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ORIGINAL PAPER

Relationship between tree morphology and growth stress in mature European beech stands

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Abstract

- ***Aims*** In European Beech (*Fagus sylvatica* L.) large growth stresses lead to severe log end splitting that devaluate beech timber. Our study aimed at detecting relationships between growth stress and some morphology parameters in trees.
- ***Methods*** Growth stress indicators were recorded for 440 mature trees in nine stands from five European countries, together with morphology parameters.
- ***Results*** Most trees displayed an uneven distribution of growth stress around the trunk. Moreover, growth stress intensity varied largely between individual trees. Geometry of the trunk was a poor predictor of growth stress intensity. Crown asymmetry resulted in a larger stress dissymmetry within trees. Trunk inclination was not correlated to max tension stress, contrary to what is usually found in younger trees. In the case of small inclination, growth stress was close to expected from biomechanics of restoring verticality. Trees exhibiting a larger inclination probably evolved a different mechanical solution: a rather large crown, lower tree slenderness and a sufficient asymmetry in growth stress as to prevent a higher inclination due to growth.
- ***Conclusion*** A large slenderness is the best accurate predictor of a large growth stress, although variations in the ratio height/diameter at breast height explained only 10 % of the variability of growth stress. A large crown surface was the best predictor of a low level of growth stress. A large spacing between trees seems a good solution to lower the risk of growth stress in mature beech.

Keywords Beech · Growth stress · Tree morphology · Forest management · Dendrometric parameter

1 Introduction

European Beech (*Fagus sylvatica* L.) is an important tree species, with a rather large distribution in western and central Europe (Alvarez-Gonzalez et al. 2010). Besides firewood, beech is mainly used for furniture, packaging, plywood and decorative veneer.

Two main defects in standing trees have important consequences on timber value in industry (Knoke et al. 2006): red heart colour (Liu et al. 2005) and high level of growth stresses leading to log end splitting in veneer industry and board warping in sawmills (Saurat and Gueneau 1976; Archer 1986; Kubler 1987).

Three main types of forest management are applied to beech stands in Europe: pure coppice for firewood; high stand and even-aged forest for sawing and veneer industries; and coppice-with-standards: middle forest combining coppice and mature trees for mixed uses. Sometimes, coppice and coppice-with-standards were transformed in high stand forest more than one century ago.

Growth stresses are always present in trees (Archer 1986; Kubler 1987; Fournier et al. 1994a; Thibaut and Gril 2003; Jullien and Gril 1996, 2008).

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Contribution of the co-authors The last author is at the origin of the research project; he has coordinated it. The four authors have participated to run the experiments. The three last authors were much involved in data analyses and in the writing of the final report of the project. The first author has coordinated the data analyses and the writing of the paper.

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Strictly speaking, the term growth stress should describe the whole stress field in a trunk resulting from tree growth. On one side, there are the stresses accumulated as a result of self weight increasing, called "support stresses." On the other side, there are the stresses resulting from the pre-stressing phenomena occurring in each new wood layer at the end of the fibre differentiation process, during cell wall lignification, called "maturation stresses" (Fournier et al. 1991, 1994a). Usually, this stress field is described on a transverse section of the bottom of the trunk, where it is supposed to be the highest.

Support stress field in a continuously growing structure differs from that occuring in classical engineering structures. Let us consider that a beech tree can be assimilated to a vertical column, perfectly cylindrical with dimensions R and H, radius and height of the column (assuming that the weight of branches compensate the loss of stem diameter as we go from bottom to top of the tree). A simple rule of allometry is used to link $h(t)$ and $r(t)$ all along tree growth: $h(r) = H(r/R)^{2/3}$.

If the column is built classically by piling successive elements of radius R and thickness T, until reaching the height H (Fig. 1), there will be a uniform compressive stress field all over the section with the stress magnitude: $\sigma_0=\rho gH$, where ρ is the density of the material (ρ=1,000 kg/m^3 for green beech wood) and g is the gravitational field (g=10 m/s^2). For a 30-m-height column made of green wood, σ_0 will have a uniform low value of 0.3 MPa.

