Ann Sci For (1994) 51, 301-313

Original article

A study on growth stresses, tension wood distribution and other related wood defects in poplar (*Populus euramericana* cv I214): end splits, specific gravity and pulp yield

P Castéra [1], G Nepveu [2], F Mahé [1], G Valentin [1]

[1] *Laboratoire de Rhéologie du Bois de Bordeaux (CNRS / INRA / Université de Bordeaux), Domaine de l'Hermitage, BP 10, Pierroton, 33610 Cestas ;*
[2] *INRA, Station de Recherche sur la Qualité des Bois, Centre de Recherches Forestières, Champenoux, 54280 Seichamps, France*

(Received 25 January 1993; accepted 1st December 1993)

Summary — The development of radial shakes after felling the tree has been observed on transverse sections of 15 poplar logs. The importance of end splitting is related to the distribution of internal stresses in the stem (growth stress), the angular variations of wood structure (specific gravity and pulp yield), and the transverse mechanical resistance of wood. To investigate growth stresses, longitudinal displacements after stress release were estimated at the periphery of the stem using the single hole method. At least 4 measurements were necessary to estimate the maximum displacement value and the circumferential heterogeneity of the stress field. The position of this maximum was generally found on the upperside of the trees. To examine end splitting, the radial and longitudinal extension of splits were roughly estimated for all visible shakes occurring on cutting sections near stress measurements (breast height). Shakes were also measured for comparison at the felling section of the logs. The dimensions of the longest shake were used as an indicator of the severity of end splitting. A complete map of wood basic specific gravity was made at the breast height level for all trees. This is associated with pulp yield measurements, an increase in density and pulp yield being generally considered as an indicator of gelatinous fibres. Peak values of growth stresses in the stem were associated with a significant increase in pulp yield and specific gravity. The study was completed by a set of experiments on resistance to crack propagation *via* TR bending specimens. The critical stress intensity factor K_{IC} was calculated. Quantitative measurements of end splitting have proved to be a useful tool for assessing the technological impact of growth stresses in trees; the importance of cracks is clearly related to the maximum value of displacement at stress release. However, crack propagation can also be explained by cell-wall properties and transverse cohesion of green wood. Further research should focus on this second aspect, in order to determine structural properties of importance in crack propagation.

growth stresses / end splitting / tension wood / fracture toughness / poplar

Résumé — Contraintes de croissance, bois de tension et défauts associés chez le peuplier I214. Fentes d'abattage, densité du bois et rendement en fibres. *L'influence de contraintes internes élevées dans l'arbre, et du comportement mécanique transverse du bois, sur l'importance des fentes d'abattage, a été étudiée chez 15 peupliers I214 (clone sensible au problème) agés de 30 ans. Pour ces arbres le protocole suivant a été adopté : i) Estimation des déformations résiduelles en 4 points à la périphérie du tronc, à une hauteur de 1,30 m. La position du pic de déformation est généralement estimée par la direction d'inclinaison de l'arbre mesurée sur 6 m. ii) Quantification des fentes sur la section d'abattage et sur une section voisine des points de mesures des déformations : longueur et profondeur maximale estimée des fissures. Les dimensions de la plus grande fente ont été prises comme indicateur de l'importance des fentes. iii) Cartographie de densité : des rondelles prélevées dans la même zone ont été découpées en 24 secteurs angulaires et 4 tranches radiales correspondant à des événements précis (années d'élagage, éclaircie). La présence de bois de tension est évaluée par des zones de densité plus élevée. L'estimation a été complétée par des mesures de rendement en pâte (présence de fibres gélatineuses). La notion de «bois de tension» est dans notre esprit plus mécanique qu'anatomique, et traduit effectivement un changement des propriétés du bois dans les zones plus tendues de l'arbre. iv) Résistance à la propagation de fissure : l'étude a été complétée par des essais de propagation de fissure en mode I réalisés sur des éprouvettes de flexion 3 points en configuration TR (éprouvette SENB, propagation radiale). Cette étude montre qu'une estimation même simplifiée de la fissuration à l'abattage met en évidence l'impact technologique des contraintes de croissance : les arbres pour lesquels des fentes importantes ont été observées présentaient également des pics de contraintes internes. Les cartographies de densité montrent clairement des secteurs de surdensité dans les zones «tendues», parfois limités à la périphérie du tronc, parfois très précoces (près de la moelle). Enfin la fissilité du bois, indicateur de cohésion cellulaire, semble également jouer un rôle dans la variabilité de la fissuration. Ce deuxième aspect devrait être développé ultérieurement.*

contraintes de croissance / fentes d'abattage / bois de tension / ténacité / peuplier

INTRODUCTION

The development of internal stresses in the stems of trees has been widely discussed in recent literature (Archer, 1986; Fournier *et al*, 1991, 1992; Okuyama *et al*, 1992). The technological consequences of stress redistribution after felling the tree and processing the logs is of economical importance for a number of hardwood species, such as poplar, eucalyptus, and beech. End splits of logs, when severe, can dramatically reduce the output in sawing or peeling processes. The quality of products is also affected by the presence of woolly wood, usually combined with higher growth-stress values at the periphery of the stem.

