Modifying the elastomechanics of the stem and the crown needle mass distribution to affect the diameter increment distribution: A field experiment on 20-year old *Abies grandis* trees

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ABSTRACT: In the spring of 2000, field experiments were begun on three 20-year old grand fir (*Abies grandis*) to influence the elasto-mechanical behavior of the stem, as well as the distribution of the assimilate crown production. The aim was to analyze, and then describe and model the expected resulting change in stem growth. Three stem sections of one fir were reinforced by rigidly attaching T-shaped steel bars to reduce bending stresses. Preliminary calculations with an elasto-mechanical tree and force model (that had been developed for a different tree, but was adapted by taking the size differences into account) gave first indications for the experimental design in regards to the necessary number of the bars and their dimensions required to guarantee that the stem rigidity would be highly increased. Furthermore, the simulations proposed no increased risk of stem breakage in the non-reinforced stem parts. The stability of the second tree was decreased by hanging sand bags with defined masses on the branches. Directly after loading, a significantly changed swaying behavior could be observed, which should cause correspondingly higher stress in the fibers. As for this load case, the simulated results prognosticate only a negligible increase in stress. The roughly-adapted model used, is seemingly invalid for this tree. In regards to the third tree, the bark at the base of all branches of the eastern half of the crown was removed to prevent any import of assimilates into the stem. The branches were not cut off because the mass distribution and thus, the mechanical behavior, of the tree was to be influenced as little as possible. The experiment will be concluded in the winter of 2003, after a four-year growth period. In addition to detailed stem analyses, the spatial crown structure with its needle and branch mass distribution, as well as the mechanical wood properties of the stem will be measured.

Keywords: *Abies grandis;* elastomechanics; field experiment; stress; strain; diameter increment distribution

Studies on quantitative stem growth, as well as on the temporal change of stem form and of material wood properties have always been of great importance in forestry and forest sciences. Nowadays, the focus has shifted to physiological functions of the tree, because they are the driving force that determine growth and shape development of the stem in order to guarantee both mechanical stability and sufficient water supply to the foliage. Since the nineties, international workshops have dealt especially with tree growth models which combine structure and function (FSTM, functional-structural tree models: 1st Workshop in Helsinki 1996, special issue of Silva Fennica, *31* (3), 1997; 2nd Workshop in Clermont-Ferrand 1998, special issue of Annals of Forest Science, *5 7*(5/6), 2000; 3rd Workshop in Québec 2001).

The mechanical hypothesis, or theory, plays the most important role among the functionally related approaches explaining growth. The idea that cambial activity is controlled by tree movement and thus, by mechanical stress or strain goes back to the 19th century (SCHWENDENER 1874; METZGER 1893). About one century later, biomechanical science experienced a renaissance (NIKLAS 1992) by establishing its own workshops (VINCENT 1994a,b; JERONIMIDIS, VINCENT 1997a,b; SPATZ, SPECK 2000).

Many experiments give evidence to the influence of mechanical stress on plant growth, especially on diameter growth (review: MITCHELL, MYERS 1995; TELEWSKI, PRYN 1998; PRYN et al. 2000). But there is an eminent lack in understanding the functional chain between mechanical trigger and cambial activity, let alone quantitative model approaches to describe stress-induced growth. Assumptions such as the "constant stress theory" (WILSON, ARCHER 1979; MATTHECK 1990, 1993) are contested (NIKLAS 1999; NIKLAS, SPATZ 2000), as even online measurements on stems bent by wind do not show any theory-conform, height-independent strain homogeneity (BLACKBURN 1997).

In spite of the very numerous mechanical experiments on trees, you can scarcely find an exact and complete description of the tree as an acting mechanical system that, in addition, changes its geometric and material properties during their observation. Thus, satisfying analyses of the relationship between mechanical influence and growth reactions are hardly possible, per se. As a consequence, controlled thigmomorphogenetic experiments are demanded where growth and thus, the change of size and mechanical properties is registered and where applied forces are modified during the experiment in order to achieve a constant effectiveness (TELEWSKI 2000). Acting forces need not necessarily be constant, if they are continuously recorded as, e.g., in the experiments of BLACKBURN (1997). But such online strain measurements are expensive as they require a relatively sophisticated equipment and constant monitoring. Further, if the plot is open to the public, the risk of wanton damage must not be underestimated. Therefore, an alternative experimental design, which is not so demanding, is desirable and is presented in this work.