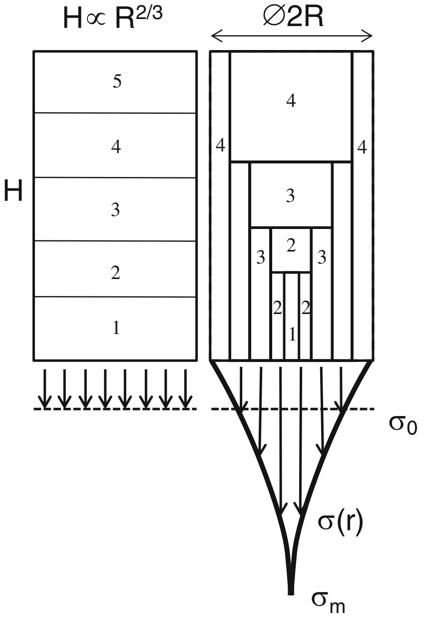


Fig. 1 Compressive support stress distribution at the *bottom* of a column. *Left*: classically built by piling successive discs of radius R; the stress field has a uniform value: $\sigma_0=\rho gH$; *right*: incremental building by successive additions of new layers and terminal elements. A simple rule of allometry is used to link $h(t)$ and $r(t)$ all along tree growth: $h(r) = H(r/R)^{2/3}$. The compressive stress is maximum at the centre of the cylinder and zero on the periphery

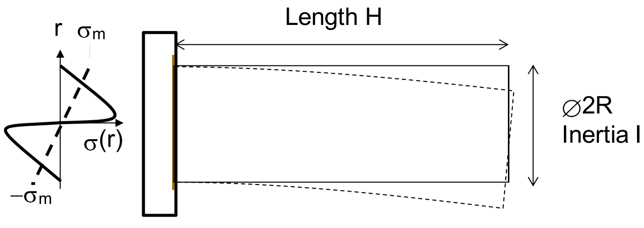
In a growing column, each new wood layer starts to be loaded only after it is formed, so we have an incremental problem. From the moment that it has been produced at the distance r from the pith until the final growth of the tree at radius R, the wood layer situated at r position will support an increase of compressive stress due to each new layer deposition. So the final stress will be highest near the pith (the first growth ring will support all the successive increase of compressive stress due to growth). On the contrary, the last growth ring, being just elaborated, will not support any stress from what happens before its birth.

In the studied case, the solution of the incremental calculation of stress level at each r position in the bottom section is very simple: $\sigma(r)=-4\sigma_0(1-(r/R)^{2/3}))$, where $\sigma_0=\rho gH$. In this case, compressive stress is zero at periphery and four times greater than the uniform case value σ_0 in the section center (Fig. 1). This maximum value is only 1.2 MPa anyway, which means that compressive support stress is very low compared with wood resistance to axial compression (around 50 MPa for green beech wood).

The same remark can be applied to a cantilever beam. For a classic beam anchored at one end after the making of the beam, there is maximum tensile stress $+\sigma_m$ at the top of the beam, at anchorage level, and a maximum compressive stress $-\sigma_m$ at the bottom (Fig. 2).

For a growing anchored beam, the incremental solution is very different, because, again, the last growth ring should have a zero stress all around the beam. The calculus shows that the tensile and compressive stresses are at maximum not far from the pith, with a much higher level than σ_m (Fig. 2).

For a slightly inclined column, the support stress field at bottom is the sum of the compressive stress field calculated for a vertical beam and the flexure stress field obtained by multiplying the values for a horizontally anchored beam by the beam inclination (TI) in percent. For TI=5 %, the



Bending of a cantilever beam under its self weight loading

Fig. 2 Bending support stress distribution for horizontal cantilever beam, subject to gravity. *Graph* at the *left* of the *figure*: *dotted line*, stress distribution for a man-made cylindrical beam at the level of anchorage; the stress field is maximum in compression at the *bottom* and in tension at the *top* of the beam with absolute value σ_m; *continuous line*, stress distribution for a growing stem with the same rule of allometry as in Fig. 1; the stress is zero on the periphery of the beam and reaches a maximum near the centre changing abruptly from compressive (*bottom part*) to tensile (*top part*) compressive stress field is negligible as compared with the flexure one (Fig. 3).

But we know that the growth ring, just produced at distance r from the pith, is in fact pre-stressed during wood maturation in tension with a rather high value ($\sigma_{\mathrm{mat}}=$ 9.64 MPa, for example, in this case). This pre-stressing leads to a global force F_{mat} on this ring which values $2\pi \mathrm{r}(\mathrm{dr})\sigma_{\mathrm{mat}}$, “dr” being the thickness of the incremental new ring produced at r position. In order to balance this force, F_{mat}, there will appear a uniform compressive stress σ_{comp} in the existing core which is radius r, $\sigma_{\mathrm{comp}} = F_{\mathrm{mat}}/(\pi r^2)$.

The calculus of this increment from the first ring to the periphery gives the classical “Kubler model” of growth stress which we call the maturation stress field.

At the end, the growth stress field is the sum of these three distributions (Compression + Flexure + Maturation) (Fig. 3).

For a vertical, straight, equilibrated tree, the growth stress field is practically equal to the maturation stress field. For more or less inclined or unbalanced trees, the stress field is no more symmetrical. Any dissymmetry in maturation stress between two sides of the trunk will also change the stress field a lot (Fournier et al. 1994a), but the stress value at tree periphery is always the maturation stress in the last ring.

