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Size Effect in Crack Shear Strength of Wood

S. Morel and G. Valentin

Laboratoire de Rhéologie du Bois de Bordeaux, Domaine de l'Hermitage, BP. 10, 33610 Cestas Gazinet, France

ABSTRACT. It is known for long time that the size of a structure has an important effect on its fracture stress. This phenomenon is called size effect and it seems that it can be attributed to the influence of a damaged zone which develops around the fracture area. Investigations have been made on size effect in shear fracture on two species of wood : Maritime Pine and Norway Spruce. The experimental fracture stresses and energy release rates of geometrically similar specimens of different sizes are analysed according to the size effect law of Bazant. This theoretical model allows an estimation of the evolution of fracture stress and energy release rate in terms of structural size but also an estimation of the dimensional validity areas respectively attributed to non-linear fracture mechanics and to linear elastic fracture mechanics. A comparison of the results was made in order to determine the relative brittleness of Pine and Spruce.

1. INTRODUCTION

In a building material such as wood, the fracture characteristics obtained in laboratory with small specimens must be applied to structures with large dimension. So, it is necessary to know the evolution of fracture characteristics according to the size of the structure. Indeed, when the volume of a structure increases, the strength generally decreases and it appears that this increase of specimen size produced an increasing brittleness. Several works based on the well-known Weibull's weakest-link theory have been made to describe the size effect in wood [5, 7]. This theory governs the size effect in unnotched wood structures failing at the initiation of the first macrocrack from the worst defect (knot, resin pocket...). In this work, this statistical size effect is assumed to play only a minor role. Indeed, the notched fracture specimens used here, show a stable crack growth before the failure. Linear elastic fracture mechanics (LEFM) takes into account the scale effect but is not sufficient to explain the evolution of fracture characteristics. Another approach, "the size effect law" proposed by Bazant [3] and established from LEFM, allows the description of a large part of these phenomena, and mainly the scaling of small to large structures. This method initially proposed for concrete and ceramics [3] can also be applied to wood failure [1, 9]. In this approach, it is assumed that a damaged zone in front of the crack tip originates some modifications of the stress and displacement fields surrounding this zone. According to the size of the structure, these modifications are more or less important and give rise to modifications of macroscopic behaviour of the structures. In this paper, the size effect law is employed for explaining experimental results of shear fracture in Maritime Pine and Norway Spruce. Geometrically similar specimens of sufficiently different sizes were tested.

2. SIZE EFFECT LAW.

In linear elastic fracture mechanics (LEFM), assumption is made that the material is elastic at every point and especially at the crack tip where infinite stresses are analytically obtained. This assumption is never completely fulfilled with real materials. Physically, there always should exist a zone in front of crack tip (fracture process zone) which is in state of progressive damage. In an infinitely large specimen, this zone occupies only an infinitesimal volume of the body; the entire body can be considered as elastic which is the assumption of LEFM. Now, if the fracture process zone occupies an important volume of the

structure, the stress and displacement fields surrounding this zone are highly perturbed, leading to a behaviour looking like ductility. So, LEFM cannot be used.

Independently of the type of the real toughening mechanism in fracture process zone, the size effect law takes into account this area by assuming an equivalent crack length a at failure:

$$a = a_0 + c$$

where a_0 is the initial crack length and c is the elastically equivalent process zone length.

By inserting this equivalent crack length in some equations of LEFM, Bazant obtains an analytic expression of fracture stress as a function of a characteristic dimension d of the structure. The expression (1), called size effect law has been successfully applied to wood in shearing mode [9].

$$\tau_c = \frac{B \cdot \tau_{ref}}{\sqrt{1 + d/d_0}} \quad (1)$$

where τ_c is the critical shear stress at failure

d is a characteristic dimension of the structure

B , d_0 , and τ_{ref} are empirical constants

A similar expression (with shear stress replaced by normal stress) has been applied to describe the failure of ceramics, concrete and rocks [3] and wood in opening mode [1]

Moreover, the size effect law allows to determine the evolution of the critical energy release rate G_{IIC} as a function of the fracture energy G_{IIF} and the characteristic dimension d (equation 2) :

$$G_{IIC} = G_{IIF} \cdot \frac{d}{d + d_0} \quad (2)$$

with d_0 is an empirical constant.

