Rapid measurement of trunk MOE on standing trees using RIGIDIMETER

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Original article

Rapid measurement of trunk MOE on standing trees using RIGIDIMETER

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Abstract – Rigidimeter is a device developed in order to determine the modulus of elasticity (MOE) of standing trees. It was used on a hybrid Larch clonal test located at INRA, Orléans, France. Some of the examined trees were felled and remeasured. The goal of this study was to contribute to the validation of the Rigidimeter, as a fast non-destructive and reliable tool for rapid evaluation of MOE, an important mechanical property of wood. Two measurements in orthogonal directions improve the accuracy especially in the presence of reaction wood. We have showed that two measurements of diameter including bark with a precision of ± 1 mm are sufficient to obtain a reliable second moment of area, which is an important parameter for the estimation of trunk MOE. Bark MOE is small compared to wood MOE, but bark thickness influences the measurement of tree diameter. A correction may be necessary to account for the presence of bark. We propose a method for estimating MOE of different trunk layers, such as bark and mature wood layer.

genetic improvement / modulus of elasticity / standing tree evaluation / larch

Résumé – Mesure rapide du module d'élasticité des arbres sur pied à l'aide du Rigidimètre. L'appareil que nous avons développé pour mesurer le module d'élasticité (MOE) des arbres sur pied, le Rigidimètre, est utilisé dans un test de mélèze hybride à l'INRA d'Orléans en France. L'objectif de l'étude est de contribuer à la validation de sa fiabilité pour la détermination rapide de cette propriété mécanique importante. Nous évaluons ici (1) la méthode de mesure du diamètre du tronc, (2) l'influence de l'écorce, (3) quelques détails de la procédure de mesure sur la précision de l'estimation du MOE du tronc. La méthode de mesure du diamètre proposé permet d'estimer correctement le moment quadratique de la section du tronc, un paramètre important de l'estimation du MOE. L'écorce influence l'estimation du MOE, non pas au travers de son MOE propre qui semble très faible, mais par l'intermédiaire de son épaisseur qui fait varier le diamètre sur écorce. Nous proposons une méthodologie de l'utilisation de l'appareil qui permet d'estimer le MOE des derniers cernes fabriqués, c'est-à-dire du bois adulte dans l'arbre sur pied.

génétique / module d'élasticité / arbre sur pied / mélèze

1. INTRODUCTION

For evaluation of genetic tests of forest trees, wood rigidity measurements are of high technological importance [21]. They can be obtained indirectly from density measurements [1, 7, 19, 30, 32, 33] on small wood samples drilled from the trunk. Microdensitometry gives extensive information on radial growth, based on wood density variation along the diameter [22]. However, the results cannot be obtained immediately. The Pilodyn tester uses the depth of needle penetration into trunk for density estimation and gives results rapidly at low cost [4, 5, 8, 25, 26, 29, 30]. The measurements must be repeated to obtain statistically valid results. The Resistograph gives also information related to wood quality in the radial direction [3, 23]. Certain wood quality information can also be obtained from ultrasonic velocity measurements or stress wave techniques [9, 27].

Vafai and Farshad [28], Langbour [16], and Koizumi [10, 12] have demonstrated that it is possible to measure directly wood rigidity on standing trees with mechanical methods,

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using bending tests. Koizumi [11, 13–15] applied successfully his method in Japanese larch (*Larix kaempferi*) and Japanese cedar (*Cryptomeria japonica*) breeding programs. Mamdy et al. [18] and Rozenberg et al. [24] used Koizumi's method and obtained a good correlation between the equivalent modulus of elasticity (MOE_{eq}) of standing Douglas-fir (*Pseudotsuga menziesii*) trunks and standardized samples cut from the felled trees. The measurements on standing trees must be both rapid and accurate in order to be used beneficially for tree breeding.

With these objectives, a new device, the Rigidimeter, has been proposed [6, 17]. This device makes possible testing of at least 50 trees per day. When used on Douglas-fir and larch (*Larix* sp.) test populations, the performance of Rigidimeter was satisfactory [17]. In this paper, further aspects concerning accuracy of measurements are discussed using results obtained from a larch experimental population. A good accuracy is necessary in order to use Rigidimeter as discriminating device for rigidity of mature wood. First, we explain a proper way to perform MOE measurements using a bending test. Secondly, we examine the effects of (i) trunk taper and crookedness, (ii) cross-sectional shape, (iii) presence of bark and (iv) juvenile wood on the precision of MOE evaluations.