So, it should be kept in mind that measurement of maturation strains at tree periphery is just a picture of the present pre-stressing action of the last grown wood in the tree.

Previously inclined young trees in the process of vertical recovery have trunks curved upwards with tension wood on the upper part of the trunk (Alméras et al. 2005). But, this might not be true for old mature trees with big diameters.

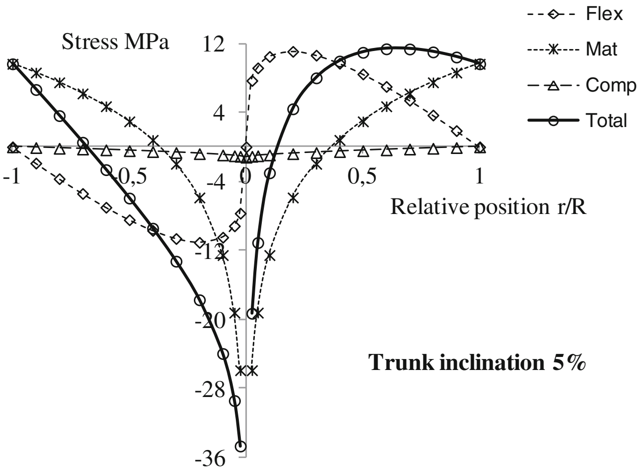


Fig. 3 Growth stress distribution at tree base level for a beech “equivalent tree” of characteristics—diameter 50 cm, height 30 m, trunk inclination 5 %, constant peripheral maturation stress: 9.64 MPa; same rule of allometry as the beam in Fig. 1. *Flex*: flexure support stress calculated by incremental accumulation of gravity forces; *Comp*: compressive support stress calculated in the same manner; *Mat*: maturation stress, calculated using Kübler model; total, Growth stress = Flexure support stress + Compressive support stress + Maturation stress

Because maturation strain is the driving phenomena leading to very important problems in forest industries using beech wood (accidents due to log end splitting, severe loss in sawmills or veneer industry), it is of uttermost importance to try and understand what the main factors are influencing the level of maturation strains in beech tree, in order to improve both forest management and log use.

The objective of this paper is to examine whether growth stress level in beech could be anticipated from observations on standing trees, as trunk inclination and sinuosity, crown size, position and symmetry or tree slenderness. Moreover, using plots from very different silvicultural treatment was a way to confirm on a broad scale the former results on the influence of forest management on growth stress in beech.

2 Materials and methods

2.1 Stand selection

The stands have been selected to emphasize similarities and differences between the growth stress levels of trees under well-defined growing conditions. In total, nine stands in the following five countries were used for the study: Austria, Switzerland, Germany, Denmark and France.

Six stands are classical high stand forest; the following list contains stand designator, site, altitude and average tree age:

- Aa = Purkersdorf, Austria (altitude (alt.) 400 m, about 150 years)
- Ab=30 km of Salzburg (alt. 900 m, about 140 years)
- Dk = Ravnsholte, Denmark (alt.120 m, about 120 years)
- Fa = Moyeuvre, France (alt. 320 m, about 110 years)
- Sa = Baden, Switzerland (alt. 450 m, about 110 years)
- Sb = Le Fahy, Switzerland (alt. 500 m, about 170 years)

Two stands are middle-forest-type management:

- Fb = Ecouves, France (alt. 200 m, about 150 years)
- Fc = Sassey, France (alt. 250 m, about 130 years)

The trees of the German stand were first grown under a middle-forest management system. The treatment of this stand was later on given up and replaced by a high-forest management system.

- G = Schefflenz, Germany (alt. 270 m, about 190 years)

2.2 Tree selection

Out of the nine stands, 50 trees per stand were selected for detailed investigations. Trees were chosen with a mean diameter at breast height of at least 45 cm and without branches up to a height of at least 4.5 m. Trees with obvious damages of the bark, wavy grain or rotten trunks were not selected.

2.3 Tree morphology

The total height of the tree (*H*) and the diameter at breast height (*DBH*) were systematically measured. Slenderness was calculated as the ratio between total height and diameter at breast height (*H*/*DBH*). The trunk inclination at the base of the tree (*TI*) was estimated by measuring the distance between the trunk and a 2-m-long "plumb line."

Eight sticks were placed vertically below eight points describing the crown periphery. The position of the eight sticks was registered by their orientation in relation to the North direction and their distance to the trunk of the referenced tree. The area of the crown projection (crown surface, *CS*) was deduced from these measurements, as well as the geometrical centre of the crown projection which is very similar to the projection of crown centre of gravity (Barbacci et al. 2009). The distance between the centre of the crown projection and the trunk (crown eccentricity, *CE*) gives an indication of crown eccentricity related to tree base. Photos and drawings of most of the trees have been made in two different directions in order to show trunk inclination and curvature, branch orientation or abundance, fork presence and disposition.