3. EXPERIMENTAL INVESTIGATIONS.

Investigations have been made on size effect in shear fracture of wood. In order to obtain an evolution of the fracture characteristics, geometrically similar specimens of sufficiently different sizes have been fractured by shear.

3.1. Material and specimen

Two species of wood, Maritime Pine (*Pinus pinaster Ait*) and Norway Spruce (*Picea abies L.*) have been tested. Average oven dry specific weights were respectively 560 and 390 kg/m³. Tests were made on Linear Tapered End Notched Flexure specimens (LTENF) displaying a stable crack growth. Six geometrically similar specimens characterised by their height (d) : 25, 37,5, 50, 75, 100 and 200 mm (Annex 1) have been used.

The thickness (b) was kept equal to 40 mm for all specimens except the larger specimens ($d=200$ mm) which thickness is equal to 70 mm for stability reasons.

In each dimension, between 6 to 8 specimens were cut, in the longitudinal-tangential directions, from planks 75 by 225 mm. Moisture content of all specimens was found to fall between 11 and 13 %. A chevron notch with a 90° angle was machined with a band saw and prolonged on 4 mm with a razor blade as crack starter. The dimensions of LTENF specimens are given in Annex 2.

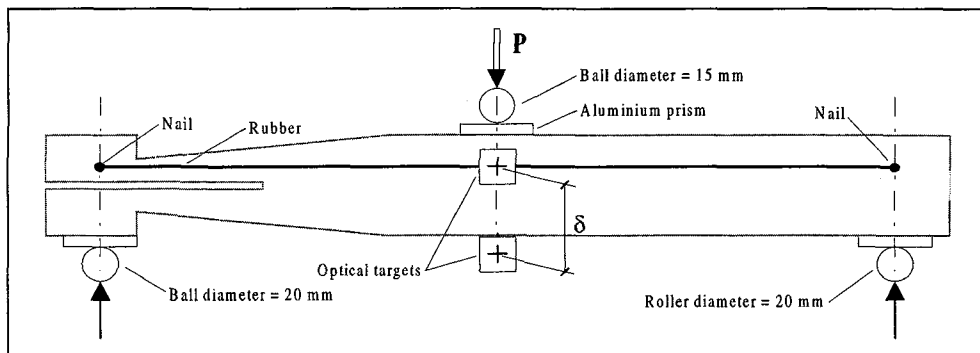


Figure 1 : Test set-up with loading arrangement and optical displacement measurements.

3.2. Testing

Tests were made in three points bending at constant cross head displacement rate. Testing arrangements have been described in a proposal by RACOIS [8]. During tests, load-deflection values were continuously recorded. Deflection was measured with an optical extensometer without contact with the specimen. Figure 1 displays the general arrangements with the two targets, one glued at the centre bottom of the specimen, and the other fixed on a rubber string pinned by two small nails near the neutral axis of the beam at the straight above its supports. Figure 2-a shows a typical load-displacement curve. On such a curve, the part at quasi constant load is obtained during crack growth. The fracture load P_u (ultimate load) is defined as the point at the beginning of the constant load part corresponding to the crack growth.