2. MATERIALS AND METHODS

2.1. Description of *Larix* test population

The experimental population used here is a part of the retrospective clonal trial (INRA-Orléans nursery). The test includes 62 clones of hybrid larch (EL × JL) from 4 full-sib families. Material was prepared from cuttings set in the spring of 1992. The nursery trial was planted in 1994 at a 1 × 1 m spacing. The design was a complete randomized block design with 8 blocks and one-tree plots. A systematic and a genetic thinning were carried out at the beginning of 1998. From the final cut in 2001, 108 trees representing 20 clones were used for our experiment.

2.2. MOE measurement using a bending test

In this paper, a tree trunk is considered as a beam. Based on this hypothesis, the best way to perform a bending test on a standing tree is to obtain a constant bending moment (M) along the trunk. In *figure 1* two possibilities are presented: the principle of Koizumi's device (*figure 1a*) and the principle of Rigidimeter (*figure 1b*).

The radius of curvature (R) is constant when M is constant. The measurement of displacement (v), with the crossbar attached to the trunk, gives R (*figure 2*).

For a cylindrical trunk, its diameter (d) gives the second moment of area (I): $I = \pi d^4 / 64$. The trunk equivalent modulus of elasticity MOE_{eq} is then calculated from the relationship $MOE_{eq} = M R / I$. For an elliptical trunk, characteristics of a section differ depending on the direction of measurement. Two main second moment of area corresponding to the long (I1) and short (I2) axes of the ellipse should be used. Rigidimeter should be applied in the planes containing the two directions of reference for each tree. M must be large

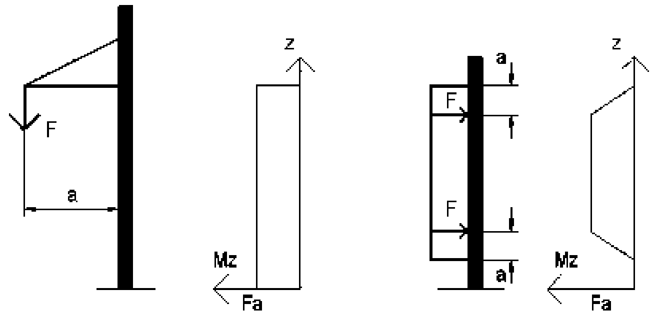

Figure 1. Principle of two bending tests on standing tree (for more details see [12] and [17]).

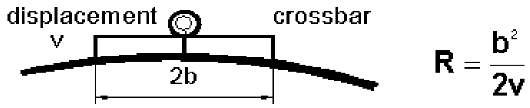

Figure 2. Principle of the trunk radius of curvature measurement.

enough to obtain a displacement of about 1 mm assuming a precision of about 1% for R, and not too high to damage the trunk wood by an excessive compression stress in the transversal direction, (i.e. it must not exceed 10 to 20 MPa). With the latest model of the Rigidimeter, the load is applied with a precision greater than 1%, by two 10 kN hydraulic jacks. To avoid damage to the bark under the Rigidimeter's supports, the area of the supports must be large enough to reduce the pressure. The best time for using Rigidimeter is also before or after the growing period.

2.3. Causes of measurement imprecision

2.3.1. Taper and crookedness

Measurement imprecision comes primarily from variation of the second moment of area I, on which are based the above relationships. Consistency of I along the trunk axis is assumed, but in reality, it is rarely obtained. Many trunks are not cylindrical but conical in shape and crooked. Stem taper and crookedness influences on MOE are simulated with a Finite Element Method (FEM) using beam elements. This method, currently used in mechanical engineering, rapidly gives a numerical solution (i.e., the displacement) to this problem [31].

2.3.2. Cross-sectional shape

Cross sections are usually assumed to be circular, which is infrequently the case. These irregularities in shape also indicate the presence of reaction wood with heterogeneous density and rigidity. For this reason, two sets of measurements were made on each tree in two orthogonal directions (i.e., two compass directions). Diameter measurements were verified using scanned images of cross-sections of 62 felled trunks. The cross-sections were cut at the same position where measurements were made on standing trees. The real value of the second moment of area, in each direction, was calculated directly using the image processing tool incorporated in Matlab 5.3®

(1999). Real diameters in two directions were deduced and statistically compared with the observed values, using the least square method.