Tension wood is usually found on the upperside of leaning trees. Severe tension wood zones can be detected visually (woolly surfaces) or estimated indirectly by dissymmetric distributions of specific gravity around the stem, but the only standard test up to now is the anatomic identification by colorific techniques of gelatinous fibres. The role played by reaction wood in growth regulation (stem movements) has been the subject of recent publications (Delavault *et al*, 1992).

The literature is not as extensive on important problems such as end splitting of logs, twists or bows of beams prior to drying, and their possible control by cultural treatments, choice of clone or processing techniques. A number of authors have examined this problem, *eg*, Boyd (1955), Barnacle (1968, 1973), Priest *et al* (1982) and recently, Persson (1992), among others. From a mechanical point of view the occurrence and propagation of radial shakes at the end sections of logs depend on 2 factors: the loading conditions of the structure (local stress field); and the material behaviour (elastic and viscoelastic deformability, crack growth strength). Calculations of stress redistribution after felling have been discussed by some authors (Wilhelmy-Von Wolff, 1971; Mattheck, 1991). These workers show that the highest probability of crack initiation occurs near the pith, due to high tangential stress. In fact end splits are very frequent in logs. Observations made on samples of poplar logs in different stands indicate that the proportion of logs that contained no visible shake immediately after felling was less than 10% (observations made with the help of the technical Division of the ONF, National Forest Office).

The second factor to be studied is related to the propagation conditions of existing shakes, which mainly depend on material properties. An illustration of this is given in figure 1, showing the radial extension of end splits between time 0 after felling 24 h later. The initial distribution of shake lengths in the sample of logs is dissymetric, with a maximum occurrence of small shates and a few large ones that generally reach the outside. The extension of splits within 24 h is represented by a deviation of points from the straight line $y = x$. However, these observations only give a rough estimation of splits extension, which occurs in the radial direction, which is limited by the log diameter and the longitudinal direction.

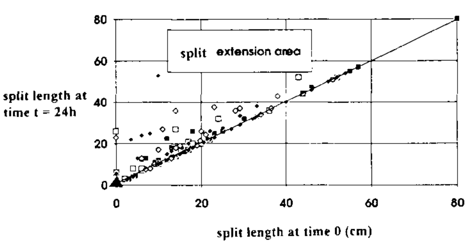

Fig 1. Radial extension of end splits at the end of the log within 24 h of felling the tree. Measurements have been made on 4 mature poplar stands in the south-east France and about 20 trees per stand. The straight line $y = x$ represents no extension.

In this paper we analyze the severity of end split in 15 poplar trees (*Populus euramericana* cv I214) in terms of growth stress, tension wood occurrence and crack growth strength measured on air-dried specimens. The trees were sampled in a mature ONF plantation and had been submitted to various pruning conditions over 2 different periods. One objective is to predict the probability of end splitting before felling the tree by growth strain measurements. Another aspect concerns the prediction of tension wood by density measurements at different angular positions on a stem. Finally, this study is an attempt to use crack propagation experiments to explain end splitting of logs.

MATERIALS AND METHODS

Fifteen trees were sampled in a 28-year-old experimental poplar plantation. The stand belongs to the ONF. Different cultural treatments have been applied to the stand. In 1968 an initial pruning treatment was carried out, when the trees were 6 years old. The objective was to compare 2 different pruning intensities, at 50 and 60% of the total height of the trees. Some of the trees in the stand were kept unpruned for reference. The same pruning operations were repeated in 1972 and 1976, in order to maintain the pruning level at 50 and 60% of the current height. Finally, a thinning treatment was made in the plantation in 1986.

Our sample contains 5 unpruned trees, 7 pruned trees at the 50% level, 3 pruned trees at the 60% level. It should be noted that pruning poplar trees is often aimed at improving the form of the stem (suppression of forks) and is expected to have an effect on tension wood and growth strain distribution. However, this effect will not be analyzed here due to the limited sample size.

The mean leaning angle of the trees was measured on a 6 m height; in the following sections position 1 always refers to the upperside of the stem. To complete the description, we also measured the extension of the crown in 4 perpendicular directions, and the shape defects of the stem (curvatures, torsion) were described qualitatively. The main morphological features of the trees are given in table I.

Table I. Morphological characteristics of the trees.

Tree No	Crown radius				Pruning	H	α	Stem form
	R_1	R_2	R_3	R_4				
11	5.8	5	7	6.8	60%	35.3	43	1 fork
23	3.5	6.8	7.5	6.7	60%	37.3	70	curved
39	4.1	5.5	5.2	6.3	50%	35.3	83	flexuous
48	4.4	8	5.7	4.1	unpruned	37.3	98	2 forks
58	3.7	6.9	5	4.1	60%	38.3	–	flexuous
67	3.4	4.1	5.3	6.2	unpruned	40.3	100	forks
78	2.5	3.9	3.8	3.7	50%	37.8	95	forks
80	3.3	7.2	6.4	6.7	50%	37.8	69	flexuous
81	2.6	6.4	4.5	6.5	50%	37.3	86	tilted
88	3.6	4.9	5.5	5.9	unpruned	37.8	53	forks
89	5.9	6.1	5.3	6.2	unpruned	37.8	49	flexuous
90	4.8	4.8	7.7	6.4	50%	36.3	92	tilted
92	3.8	5.2	3.9	5	50%	35.3	58	flexuous
94	5.3	5.3	5.2	6.8	50%	38.3	71	flexuous
100	3.7	7.5	5.8	8.5	unpruned	37.8	66	straight

R_i crown radius at position i (m); α: deviation from the vertical position (horizontal distance in cm between the position of the stem at a 6 m height and the base); H: height (m).