In addition to mechanics, other factors such as the supply of assimilates have an obvious influence on secondary stem growth. Ever since PREßLER (1865) and HARTIG (1870), it has been know that the tree status which is defined by the size and the vigor of the crown determines the absolute secondary growth, as well as the vertical distribution of the diameter increment along the stem. Moreover, highly detailed stem analyses show dependencies between the amount of needle mass of single branches and the increment of the stem directly below the point of branch insertion (FAYLE, MACIVER 1985). Simple models assume a direct proportionality between area increment of the stem at a certain height position and the amount of the needle mass above (MITCHELL 1975; DELEUZE, HOULLIER 1995; DE REFFYE et al. 1997), which is analogous to the pipe-model theory. More complex is process-oriented modeling as, e.g., performed by DELEUZE and HOULLIER (1997), who followed THORNLEY's idea (1972a,b) of relating the cambial activity with the concentration of assimilates, the distance from source (needle mass) to sink (cambium), and the transport resistance.

Again, experiments that shall reveal a quantifiable influence of the assimilate supply on cambial reactions must have a pragmatic design, because long-term measurements simultaneously at many points located on the stem surface cannot be realized on large trees. Experiments with detailed destructive analyses at the close of the observation offer a feasible possibility: on the one hand, the spatial annual increment stem layers can be scanned (GAFFREY 1995) and on the other, the spatial and year-wise differentiated distribution of the needle masses can be measured or estimated with a bias-free method of high accuracy (GAFFREY, SABOROWSKI 1999; SABOROWSKI, GAFFREY 1999; CANCINO et al. 2002). Moreover, age and exposition of needle masses must be taken into account in order to improve the correlation with its photosynthesis production.

Objections against diameter growth ruled by the mere presence of assimilates were brought forward early on (JOST 1891; BÜSGEN, MÜNCH 1927). Assimilates being the precondition for growth but never the reason, it was argued. On the other hand, a relationship between the distribution of needle masses and of wood increment is proven, e.g., by ONAKA's comprehensive pruning and girdling studies (1950a,b) – as well as weather-induced fluctuations of the total yearly photosynthesis production resulting not only in a general reduction of wood increment, but affecting its spatial distribution (DUFF, NOLAN 1953; FAYLE, MACIVER 1985; SLOBODA, GAFFREY 1999).

In respect to the design of field experiments for obtaining a significant and quantifiable nutrient-supply dependent effect, the distribution of the needle mass and its assimilate production should massively be influenced. But simultaneously, the elasto-mechanical behavior of the tree should not be touched, because otherwise, an effect due to changed fiber stresses will be superposed, which will be difficult, if not impossible to segregate.

MATERIAL

In the spring of 2000, field experiments were begun on three dominant 20-year old grand fir (*Abies grandis*), which had an average height of 16 m and a diameter range from 19 to 25 cm, a size that was sufficient for the treatments described below. This tree species shows a very fast growth with an annual diameter increment of about one centimeter, and more. If there is any treatment-induced change in growth, the effect will be recognizable after a few years. Therefore, the close of the experiment is planned after the fourth vegetation period, in the fall or winter of 2003.

The plot is located in the Reinhausen forest (elevation 320 m), about 15 km to the south of Göttingen in Lower Saxony and is characterized by a mean annual temperature of 7–8°C and a mean annual precipitation of 650–770 mm (14–15°C and 325–375 mm in the vegetation period). The soil consists of loess loam with sufficient water supply.

The experiment had to be set up without repetitions due to very restricted financial and staff resources, i.e., these results will not be suitable for statistical generalizations. Nevertheless, this does not automatically imply that generalizations will not be possible at all, especially, if effect-induced, tree-specific observations will be very striking.