Crown shapes were visually separated in two classes: "symmetrical" (S) and "asymmetrical" (AS). For trunk shape, four classes have been defined: straight (more or less inclined) trunk (T1), trunk curved at base (T2), trunk with one big curve (T3) and sinuous trunk with more than one curve (T4) (Table 1).

Table 1 indicates the number of trees (with a complete set of measurement) for each stand in each category of crown and trunk shape. The symmetric crown category is a little less represented than the dissymmetric one (194 compared with 246). The trunk category T1 corresponding to straight trunks is much more represented than the sinuous trunks T2, T3 and T4 (251 compared with 48, 81 and 60).

2.4 Growth stress description

Eight values of growth stress indicator were measured on stem periphery, at breast height. Each indicator is obtained by the single-hole method (Fournier et al. 1994b; Yang et al. 2005). It consists in debarking a circumferential part of the trunk, fixing pins to the wood at two points which are aligned in the longitudinal direction of the trunk at a 45 mm distance, drilling a 20-mm-diameter hole between the two pins and measuring the relative displacement of the pins due to the drilling. This displacement, being referred to as growth stress indicator (GSI) in micrometres is positive each time the maturation stress is a tensile stress (a negative value would indicate compression wood). GSI value is proportional to the local longitudinal maturation strain (ε_M) through formula 1 (Baillères 1994).

$$\varepsilon_M = 12.9 \cdot 10^{-6} \cdot \mathrm{GSI} \tag{1}$$

Maturation stress σ_G can be deduced from maturation strain ε_M by formula 2 where *E* is the longitudinal modulus of elasticity of beech wood in the measurement zone.

$$\sigma_G = \varepsilon_M \cdot E \tag{2}$$

For angiosperms, *E* does not vary so much between tension and normal wood (Alméras et al. 2005). So GSI is a good proxy of growth stress at stem periphery of one tree. Between beech trees, *E* can vary at a maximum by a factor of 2, thus strictly speaking, GSI is a better proxy for maturation strain than for maturation stress.

The GSI was measured at eight points that were evenly distributed along the circumference of each trunk, and the

Table 1 Repartition of trees of each stand in each morphological category of crown and trunk

Stand	Nb	Crown Sym	Crown Assym	Trunk T1	Trunk T2	Trunk T3	Trunk T4
Aa	45	14	31	20	6	7	12
Ab	49	17	32	35	6	7	1
Dk	50	34	16	27	7	6	10
Fa	50	14	36	32	4	11	3
Fb	50	20	30	27	3	12	8
Fc	50	28	22	32	1	13	4
G	46	24	22	22	6	13	5
Sa	50	19	31	19	15	4	12
Sb	50	24	26	37	0	8	5
Total	440	194	246	251	48	81	60

sym symmetric, *asym* asymmetric, *T1* straight, more or less inclined trunk, *T2* trunk curved at base, *T3* trunk with one big curve, *T4* sinuous trunk with more than one curve position of the points was defined in reference to the north direction as it is shown in (Fig. 4).

The minimum (Min), maximum (Max), mean (Mean) value of the eight indicators per tree and the difference between the maximum and the minimum values (Range = Max−Min) were calculated for each tree in order to obtain four growth stress tree parameters for the analysis.

3 Results

3.1 Global results

In Table 2, an overview of all relevant GSI and dendrometric parameters for all trees is given. Variations are rather low for *DBH*, height and tree slenderness but very high for crown area, crown eccentricity and trunk inclination, and high for all GSI tree parameters.

The distribution of all GSI measurements (eight per tree, Online Resource 1) is classical with a clear peak around 45 μm (0.058 % strain value) and a long trail for tension wood zones values. It is comparable to what was found for other hardwood species (Fournier et al. 1994a, b; Alméras et al. 2005).

There was a clear correlation between the direction of leaning of a given tree and the direction of the maximum stress measurement at the circumference (Becker and Beimgraben 2001).

Assuming a mean value of 12 GPa for beech green wood MOE, the mean maturation stress value σ_G over all trees is 9.64 MPa.

The differences between low stressed and highly stressed trees are important (more than a four times ratio between the 5 % higher and lower percentiles) for all the GSI tree parameters (Fig. 5). Forty-five percent of the trees have a range of growth stress higher or equal to 15 MPa and only 15 % lower than 8 MPa (around 50 μm for GSI value).