Growth strains

Residual longitudinal strains were measured on standing trees at breast height level. We used the single hole method (Archer, 1986) to estimate the tensile strains in the fibre direction at the periphery of the stem. With this method we measured a displacement after stress release. The values themselves are not of great interest but we can analyze angular variations of these displacements for different trees by this method. Actual growth-strain values can be evaluated by a mechanical analysis of stress redistribution around the hole with underlying assumptions on the mechanical behaviour of green wood (Archer, 1986), but this is not the purpose of this study.

Measurements were usually made in 4 perpendicular directions. In most cases this was enough to approximate the maximum displacement value, corresponding to the upperside of the stem (position 1). However, for a few trees the distribution around the stem did not indicate the position of this maximum clearly, and complementary measurements were necessary. Figure 2 shows the distribution of displacements at stress release that is normally observed around the stems with the expected maximum in position 1, and the distribution that was measured for one particular tree. This remark emphasizes the fact that displacements, and their corresponding growth strains, do not follow simple angular distributions, and the observed maximum value may underestimate the actual maximum.

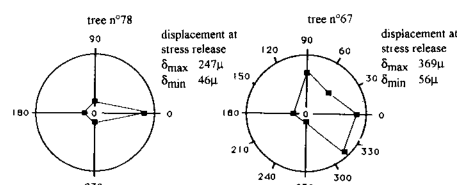

Fig 2. Angular distribution of displacements at stress release (microns) in the stem. Position 0 on the right refers to the upperside of the leaning tree (position 1 in the text). The maximum strain is generally found at this position (left).

End splitting

The occurrence and development of end splits were recorded at the felling section and a second transverse section near the stress measurements. In the first case the observed shakes are the consequence of the growth stress redistribution combined with the impact effect of felling. In transverse sections that were cut after felling the development of shakes is more directly related to the stress field in the stem.

The orientation and radial and longitudinal extension of shakes have been measured as indicated in figure 3a. The measurements only give rough estimations of crack dimensions, and should be considered as qualitative rather than quantitative information on the severity of end splitting. The maximum depth of shakes was estimated by the penetration of a flat graduated rule.

Using one particular example, figure 3b shows that the form of end splitting was usually different on the felling section and the section at breast height. On the following sections only the measurements at the breast height level will be considered.

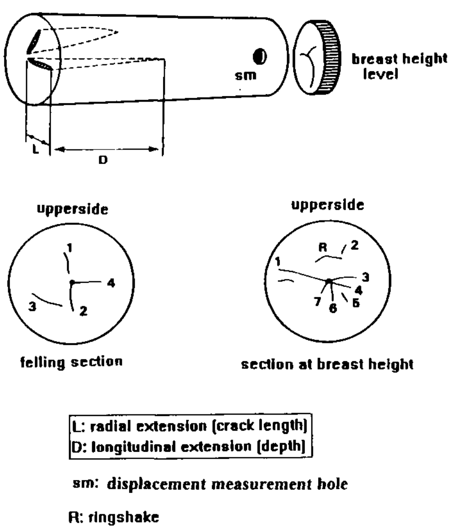

Fig 3. Top: qualification of end splitting in logs. Measurements were made both on the felling section and at breast height level. Bottom: variations in end splitting between the 2 sections for one particular tree. Most shakes initiate from the pith.

Tension wood

Discs were collected near the strain measurements and divided into 24 angular sectors and 4 radial zones, giving 96 wood samples for each log. From these samples, a map of wood density was established for all trees. The innermost samples (first zone) correspond to the period of growth before the first pruning (1962–1968), the second radial sector represents the period between the first and third pruning operations (1969–1976), the third sector ends before the thinning treatment (1986),and the outermost zone starts after thinning. An example of the maps is given in figure 4. Dark zones correspond to higher density values.

This map was completed by a qualitative notation of woolly wood on 450 wood samples representative of the range of variability of wood density in the 4 radial zones. Finally, the pulp yield of each sample was measured.

All measurements on discs were carried out at the Wood Quality Research Laboratory at INRA Nancy. Due to the large number of samples, an anatomical verification of tension wood occurrence (gelatinous fibres) by standard colorific methods, has only been made for 2 trees in this study.

Crack growth strength tests

Crack growth strength can be estimated by loading a precracked specimen and measuring the critical load at the onset of unstable growth. This is the aim of fracture mechanics, which is usually applied in timber engineering (Ashby *et al*, 1985). A material property called fracture toughness K_{IC} can be deduced from the critical load and a geometric calibration factor (see for instance, Valentin *et al*, 1991).