2.3.3. Presence of bark

In order to simplify the measurement process, diameter is obtained in those two directions including the bark. Thus MOE_{eq} includes bark stiffness which is smaller than wood rigidity [20]. One can consider that each annual ring (i) is concentric and has a specific longitudinal MOE termed E_i. The trunk equivalent bending stiffness is then equal to the sum of the bending rigidity of each layer [2, 7] (Eq. (1)).

$$MOE_{eq} I_{trunk} = \sum_{i=1}^{N} E_i I_i \tag{1}$$

If bark is considered the outermost layer (N) of the elastic modulus E_b, d_{ext} is the trunk diameter over bark, and d_{int} is the trunk diameter under bark, then equation (1) can be modified to give equation (2):

$$MOE_{eq} d_{ext}^4 = E_b (d_{ext}^4 - d_{int}^4) + \sum_{i=1}^{N-1} E_i (d_{i+1}^4 - d_i^4) \tag{2}$$

Two methods were used to measure E_b:

(a) Tensile tests with a INSTRON™ machine equiped with 5000 N load cell and mechanical extensometer. Five bark samples (200 × 20 mm) were collected from 3 trees immediately after felling.

(b) Bending tests on five felled trunks 2 meters long, with and without bark.

Predicted and observed values seemed to be in good agreement, but could not be statistically compared due to the small sample size.

2.3.4. Presence of juvenile wood

For a young tree, heterogeneity of density and rigidity comes from the presence of highly variable juvenile wood core, which can occupy a large part of its cross section. Bending stiffness therefore depends on both juvenile and mature wood MOE, and to some extent on bark MOE. As shown for bark, two subsequent measurements using the Rigidimeter make it possible to extract the MOE of an external layer. This technique can be applied to find the MOE of the one or several outermost annual rings comprising only mature wood. The Rigidimeter's ability to detect a certain difference in MOE between juvenile and mature wood was examined by sensitivity analyses using computer simulations.

3. RESULTS AND DISCUSSION

3.1. Effect of stem taper and crookedness on MOE_{eq} values

The Finite Element Method with beam elements, was used to simulate the radius of curvature for a crooked tree. For a crooked trunk with a deviation of up to 50 mm, the radius of curvature was not different from that of a strait trunk. For a trunk, of conical shape (e.g. with a diameter decrease of 10 mm m^{-1}) the radius of curvature was only slightly (e.g. 1%) less than for a trunk of cylindrical shape. As a consequence MOE was also decreased by the same amount. These results suggest that natural geometry variations do not affect significantly the MOE measurement.

3.2. Trunk diameter measurement: influence of a non-circular cross-section

Trunk cross-section can be considered circular if growth is regular. Diameter is usually, measured with a precision of 1 mm; thus for a diameter of 150 mm, uncertainty regarding the second moment of area (I) is approximately 3%. Under the influence of a prevailing wind, the tree reacts and modifies its wood by creating reaction wood and an elliptical cross-section [32]. Measurement of the radius of curvature and thus estimation of MOE depends on this direction for geometric reasons and because of mechanical variations in trunk cross-section.

For practical reasons, MOE is usually measured by Rigidimeter positioned in two orthogonal directions, with the same reference direction for all trees. Two diameter values used in MOE calculations are obtained for each tree by taking measurements in the same directions. We obtained a maximum difference between two diameters measured on standing larch trees of ± 6 mm. Those diameter values were compared with diameters deduced from the real value of the second moment of area obtained from the scanned images of cross-sections (*figure 3*). The slope of the regression line was 0.99 with an R^2 of 0.91. Calculating two MOE values for each tree from diameter measurements made on standing trees is thus a good approach, because the obtained second moment of area is close to the real value. Two different values of MOE obtained in two different directions show that wood material varies with the orientation within a cross-section, and perhaps indicates the presence of reaction wood. Consequently, the magnitude of these two values can be used to study the effect of the prevailing wind or the terrain slope on the formation of reaction wood.

3.3. Influence of bark

Although, it is faster to measure diameter over bark, the resulting MOE includes the bark rigidity that can modify the

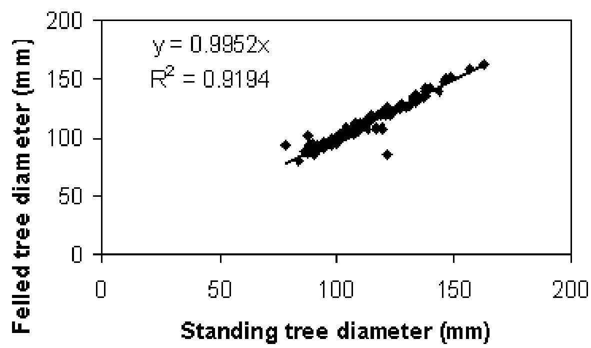

Figure 3. Comparison of the trunk diameter measurements.

