the specimen at every $1/\eta$ fraction of the span. It should also be noted that after 32 mm dia. dowel insertion, the mean RF velocity decreased by 25%, but the LF TOF velocity by only 9%. Higher longitudinal resonance frequency harmonics gave more representative E_s and E_r estimates. However in larger, wet specimens there was a trade-off between accuracy and ability to detect higher harmonics.

4.2. Phase 2: log testing

Resonance tests on 150 Sitka spruce logs saw a 22% overestimate between their RF E_d and the average E_s from 645 beams later cut therefrom. Low E_d:E_s correlations were found, the best of which lay in the second harmonic (R^2 = 0.31). Adjusting for the usual overestimate (*c.* 35% here) correct average log stiffness classification was achieved. This did not work with TOF-derived values: a mean of 23 GPa, a 182% overestimate, was found. For fresh Sitka spruce logs, second harmonic velocities of 3500 ms^{-1} and 4115 ms^{-1} were proposed as representing average thresholds for grades C16 and C24 respectively. Saw-milling practice may cause deviations from these reference velocities.

4.3. Phase 3: beam testing

In tests on dry beams, all acoustic methods for E_d had good correlations and excellent inter-test repeatability; the first harmonic had the highest correlation to E_s ($R^2 = 0.71$), whilst PUNDIT™ had lowest ($R^2 = 0.61$). The overestimate was *c.* 4.5%, except in the first harmonic with 6.3%. The third harmonic was the closest (E_d to E_s overestimate of 4.3%), though a reduced number of samples due to higher signal:noise ratios meant that the second harmonic was potentially more appropriate ($R^2 = 0.69$). For dry beams, reference velocities for Sitka Spruce were 4040 ms^{-1} and 5070 ms^{-1} for grades C16 and C24 respectively.

No significant correlation was seen between Q-factor ζ and any mechanical property (particularly KAR) of either logs or beams. No improvement in correlation to E_s or E_r was seen when ζ was combined with RF, LF or TOF E_d data.

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