To allow a complete interpretation of crack development, wood samples were cut in positions 1 and 3 (opposite) of 7 characteristic logs near strain measurements (figure 5a) and stored until they reached a final average equilibrium moisture content of 12% (storage for 3 months at 20°C and 65% RH). The logs were chosen to be representative of the variability of growth stress (estimated by the residual displacements). The fracture toughness was calculated on SENB (simple edge notched in bending) specimens on a

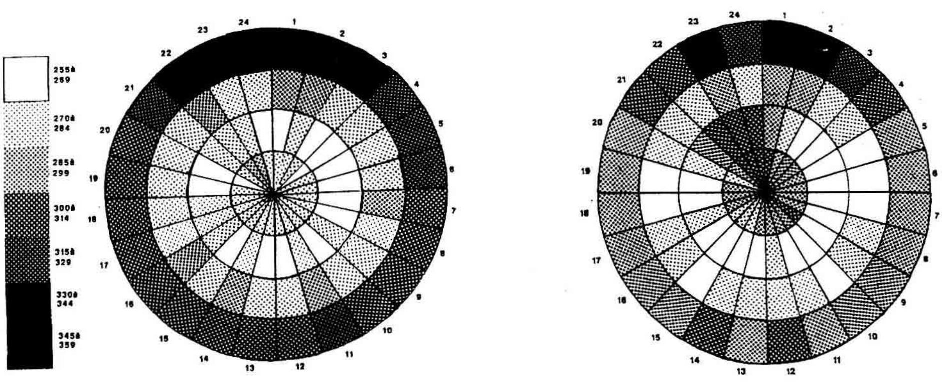

Fig 4. Map of wood density on discs collected at breast height and divided into 4 radial zones and 24 angular sectors (example).

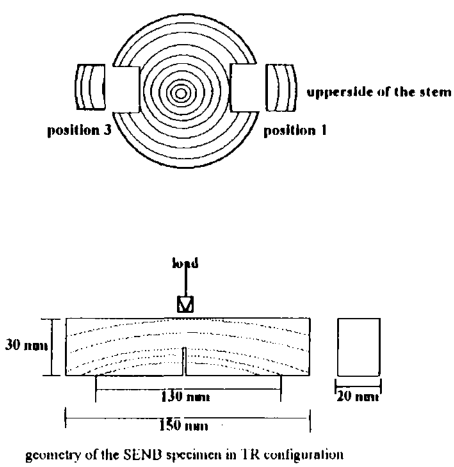

Fig 5. Sampling procedure and methodology for the mechanical tests. Tests were performed in air-dried conditions at room temperature.

bending apparatus equipped with a 100-DaN load cell. Experiments were carried out at the Wood Rheology Laboratory in Bordeaux.

The geometry of the specimens in shown in figure 5b. The dimensions were 150 x 30 x 20 mm. The initial crack is radially oriented and the normal direction to the crack plane is tangential (TR geometry). Under this loading condition, the propagation occurs in the opening mode (mode I) and is perpendicular to growth rings, that is, similar to radial shakes. This direction of cracking has been studied previously by Sobue and Asano (1987).

On each test, we recorded the load applied, the displacement of the load, and the crack opening with a LVDT transducer. From the results a critical stress intensity factor K_{IC} was calculated. Some experiments were performed in green conditions but the estimates obtained for K_{IC} were not as precise.

RESULTS

Three trees from the whole sample exhibited severe end splitting (estimated as the length of the longest shake). However, end splits developed on all logs, which confirms the general propensity of this clone to have this problem. The general features of end splitting, and related displacement values, specific gravity and pulp yield for the sample are presented in table II. The values of specific gravity and pulp yield have been calculated for the same sample and only the between-tree variations are presented here.

Table II. Displacement after stress release, end splitting, specific gravity and pulp yield values.

	Average	*Maximum*	*Minimum*	*CV (%)* *
End splits				
Felling section				
Number	4	8	1	40
Length (cm)	11.8	28.5	2.0	52
Breast height				
Number	5	8	2	49
Length (cm)	7.8	32	1.0	55
Displacements (μ)				
1	237	339	109	26.6
2	85	284	42	68
3	69	93	43	22
4	64	115	46	25
Basic specific gravity (g/dm^3)				
Core zone	284	303	263	3.6
Outer zone	314.5	332	302	2.1
Pulp yield (%)				
Core zone	48.1	51.5	46.6	2.4
Outer zone	51.2	52.6	49.9	1.6

* CV %: coefficient of variation (between-tree variability only).

Distributions of the variables

The distributions of displacements at stress release values δ, basic specific gravity S_g, shakes length L and pulp yield py are presented in figure 6a–d. The δ distribution represents an average of 4 measurements per tree. The histograms of displacement values, specific gravity and pulp yield measurements exhibit a dissymmetrical form, the right part generally corresponding to position 1 in the stem. Two populations can be separated, with an average value and a standard deviation for each population. One of these is composed of normal wood and is homogeneous in Sg, δ and py. The second population corresponds to the peak values of all variables, and is called 'tension wood', although the anatomical features of tension wood are not necessarily present. The term 'tension wood' refers to positions in the stem where higher growth stresses are observed. The values in this region are scattered due to different degrees of dissymetry in the stems. The dissymetrical form of the angular distribution of growth stresses seems to occur regularly in tree stems, as noted by Fournier *et al* (1992).