classification of trees in a population. To evaluate this influence, we used the relationships from equation (2) adapted to this particular problem. Assuming trunk wood is homogeneous and has a modulus of elasticity E_w, then bark MOE E_b can be obtained from equation (3):

$$E_b = \frac{MOE_{eq} d_{ext}^4 - E_w d_{int}^4}{d_{ext}^4 - d_{int}^4} \quad (3)$$

Similarly, wood MOE E_w can be estimate from MOE_{eq} with the bark correction of equation (4).

$$E_w = \frac{MOE_{eq} d_{ext}^4 - E_b (d_{ext}^4 - d_{int}^4)}{d_{int}^4} \quad (4)$$

From the two methods used to measure E_b (a tensile test on a bark sample and a bending test on five felled trunks with and without bark) we obtained mean values ± standard deviations of 60 ± 25 and 45 ± 20 MPa, respectively. It must be remarked that the low bark MOE gives a minor contribution to the trunk bending rigidity. A mean bark thickness of 5 mm (± 0.5 mm) was measured on the felled tree cross sections. If bark thickness in a tree population is uniform *figure 4* shows that for different trunk diameters, the ranking within a population may be changed, by measuring diameters including bark. In that case, a correction accounting for the presence of bark is necessary.

3.4. Presence of juvenile wood

The modulus of elasticity measured on young trees may be different from that measured on the same trees when older. It may be desirable to classify trees using the outer mature wood portion. As it was shown previously, with two subsequent measurements using Rigidimeter it is possible to extract the MOE of an external layer. This technique could be applied to find, for example, the MOE of two last annual rings. The procedure was simulated under the following assumptions. By applying a load of 10000 N to a trunk with 150 mm in diameter (dbh) and with MOE of 8000 MPa for the juvenile wood, the measured displacement v would be 1.89 mm. Such a tree may have a cambial age of 15 years at dbh, if radial growth is on average 10 mm per year. The Rigidimeter can then be used after two years to re-measure the MOE including the two last annual rings. If they correspond to mature wood, an increase of 20% in MOE can be expected for those two last rings. With the same growth in diameter (10 mm $year^{-1}$) the displacement would be 1.06 mm. If the two last annual rings are of juvenile wood, with the same diameter (170 mm) the displacement would be 1.14 mm. The two consecutive Rigidimeter measurements would detect the difference (0.08 mm) and indicate a difference in MOE due to mature wood. It should be noted that the MOE of external annual rings can be measured with better accuracy than the MOE of bark, because wood has a greater bending rigidity than bark.

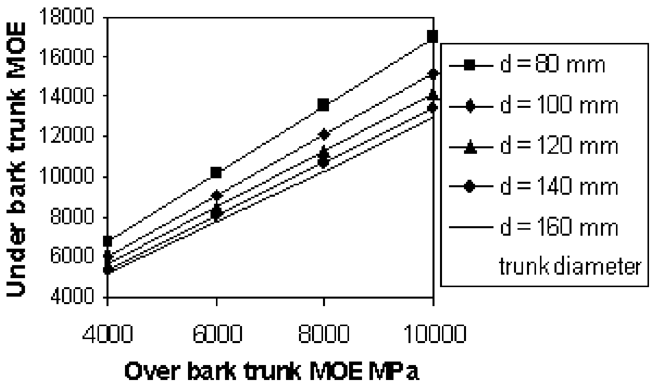

Figure 4. Comparison of the trunk MOE with and without bark.

4. CONCLUSION

The purpose of the Rigidimeter is for the evaluation in tree breeding. It is an accurate bending device able to test trunks of about 80 to 200 mm in diameter. To optimise its use, displacement measured to obtain the radius of curvature must be approximately 1 mm. Two sets of measurements in orthogonal directions improve the accuracy, especially if reaction wood is present. We have showed that diameter measurement at ± 1 mm including bark is sufficient to obtain the second moment of area.

Trunk MOE differs from wood MOE, but that should not modify the ranking of trees within a population if the variation of bark thickness and diameter are small. If the bark thickness and diameter within the population are heterogeneous, it is necessary to include a correction factor for the calculation of wood MOE.

We also propose the use of this device at two subsequent times in order to obtain MOE of mature wood layer. The first measurement gives the estimate for the juvenile core. MOE of the newly accumulated mature wood layer can be determined from the second measurement. The results of simulation presented in the section 3.4 suggest that the difference of displacement between a more juvenile and more adult tree is measurable. The MOE of the mature wood layer can be used as a classification criterion in tree selection and breeding.

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