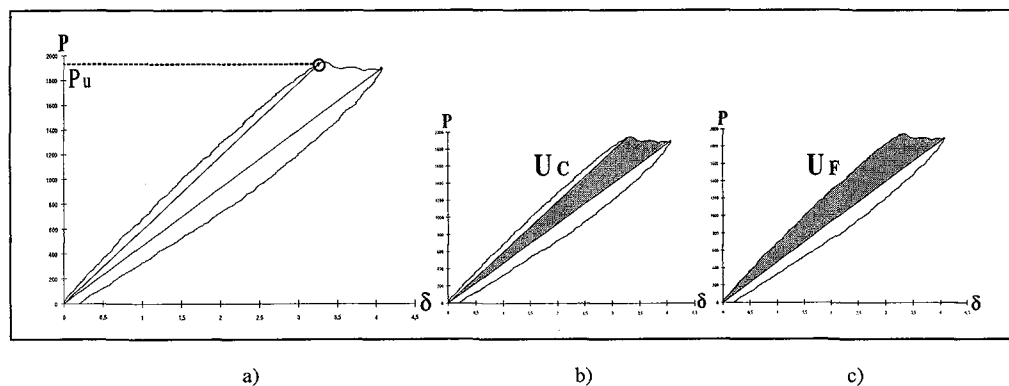


Figure 2 : Typical load-displacement curve of LTENF specimen and calculation of fracture energy.

The critical shearing stress is estimated by :

$$\tau_c = \frac{3}{4} \cdot \frac{P_u}{b \cdot h} \quad (3)$$

where : - P_u is the ultimate load (fig.2-a)
 - b is the thickness of specimen
 - h is the height of the specimen at the end of chevron.

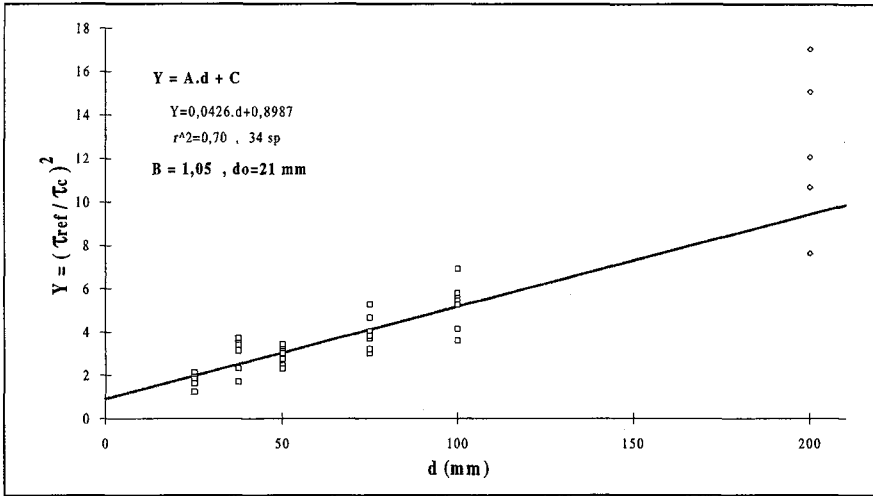


Figure 4 : $(\tau_{ref} / \tau_c)^2$ versus height d (mm) of specimens (Maritime Pine)

Effectively, relation (1) has only been established for homothetic plane specimen (ie identical thickness). However, these experimental stresses are not very far from the best of fit line as can be seen on figure 4.

Using these values in equation (1) gives a prediction of the size effect in Maritime Pine (Fig.5).

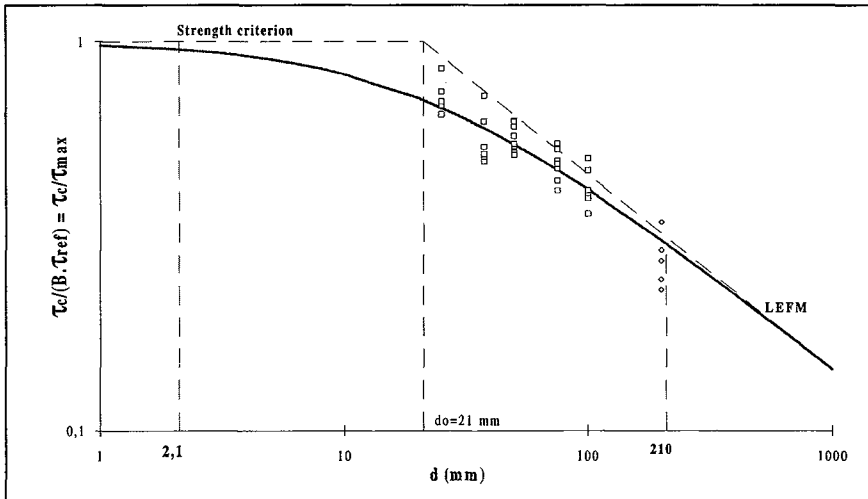


Figure 5 : Size effect on stresses in Maritime Pine : τ_c / τ_{max} versus d (mm) ($\tau_{max} = 6,3$ MPa)