Angular variations of growth stress, wood specific gravity and pulp yield

The circumferential heterogeneity of δ in the stem is defined as the ratio of the peak value δ_{max} (tension zone) and the minimum value observed. The local heterogeneity is the ratio of the displacement value at position x

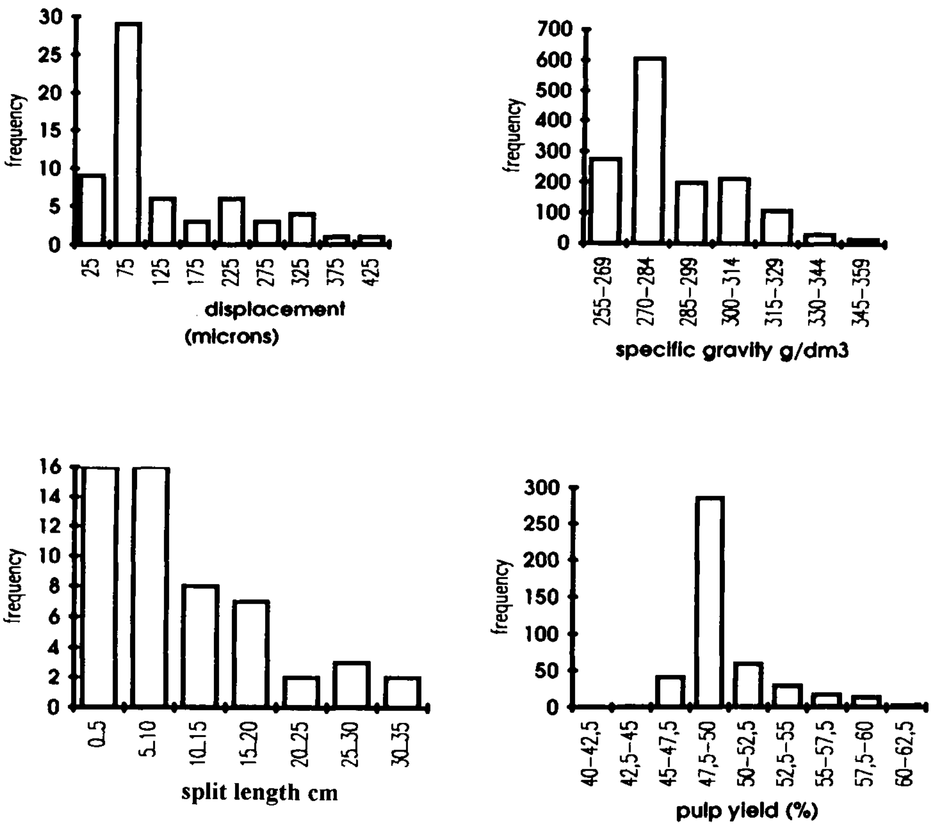

Fig 6. Distributions of the main variables: displacement at stress release (4 measurements per tree); specific gravity (96 measurements per tree); length of end splits; and pulp yield.

(the angular position) and the minimum value. Similar definitions of heterogeneity are given for specific gravity and pulp yield. In figure 7 the heterogeneity of specific gravity $Sg(x)/Sg_{min}$ has been plotted against the heterogeneity of displacements $\delta(x)/\delta_{min}$ for some typical trees. Position 1 usually corresponds to peak values of displacements at stress release as well as specific gravity. This confirms the relationships existing between wood structure and growth stress in the stem. However, the combined evolution of these 2 parameters differs from tree to tree, and in some cases the respective positions of Sg_{max} and δ_{max} are different (tree No 89 for instance). Furthermore, the area of the polygon [1,2,3,4] is variable, which indicates that the extension of the tension zone is also variable.

The angular and radial variations of specific gravity and pulp yield have been calculated from all disc maps. Two examples of the variations of these parameters are shown in figure 8.

Individual variations in radial patterns of these parameters depend on the history of each tree. The thinning treatment had an effect on specific gravity and probably tension-wood occurrence, although this observation needs to be confirmed. In the case