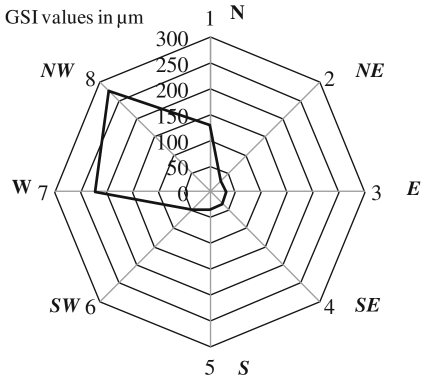


Fig. 4 Distribution of eight GSI values in relation to the cardinal points. Positions *1*, *2*, *3*, *4*, *5*, *6*, *7* and *8*: respectively N, NE, E, SE, S, SW, W and NW. In this example (tree G44), the tension wood zone stretches from the north to the west. GSI values are expressed in micrometres, as measured in situ on the tree by the hole drilling method

3.2 Mean results by stand, trunk and crown type

In Online Resources 2 and 3, the mean values of GSI and morphological parameters measured on standing trees, by stand, trunk and crown type are shown.

Differences are much higher between stands than between trunk or crown types (Table 3). There are significant differences between stands at 0.1 % level for all GSI and dendrometrical parameters.

Trunk type never gives significant difference except for trunk inclination. Crown asymmetry leads to significant differences for all dendrometrical parameters (higher for *DBH*, crown parameters and trunk inclination), and for GSI range (at 1 % level).

3.3 Correlation between parameters

In Table 4, the coefficients of correlation for measured growth stress and tree morphology data for all straight trees (trunk type 1, 251 trees) are indicated. However, the results are fairly identical if these values for all 440 trees (inclined and not inclined) are being correlated.

There are strong significant positive correlations among GSI parameters (except for Min and Range) and also among tree dimension parameters (*DBH*, Height, crown surface). Parameters expressing the disequilibrium of the tree (trunk inclination and crown eccentricity) are not significantly related to tree dimension except for trunk inclination and total height.

All GSI parameters have strong significant correlation at the 0.1 % level with slenderness (always positive) and crown surface (always negative). The influence of *DBH* is very similar to that of crown surface and height to slenderness (same sign, but lower level of significance if any). It should be noted that slenderness of trees explains only 10 % of GSI Max variability (Fig. 6).

Trunk inclination has a strong negative significant correlation only with GSI Min and GSI Mean.

This tendency can also be observed on stand level (Online Resources 4 and 5).

4 Discussion

Ideally, if equilibrated during its whole life, a straight vertical tree is expected to have an equilibrated level of growth stress around the circumference of its trunk. However, for the trees in this study, this was only the case for rather few trees. Most of the trees have a marked asymmetry of GSI corresponding to a response to a mechanical disequilibrium of the tree (mainly tree inclination).

Table 2 General results for the 440 trees

	GSI Min mm	GSI Max µm	GSI Range µm	GSI Mean µm	*DBH* cm	*H* m	*H/DBH* m/m	*CS* m^2	TI %	*CE* M
Mean	24	122	97.1	62	60	33.3	56.3	83.7	4.0	1.8
Median	21	121	95.5	59	58	33.5	56.6	68.7	3.0	1.6
SD	16	49.8	45.0	26	11	4.1	9.1	54.9	4.0	1.1
Min	–	21.0	16.0	12	43	21.0	34.2	14.0	–	0.1
Max	114	295	269	155	113	44.0	83.2	439	23.5	6.6

GSI growth stress indicator measured in micrometres

Min minimum, *Max* maximum, *Range(= Max− Min)* difference between maximum and minimum, *Mean* mean of the eight GSI values measured on each tree, *DBH* diameter at breast height in metres, *H* height in metres, *H/DBH* slenderness, *CS* crown surface in square metres, *TI* trunk inclination in percent, *CE* crown eccentricity in metres

Each time there is a need for a strong mechanical reaction, e.g. aiming at changing trunk geometry in order to restore verticality after some accidental leaning the cambium will produce tension wood (Coutand et al. 2007; Jourez and Avella-Shaw 2003; Alméras et al. 2005, Alméras and Fournier 2009; Wilson and Archer 1979; Wilson and Gartner 1996; Moulia and Fournier 2009). The tension wood is being produced on one side of the trunk, usually on an angular section ranging from 90° to 120°. When tension wood occurrence lasts long enough at the same position of the trunk, a tension wood growth layer of a sufficient dimension will develop with the result that the tensile force is much higher at this position of the trunk circumference. This introduces a bending moment and a change in curvature of the trunk results. The tension wood is positioned on the concave side of the curvature (i.e. on the upper side for an inclined tree restoring its verticality).