In figure 5, three areas can be distinguished :

- height d of the specimen < 2,1 mm

Theoretical curve becomes asymptotic to an horizontal line. In such structures, there is no size effect, the ultimate load is proportional to a strength criterion. However, these dimensions have not a physical sense for wood material whose heterogeneities dimensions are of this order.

- height $d > 210$ mm

The theoretical curve tends toward a straight line with $-1/2$ slope which is the size effect exhibited by LEFM. For these large structures, the fracture process zone can be neglected because it occupies an infinitesimal volume of the body. Therefore, the entire body can be treated as elastic. The stress and displacement fields surrounding the process zone are the asymptotic elastic fields and consequently the failure load can be given by LEFM. Theoretically, these large structures display brittle failures.

- $2,1 < d < 210$ mm

These dimensions are generally used in wood design, so they have an economical interest. In such structures, the fracture process zone must be taken into account. The size effect is transitional between strength criterion analysis and LEFM. In this range, the ultimate loads can be determined by non-linear fracture mechanics and relation (1).

The abscissa of intersection point d_0 between the straight lines representative of LEFM and strength criterion analysis depends on the geometry of the structure and will be used to determine the relative brittleness of Pine and of Spruce.

The main consequence of the size effect law is the influence of the size of the structures on the stress at failure. But theoretically, this size effect is caused by the evolution of the energy release rates according to the size of the specimens.

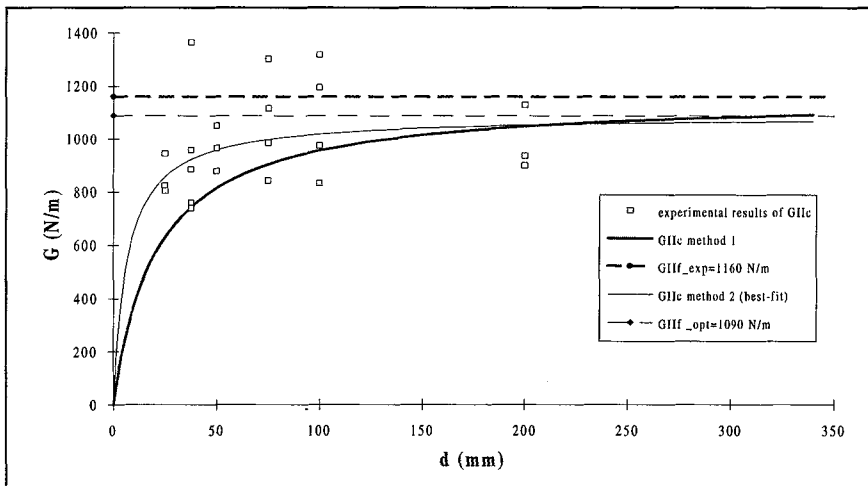


Figure 6 : Size effect on energies in Maritime Pine : G_{IIc} and G_{IIIF} (N/m) versus d (mm)

Specimens whose crack surfaces deviate from the initial crack plane have not been taken into account in the calculations of the energy release rates G_{IIc} . All experimental G_{IIc} and G_{IIIF} values are given in Annex 3. Figure 6 displays experimental values of G_{IIc} and average value of fracture energy G_{IIIF} for specimens of various dimensions. G_{IIc} appears to be a function of the structural size d . The progressive increase of the specimen size produced an increase of the energy release rate up to an asymptotic value equal to the fracture energy G_{IIIF} . Indeed, in an infinitely large specimen, the influence of the process zone on the stress and displacement fields can be neglected. In such structure, the stress and displacement fields are known to be the same for any specimen geometry. In the same way, G_{IIIF} is defined as the limit of G_{IIc} for an infinitely large specimen.