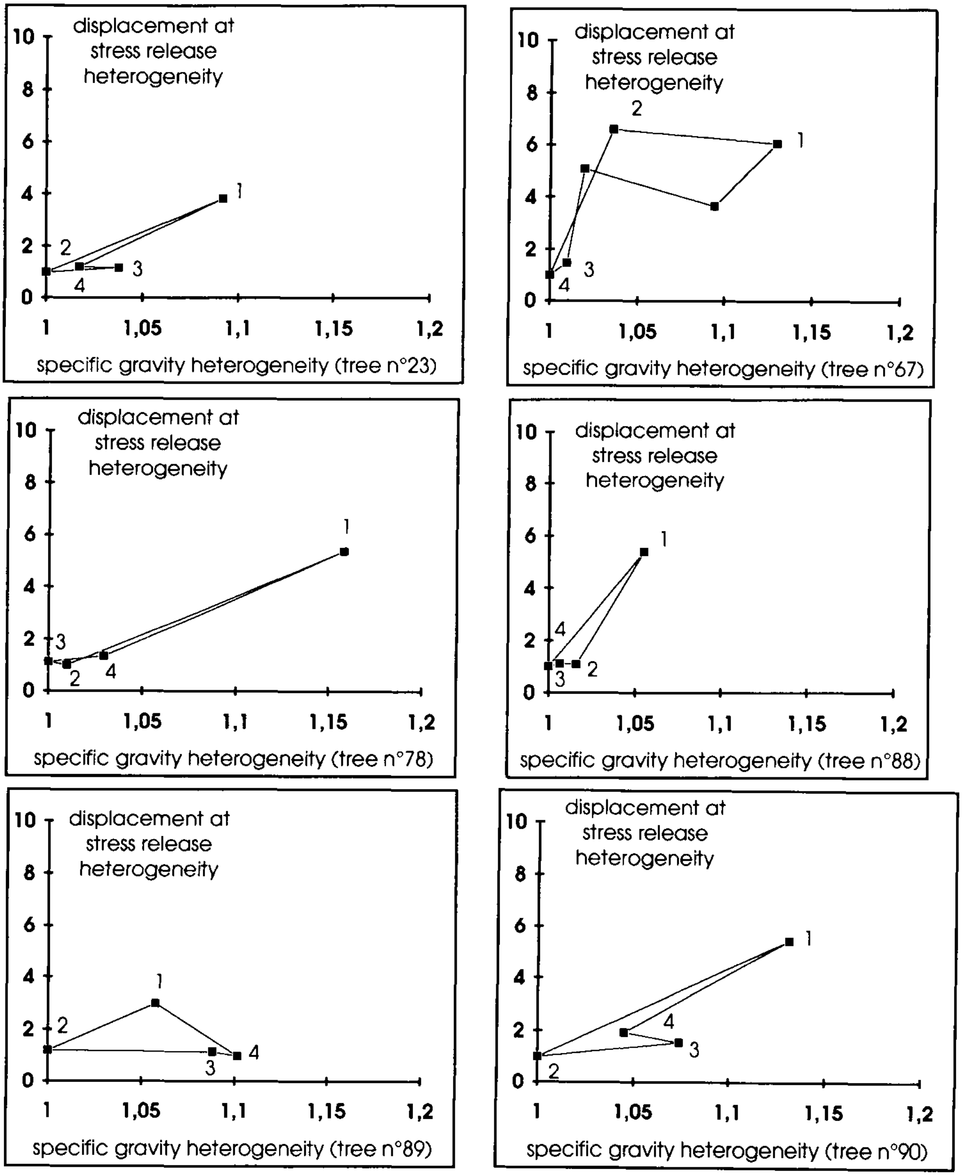

Fig 7. Circumferential heterogeneity in growth strains and specific gravity for some typical trees. Positions 1, 2, 3, 4 refer to angles of 0, 90, 180, 270° around the stem.

of tree No 88 the angular dissymmetry in specific gravity and pulp yield seems to be directly related to the thinning treatment.

On the other hand, tree No 67, which was severely damaged after felling, presented a different radial pattern, with peak values in

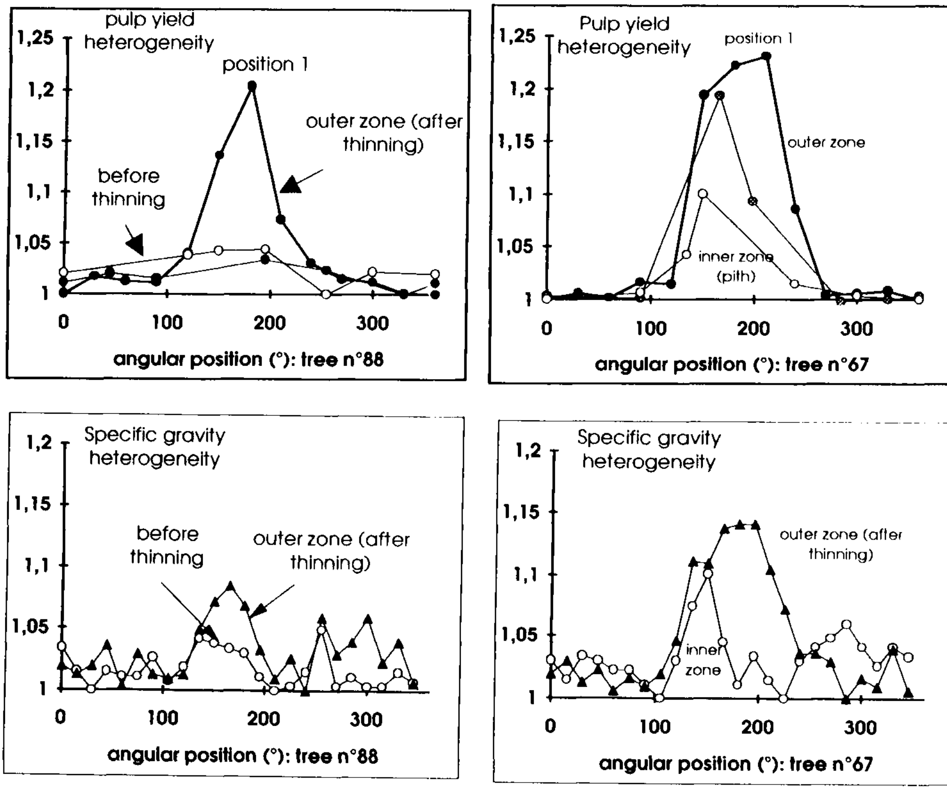

Fig 8. Angular variations of specific gravity (map) and pulp yield for 2 characteristic trees.

pulp yield and specific gravity appearing very early.