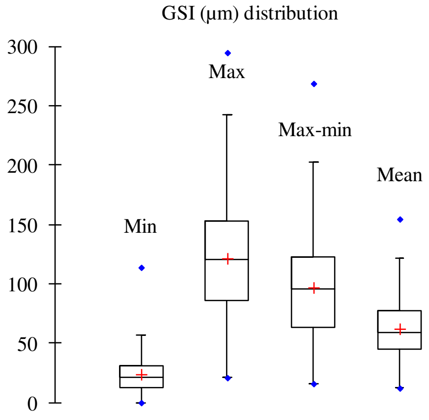


Fig. 5 Distribution of tree growth stress indicator (GSI) parameters for the 440 trees. *Min*: minimum of the eight values for each tree; *Max*: maximum of the eight values for each tree; *Max−Min*: difference between the maximum and the minimum of the eight values for each tree; *Mean*: mean of the eight values for each tree. All the values are expressed in micrometres

4.1 Maturation stresses

Ranking the eight GSI values from the smallest (Min) to the highest (Max) in each tree leads to a typical distribution in two parts (Fig. 7). The four lowest values increase linearly with a rather low slope while the four highest values increase linearly with a slope nearly three times higher. The first part corresponds globally to the sector without any tension wood (opposite wood). The second part corresponds to the peak of growth stress where the presence of tension wood can be dominant.

GSI range is used as a mechanical indicator for restoration of verticality. Under the consideration that the position of GSI Max is very close to the peak of high-tension wood sector, the difference between this GSI Max and the GSI value found on the opposite position (Tension−Opposite GSI) can be calculated. As shown in the relationship between GSI range on one side and Tension−Opposite GSI on the other side (Fig. 8), the two values are very similar and very strongly correlated. The width of the strip close to bisector line results from the fact that the "true" peak and the "true" opposite sides can be at plus or minus 45° from what was chosen. Trees strongly outside of the high correlation strip are those with unusual growth stress profile (Fournier et al. 1994a) for example with two tension peaks.

Globally, GSI Max is a good proxy for tensile side while GSI Min is a valuable proxy for the opposite side.

4.2 Tree morphology and growth stresses

There are no significant differences between curved and straight trees for growth stresses. This is rather opposite to what is usually found for small diameter trees. It could be suspected that, for big trees, highly stressed straight vertical ones are at the end of their verticality restoration phase.

It is commonly believed that trunk inclination should be a factor that positively influences growth stress (Wilson and

Table 3 Variance analysis for stand, trunk and crown type effects (440 trees)

	GSI Min μm	GSI Max μm	GSI Range μm	GSI Mean μm	*DBH* cm	*H* m	*H/DBH* m/m	*CS* m^2	TI %	*CE* m
Stand	^{a}	^{a}	^{a}	^{a}	^{a}	^{a}	^{a}	^{a}	^{a}	^{a}
Trunk type									^{a}	
Crown type			^{b}		^{a}	^{c}	^{b}	^{a}	^{a}	^{a}

GSI growth stress indicator measured in micrometres

Min minimum, *Max* maximum, *Range(* = *Max*− *Min)* difference between maximum and minimum, *Mean* mean of the eight GSI values measured on each tree, *DBH* diameter at breast height in metres, *H* height in metres, *H/DBH* slenderness, *CS* crown surface in square metres, *TI* trunk inclination in percent, *CE* crown eccentricity in metres

[a] Significant at 0.1 % level

[b] Significant at 1 % level

[c] Significant at 5 % level

Gartner 1996), because of tension wood occurrence in order to restore verticality. For the mature beech trees of the present study, there are significant negative correlations between trunk inclination, mean and minimum GSI values (for straight trees as well as for all of them).

For a better assessment of this relationship, the straight trees were classified into classes of different inclination (Online Resource 6). All classes gather roughly 20 trees, except 80 trees for the first class with zero inclination.

GSI for opposite wood (GSI Min) is slowly decreasing when trunk inclination increases up to 2.5 %. Then it suddenly drops and continues to slowly decrease after. The same general pattern is shown for GSI Mean. GSI Max begins to increase until 2.5 % inclination but decreases rather abruptly after that and stays more or less flat until the highest tree leaning, with similar values as vertical trees. GSI range is lower for vertical trees, but it stays more or less stable in inclined trees because the decrease in GSI Min compensates the decrease in GSI Max. Looking at dendrometrical parameters, trees with inclination over 2.5 % have low *H*/*DBH* (below 55) and high crown surface.