In figure 6, G_{IIc} is assumed to be predicted by relation (2). In this method (method 1), G_{IIc} is computed from $G_{IIIF} = 1160$ N/m (mean of experimental G_{IIIF}) and $d_0=21$ mm computed from relation (1) and the experimental τ_c values.

In a second method (method 2), a best-fit method is applied directly to experimental G_{IIC} values and relation (2). So, optimum values $G_{IIF} = 1090$ N/m and $d_0 = 7$ mm are obtained.

The optimum value of G_{IIF} (1090 N/m) obtained by the method 2 is near to the mean of the experimental G_{IIF} (1160 N/m). It can be noticed that these mean values are near to the fracture energy obtained by Aicher [2] ($G_{IIF}=1098$ N/m) on the LTENF specimens of 50 cm length on a similar wood species. Moreover, the evolution of the energy release rate G_{IIC} obtained by method 2 appears more realistic than by method 1.

However, the difference between the values of d_0 obtained from the stress analysis ($d_0=21$ mm) and from the energy release rates analysis ($d_0=7$ mm) seems to point out that this parameter must be taken cautiously. This last point is discussed in the next section.

4.2 Results and discussion for Norway Spruce.

Parameters B and d_0 can be obtained according to the method used for Pine. Employing $\tau_{ref} = 4$ MPa, best-fit method gives : $A=0,0417$ and $C=1,2093$ with correlation coefficient $r^2=0,67$ (32sp), and so :

$$\tau_{max} = 3,6 \text{ MPa} \quad \text{and} \quad d_0 = 29 \text{ mm}$$

The predicted size effect of Norway Spruce is given in figure 7.

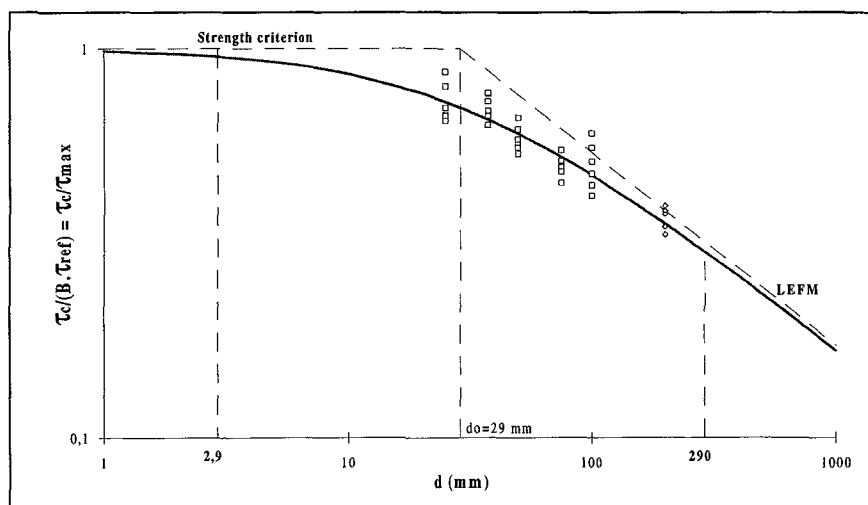


Figure 7 : Size effect on stresses in Norway Spruce : τ_c / τ_{max} versus d (mm) ($\tau_{max} = 3,6$ MPa)

As for Maritime pine, three areas can be distinguished in this figure :

- $d < 2,9$ mm (Strength criterion)
- $2,9 < d < 290$ mm (non-linear fracture mechanics)
- $d > 290$ mm (LEFM)

Experimental values of G_{IIC} are drawn in figure 8 with average value of G_{IIF} . Like for Pine, the experimental fracture energies remain constant on the range of dimensions studied ($G_{IIF}=850$ N/m of Annex 3) and the optimum value of G_{IIF} (800 N/m) obtained by the method 2 is near to this value. However, energy release rate G_{IIC} appears to be a function of the structural size d but it seems that this evolution is less important than for Maritime Pine. Moreover, method 2 (best-fit method) gives a very low value of d_0 (4mm) compared to method 1 in which $d_0=29$ mm is deduced from the stress approach.