Relationships between maximum displacement values and end splitting

From a technological point of view the major indicator of the importance of end splitting is the development of the largest shake on the transverse section, *ie* radial extension and development along the fibre axis. To estimate the importance of damage, we used a single parameter, either the radial extension *L* or the product *LD* (surface) of the shake. Figure 9 shows that the between-tree correlation between *L* or *LD* and the peak displacement value is significant, with a coefficient of determination equal to 0.67 and 0.79, respectively. With the surface the best relationship is exponential:

$$LD = s = 262.43 \bullet \exp(0.015 \bullet \delta_{max}) + \text{Res}$$

where L = maximum length in mm; D = depth in mm and δ_{max} maximum displacement at stress release (microns); Res represents the residual deviation from the regression curve.

As a conclusion to these results, we can say that the individual variability of end splitting can be explained, to some extent, by

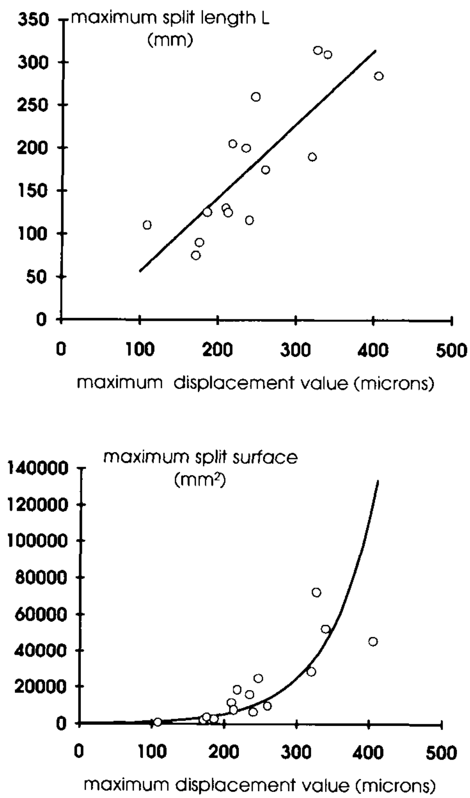

Fig 9. Top: relationship between maximum crack length and δ_{max}; bottom: relationship between crack surface *LD* and δ_{max}.

different growth-strain patterns in tree stems. High strain values increase the probability of shake development. The angular heterogeneity of specific gravity exhibits a good correlation with the dissymmetry of growth strains and could therefore be used as a predictor of tension wood in the stem.

Variability of fracture toughness

The average critical stress intensity factor K_{IC} calculated from specimens collected in tension zones and normal zones did not differ significantly in our sample. Differences appear when plotting K_{IC} against specific gravity, because specific gravity is generally higher in tension wood, as indicated in previous sections. The mean values for this parameter in normal wood and tension wood for each of the 6 logs are given in table III. A large variability has been found for K_{IC}, partly due to experimental conditions. The position of the crack tip in the ring has a significant influence on the critical load *Fq*, from which K_{IC} is calculated. When the crack tip is in the earlywood the mean value of K_{IC} is 15.2% lower than when the crack tip is in the latewood. Initial crack length was about half the height of the specimen but the current length was not known exactly until the specimen was broken; the position of the crack tip could not be controlled accurately.

Figure 10 shows the combined variability in K_{IC} and δ_{max} for the 6 trees sampled. Note that trees No 67, 90 and 78 were characterized by large end splits, while trees No 88, 100 and 39 did not exhibit severe end splitting. For trees No 67 and 90 end splitting is clearly related to high growth stresses in the stem. In the case of tree No 78, which was also severely damaged, the critical stress intensity factor is lower and therefore end splitting occurs at lower peak values of growth stresses. Although the major effect remains the amplitude of growth stresses in the stem, *ie* the loading of the crack, we believe that the ultrastructural properties of wood (cell-wall composition), which play a role in the propagation of cracks, might explain the differences between severely damaged logs and defect-free logs. The biological control of these 2 factors, *ie* growth stresses and cell-wall properties, may be quite different. Growth stress mainly depends on the individual history of trees, including silvicultural factors, such as thinning or pruning, while the composition of the cell wall might result from the combined effects of heredity and soil characteristics.

Table III. Criticial stress intensity factor measured in tension and normal zones for 7 typical trees (air-dried conditions).

Tree No	K_{IC} *(MPa•√m)*			
	Normal wood		*Tension wood*	
	Average	*CV (%)*	*Average*	*CV (%)*
39	0.309	17	0.216	2.5
56	0.192	2.3	0.264	14.8
67	0.315	2.5	0.320	3.4
78	0.232	8.6	0.202	16.7
88	0.202	4.9	0.233	16.3
90	0.204	7.3	0.264	9.6
100	0.287	15.3	0.266	3.23
Average	0.26 ± 0.06		0.25 ± 0.05	

Observations of crack surfaces from fracture toughness tests made by scanning electron microscopy (SEM) indicate different paths in green and air-dried specimens. In laboratory conditions (air-dried specimens), crack propagation generally occurs through the cell-wall layers. In green conditions, the crack mainly progresses in the middle lamella and primary wall, and only the vessels are broken.