Based on the results of big beech trees, it seems that a threshold for trunk inclination around 2.5 % exists. Above this value, all GSI values decrease strongly, except for GSI range that keeps more or less constant at a value approximately 20 % higher than for vertical trees. Straight trees exhibiting high trunk inclination do not use very high maximum GSI values on the tensile side but rather low values on the opposite side, so they keep a sufficient asymmetry in GSI in order to prevent more tree-leaning. They

Table 4 Correlation coefficients between parameters for the straight trees (type 1, 251 trees)

	GSI Min	GSI Max	GSI Range	GSI Mean	*DBH*	*H*	*H/DBH*	*CS*	TI, %	*CE*, m
Min	1	^{a}		^{a}		^{b}	^{a}	^{a}	^{a}	^{b}
Max	0.492	1	^{a}	^{a}	^{a}	^{c}	^{a}	^{a}		
Range	0.145	0.931	1	^{a}	^{a}		^{a}	^{a}		
Mean	0.779	0.854	0.647	1	^{b}	^{a}	^{a}	^{a}	^{a}	^{b}
DBH	−0.110	−0.247	−0.233	−0.177	1	^{a}	^{a}	^{a}		
H	0.197	0.136	0.075	0.208	0.359	1	^{a}		^{a}	
H/DBH	0.246	0.323	0.266	0.313	−0.666	0.437	1	^{a}		^{c}
CS	−0.236	−0.272	−0.210	−0.253	0.656	0.123	−0.498	1		^{c}
TI, %	−0.295	−0.063	0.051	−0.223	−0.087	−0.209	−0.092	0.070	1	^{a}
CE, m	−0.196	−0.073	−0.005	−0.177	0.063	−0.075	−0.140	0.149	0.440	1

GSI growth stress indicator measured in micrometres

Min minimum, *Max* maximum, *Range(* = *Max*− *Min)* difference between maximum and minimum, *Mean* mean of the eight GSI values measured on each tree, *DBH* diameter at breast height in metres, *H* height in metres, *H/DBH* slenderness, *CS* crown surface in square metres, *TI* trunk inclination in percent, *CE* crown eccentricity in metres

[a] Significant at 0.1 % level

[b] Significant at 1 % level

[c] Significant at 5 % level

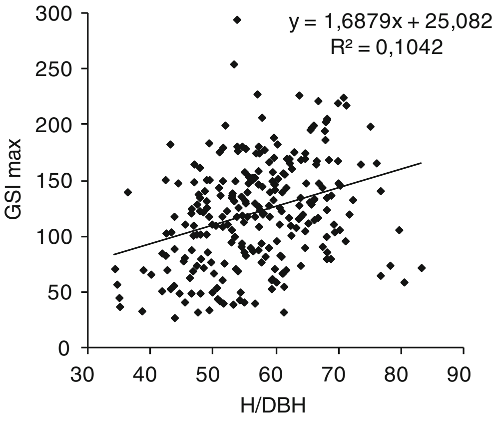


Fig. 6 Relationship between maximum growth stress indicator (GSI Max) and tree slenderness (*H*/*DBH*) for the straight trees (251 trees). GSI values are expressed in micrometres; slenderness is a number without dimension (length divided by length)

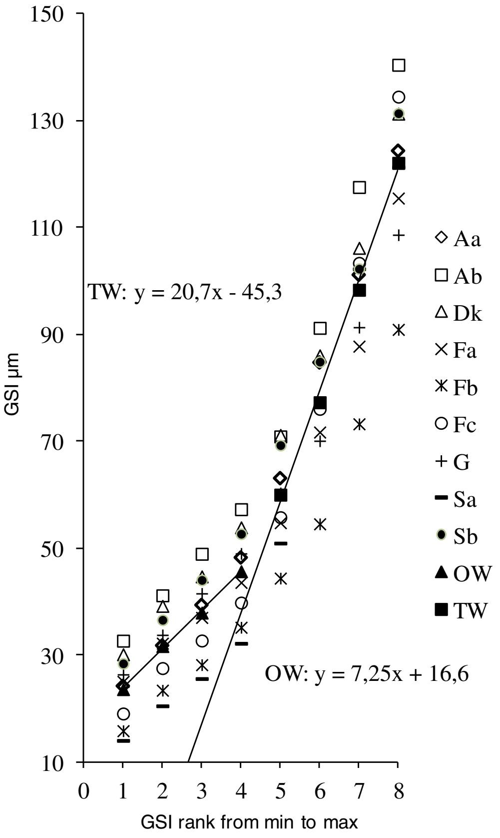


Fig. 7 Mean value in each stand of the eight GSI measurements sorted from the smallest to the highest per tree. *OW*: opposite wood; *TW*: tension wood; the eight GSI values, measured in micrometres, of each tree were first sorted from minimum to maximum in eight columns. Each *point* on the graph is the mean value for a given stand (50 trees usually) in the eight successive columns. The four lower values are quite always in the vicinity of opposite side, while the four higher ones are in the vicinity of the tensile side (the value at rank 8 is GSI Max, and rank 8 is always the centre of tension side). Stands: *Aa*: Purkersdorf, Austria; *Ab*: Salzburg, Austria; *Dk*: Ravnsholte, Denmark; *Fa*: Moyeuvre, France; *Fb*: Ecouves, France; *Fc*: Sassey, France; *G*: Schefflenz, Germany; *Sa*: Baden, Switzerland; *Sb*: Le Fahy, Switzerland