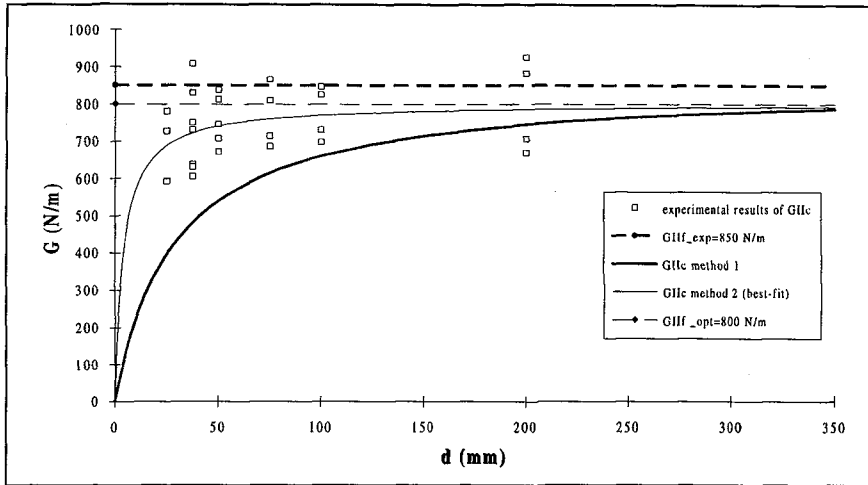


Figure 8 : Size effect on energies in Norway Spruce : G_{IIC} and G_{III} (N/m) versus d (mm)

This difference seems to point out that energy release rates are overestimated. In computations of energy release rates we ignore the roughness of the crack surface. Indeed, it can be assumed that the real crack surface is more important than the projected surface used in the computations and that the roughness vary according to the specimen size. A study of this result by an other approach, the multifractal scaling [4], is in prospect. On the other hand, the parameter d_0 is calculated according to methods which are different by nature. In calculations from the stresses, the value of d_0 is determined from the stresses corresponding to the starting of the crack growth, when, in calculations from the energy, d_0 is calculated after the crack propagation.

At last, a previous work [6] has been performed on the effects of varying dimensions on the same fracture specimen but no significant size effect has been shown. In fact, the dimensions range studied (specimen length between 37 and 75 cm) was not sufficiently large to show a size effect.

5. CONCLUSIONS.

The size effect law displays the characteristic dimension $d_0=21$ mm for Pine and $d_0=29$ mm for Spruce. The difference between these values ($d_0(\text{Pine}) < d_0(\text{Spruce})$) shows that the experimental stresses obtained for Pine are closer to the area of LEFM than the stresses obtained for Spruce. This difference seems to establish that Pine appears more brittle than Spruce. Experimentally it has been noticed that crack speeds were faster in Pine than in Spruce specimens.

The size effect has been explained by the differences between the energy release rates of small and large structures. It can be established that G_{IIC} is a function of the structural size d . It appears that the progressive increase of specimen size produces an increase of the energy release rate up to the asymptotic value G_{III} .

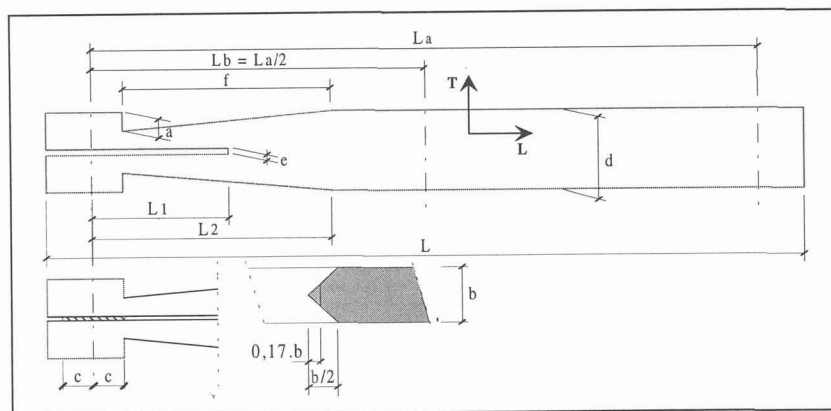
On the other hand, the fracture energy and the shear fracture stresses of Pine are higher than for Spruce. The anatomical characteristics of both species being the same, the difference between specific weights of Pine (560 kg/m^3) and Spruce (390 kg/m^3) and the intracellular fracture mode can explain the difference of these fracture characteristics.