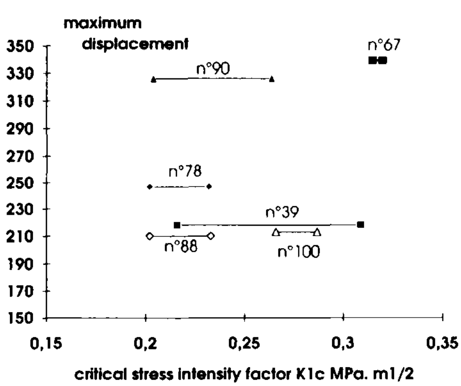

Fig 10. Variability of fracture toughness and maximum displacement.

DISCUSSION

From a technological point of view growth stresses in stems significantly affect the log quality and wood properties. Mean values of displacements at stress release do not differ greatly from tree to tree, but the presence of a local peak value is essential. The redistribution of the stress field after felling the tree results in radial shakes, with a variable degree of severity, depending on the amplitude of the maximum displacement value. The dimensions of the most significant shake are related to the value of this maximum. This is of course of interest in the prediction of the probability of end splitting before felling, and could lead to precautions to avoid (or limit) this problem. Peak values of growth stress generally result from tree leaning, although the intensity of leaning does not explain the maximum strain value.

Angular variations of specific gravity in the stem exhibit good correlations with peak strain values and tension wood, as estimated by pulp yield measurements. If tension wood occurrence were partly under genetic control, this character could be efficiently used in early selection. This could be a field of investigation for future research in poplar selection.

The use of fracture mechanics to investigate the structural factors (anatomy and cell-wall properties) that determine the conditions of crack propagation is also a promising field. Our preliminary results show that a large variability exists, within one clone and one site, in fracture toughness calculated in air-dried conditions. The extension of such results to explain crack propagation in green conditions when several cracks are present is a complex problem. Future investigations will certainly focus on this problem.

ACKNOWLEDGMENTS

We would like to thank the National Forest Office (ONF) for providing material, D Leclerc at the Technical Division of Chambery (ONF), and T Hurpeau, M Pierre, S Petit and S Garros for technical assistance at the Wood Quality Research Laboratory, Nancy.

REFERENCES

Archer RR (1986) Growth Stresses and Strains in Trees (E Timell, ed). Springer Verlag, Berlin, 240 p

Ashby MF, Easterling KE, Harrysson R, Maïti SK (1985) The fracture and toughness of woods. *Proc R Soc London A* 398, 261-280

Barnacle JC, Gottstein JW (1968) Control of end splitting in round timber. *For Prod Tech Notes,* 1-6

Barnacle JC (1973) Cracking in round timber: a discussion about causes with special references to impact. Forest Products Laboratory, Division of Building Research, Technological paper No 68, 2-13

Boyd JD (1955) Can end splitting of logs be controlled? *For Prod Newsl CSIRO* 208, 2p

Delavault O, Chanson B, Loup C (1992) Dynamique de la forme et formation de bois de réaction chez des axes de jeunes *Eperua falcata* Aubl. Proc IUFRO All division 5 conference, Nancy, August 23–28, Vol 1, p 177

Fournier M, Chanson B, Guitard D, Thibaut B (1991) Mécanique de l'arbre sur pied : modélisation d'une structure en croissance soumise à des chargements permanents et évolutifs. 2. Analyse tridimensionnelle des contraintes de maturation, cas du feuillu standard. *Ann Sci For* 48, 527-546

Fournier M, Chanson B, Thibaut B, Guitard D (1992) Comparisons between residual growth strains on different species (maritime pine, clones of poplar and eucalyptus, red oak, chestnut, beech, wapa). *Proc IUFRO* All division 5 conference, Nancy, August 23–28 Vol 1, p 62

Mattheck K (1991) *Trees: The Mechanical Design.* Springer verlag, Berlin 121 p

Okuyama T, Yamamoto H, Yoshida M, Hattori Y, Archer RR (1992) Growth stresses in tension wood of some hardwood species. *Proc IUFRO* All division 5 conference, Nancy, August 23–28 1992 Vol 1, p 273

Persson A (1992) Stem cracks in Norway Spruce: causes and consequences. *Proc IUFRO* All division 5 conference, Nancy, August 23–28 Vol 1, p 277

Priest DT, Knuffel WE, Malan FS (1982) End splitting in *E grandis* saw logs and sawn timber. National Timber Research Institute, CSIR special report HOUT 223, 20 p

Sobue N, Asano A (1987) Effects of loading speed and moisture content on crack propagation in the radial direction of wood. *Mokuzai Gakkaishi* 33, 7-11

Valentin G, Boström L, Gustafsson PJ, Ranta Maunus A, Gowda S (1991) Application of fracture mechanics to timber structures. RILEM state of the art report, VTT research note No 1262, 83 p

Wilhelmy-Von Wolff V (1971) Residual stresses in wood and their effect on crack development. PhD Thesis, University Wisconsin, 108 p