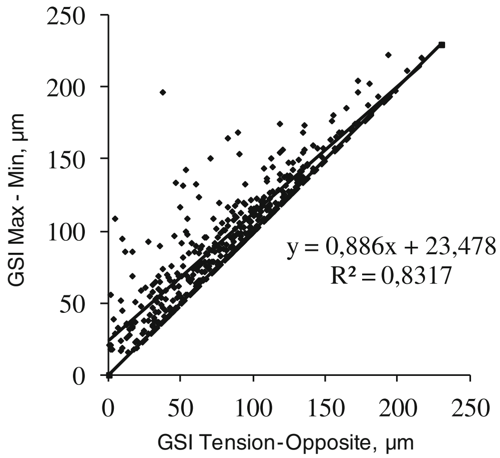


Fig. 8 Relationship between Tension−Opposite Growth Stress Indicator and Max−Min growth stress indicator for 390 trees. For each tree, the cardinal point of the maximum value was considered as the centre of tension side of the trunk. Then, opposite side centre was the cardinal point at 180° from tension side centre. GSI Tension−Opposite is the value obtained by difference between the GSI value of tension centre (GSI Max always) and opposite centre (rather often close to GSI Min), measured in micrometres. Trees strongly outside of the high correlation strip are those with unusual growth stress profile (Fournier et al. 1994a) for example with two tension peaks

have bigger crowns, and it should be looked on more closely whether this crown development contributes to some limitation in the disequilibrium of the tree.

Finally, for old mature trees, morphological traits as inclination, straightness or crown symmetry are not good candidates for the prediction of high levels of growth stresses, but they help to predict a higher asymmetry of these stresses.

4.3 Dendrometrical parameters and growth stress

Slenderness (*H*/*DBH*) and crown surface (*CS*) seem to be the best predictors of high or low growth stresses in old beech trees. A high ratio *H*/*DBH* is clearly a factor that leads to increased growth stresses. This was also shown by previous studies (Polge 1981; Ferrand 1982; Saurat and Gueneau 1976). On the contrary, big crowns (and big diameters *DBH*) are favourable factors that in general lead to a moderate to low growth stress level.

Using classes of values for crown surface and tree slenderness (Online Resource 6) shows that all GSI parameters always decrease when *CS* increases, and the reverse is true for *H*/*DBH*.

But no more than 10 % of GSI variability is explained by *H*/*DBH* and crown dimension. On one hand, there are differences between trees for the basic level of growth stress without reaction wood (see variations in GSI Min). On the other hand, GSI Max controls the value of GSI Mean and GSI Range, where GSI Max is well linked to the occurrence of tension wood produced by the tree. Not every tree in each stand was subjected to such reaction phases, and the level of reaction is therefore not the same. This explains the high variability in growth stress due to individual tree history, apart from general trends linked to forest management.

Part of the negative correlations between growth stress indicators and both *DBH* and crown surface can be linked to the very high negative correlation between slenderness and these parameters in our stands.

4.4 Forest management and growth stress

Stand effect is highly significant both on growth stress indicators and dendrometrical parameters. We can hypothesise that stand effect is strongly linked to forest management, e.g. related to mean number of adult trees per hectare. Upon the assumption of a closed canopy by the gathering of all crowns, the mean crown surface per tree is smaller for a larger number of trees per hectare.

Crown surface has a very high level of correlation with *DBH* (positive) and slenderness (negative) but not with total height; the latter one is being known to depend more on stand age and soil fertility than on forest management. It has also very significant correlation with all growth stress indicators (Table 4).

Looking at the implications to forest management, it can be deduced that low spacing of trees induce small mean crown surface, small mean *DBH* and high slenderness at a given age. Thus, higher spacing of trees seems to be a good solution to lower the level of growth stress in high forest beech stands, which confirms findings by Polge (1981) and Ferrand (1982).

5 Conclusion

Most of the trees have an uneven distribution of growth stress around the trunk, but geometry of the trunk itself was not a good predictor of growth stress level. Trunk inclination is not globally correlated to growth stress indicators. For trunk inclinations higher than 2.5 %, there appears a significant drop of maximum, minimum and mean GSI values, although the difference between tensile and opposite sides is kept more or less constant.

High slenderness ratio (*H*/*DBH*) is the best predictor of high level of growth stress, although variations in *H/DBH* explain only 10 % of mean and maximum growth stress variability. On the contrary, large crown surface is the best predictor of low level of growth stress. These two descriptors are strongly negatively correlated.

Thus, large tree spacing is a good solution to lower the risk of high levels of growth stress in beech, as it appears through the mean values per stand and as was previously stated by various authors.

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