The study performed from the stresses shows that the knowledge of the size effect law allows an estimation of the evolution of fracture stress and also an estimation of the dimensional validity areas respectively attributed to non-linear fracture mechanics and to linear elastic fracture mechanics.

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Annex



Annex 1 : LTENF specimens.

Annex 2 : Dimensions of LTENF specimens (mm).

d	L	La	L1	L2	a	f	e	c	b
25	250	220,5	40	80	7,5	70	2	10	40
37,5	375	331	60	120	11	105	2	15	40
50	500	441	80	160,5	15	140	2	20	40
75	750	662	120	225	22,5	210	2	30	40
100	1000	882	160	241	30	280	2	40	40
200	2000	1764	320	642	60	560	2	80	70

Annex 3 : Results obtained with Maritime Pine and Norway Spruce.

d (mm)	Maritime Pine			Norway Spruce		
	specimen n°	G _{IIIC} (N/m)	G _{IIIF} (N/m)	specimen n°	G _{IIIC} (N/m)	G _{IIIF} (N/m)
25	p25-1	/	/	s25-1	780	1010
//	p25-2	830	1090	s25-2	/	/
//	p25-3	810	1030	s25-3	590	730
//	p25-4	/	/	s25-4	/	/
//	p25-5	950	1240	s25-5	730	890
//	p25-6	/	/	s25-6	/	/
Mean		859	*		700	*
COV (%)		8,81	*		13,82	*
37,5	p37-1	960	1090	s37-1	730	840
//	p37-2	740	930	s37-2	750	870
//	p37-3	/	/	s37-3	640	730
//	p37-4	890	1060	s37-4	910	1060
//	p37-5	1360	1610	s37-5	630	740
//	p37-6	760	900	s37-6	830	960
//	-	-	-	s37-7	610	690
Mean		942	*		728	*
COV (%)		26,84	*		15,50	*
50	p50-1	/	/	s50-1	810	930
//	p50-2	1050	1250	s50-2	670	750
//	p50-3	/	/	s50-3	710	810
//	p50-4	970	1120	s50-4	/	/
//	p50-5	880	1030	s50-5	840	950
//	p50-6	970	1120	s50-6	750	850
//	p50-7	/	/	s50-7	/	/
//	p50-8	1050	1170	-	-	-
Mean		983	*		756	*
COV (%)		7,30	*		9,18	*
75	p75-1	990	1110	s75-1	720	790
//	p75-2	840	960	s75-2	/	/
//	p75-3	1300	1540	s75-3	690	770
//	p75-4	/	/	s75-4	/	/
//	p75-5	1120	1270	s75-5	870	970
//	p75-6	/	/	s75-6	810	870
//	p75-7	/	/	-	-	-
Mean		1063	*		770	*
COV (%)		18,33	*		10,80	*
100	p100-1	840	970	s100-1	730	800
//	p100-2	980	1070	s100-2	850	930
//	p100-3	1200	1390	s100-3	830	920
//	p100-4	/	/	s100-4	/	/
//	p100-5	/	/	s100-5	700	760
//	p100-6	1320	1480	s100-6	/	/
//	p100-7	/	/	-	-	-
Mean		1081	*		776	*
COV (%)		20,04	*		9,26	*
200	p200-1	900	1020	s200-1	710	770
//	p200-2	1130	1290	s200-2	/	/
//	p200-3	840	1060	s200-3	880	940
//	p200-4	/	/	s200-4	670	700
//	p200-5	/	/	s200-5	930	1010
//	-	-	-	s200-6	/	/
Mean		990	1160		796	850
COV (%)		12,42	16,50		15,98	12,37