Four trees with comparable symmetric crowns were selected. The stem of the first tree (d.b.h.: 24.5 cm, height: 16 m) was mechanically stabilized by T-shaped steel bars, the second (d.b.h.: 22.1 cm, height: 18 m) was destabilized by sand bags attached to the branches, and the crown of the third (d.b.h.: 18.7 cm, height: 16 m) was on one side defoliated by girdling the branches at their base. The fourth tree remained untreated as a reference.

METHODS

Affecting the elastomechanics of the tree

Basics of estimating the required dimensioning of the treatments

In field experiments, before any treatment that affects the elasto-mechanical behavior of trees is carried out, the influence of this measure should first be estimated by simulation, in order to prove that the designed dimensioning is sufficient to effect a significant change in diameter growth and, as well, that the stem will not experience extreme stresses with high risk of breakage during the runtime of the experiment. For this purpose, an elasto-mechanical model of the tree before and after the treatment begin is needed. Unfortunately, required model parameters of these fir trees (geometry of stem and crown, mass distribution of stem and crown, material properties of the stem) are a priori unknown, and will not be available until the trees are cut and analyzed.

A solution, allowing at least rough estimates, was to adjust an elasto-mechanical model that had recently been developed for a 64-year old Douglas fir tree (GAFFREY 2000; GAFFREY, KNIEMEYER 2002). Assuming that the relative geometry (shape) and the mass distribution of the Douglas fir stem is more or less identical to those of the fir trees, the size of the Douglas fir model was downscaled by applying reduction factors (d.b.h.: 0.6 cm, height: 0.7 m). Instead of the real cross-sectional shapes of the Douglas fir stem, size-identical circular ones were chosen for the fir trees. The vertical, non-uniform distribution of both the elasticity modulus and the stem wood density was maintained. In regards to the moisture content, the differentiation between heartwood and sapwood was neglected and instead, a constant value of 100% for both was assumed. Additionally, simulation studies had shown that substituting a uniform, roughly estimated moisture content by a refined, more realistic horizontal moisture content distribution has little influence on the mass distribution of the stem and thus, on stem bending due to mass-induced forces (GAFFREY, KNIEMEYER 2002). YOUNG's modulus (in the Douglas fir model[1]: 11.5 GPa at a density of 0.5 g/cm^3 and at 12% moisture content) was arbitrarily reduced to 10.0 GPa to take into account the softer wood of fir. In this very first approach, the branch masses were neglected because former studies (GAFFREY 2001) showed that the bending moments emanating from the masses of fine and regularly distributed branches (which is the case for these trees) add little to those bending moments that are caused by wind forces.

Measurements of local wind profiles do not exist. Therefore, the same model for calculating wind forces on the previously studied Douglas fir was used (GAFFREY 2000; GAFFREY, KNIEMEYER 2002). The parameters of the applied theoretical potential wind profile $v(z) = v_r \cdot (z/z_r)^c$, where $v(z)$ is the wind speed at height z, are defined as follows: v_r is the reference wind speed (here: 30 m/s) at reference height z_r, which is set to 30 m (a few meters above the canopy of the neighboring stands). The parameter $c = 0.3$ is taken from literature, proposed for this type of vegetation. The wind speed of 30 m/s (108 km/h) is chosen to simulate a very heavy winter storm and the wind direction is north-west which is common in this area. Calculating the sail area was very simplified. Based on a digital photo (without correcting the slight perspective distortion), the outline of the crown was approximated by a triangle (Fig. 1). Its area was vertically differentiated into one-meter sections. To account for the gaps within the crown, the area values were reduced by 50%. Acting wind forces are calculated by $F_w(z) = 0.5 \cdot \rho_a \cdot c_w \cdot A(z) \cdot v^2(z)$, with the air density $\rho_a = 1.2$ kg/m^3. The drag coefficient c_w is estimated to be 0.5 at calm and to decrease linearly to 0.25 minimum at wind speed of 20 m/s (these assumptions are the same as in the Douglas fir model). It is assumed that the section-wise differentiated wind forces act horizontally and mid-section onto the stem. Height-dependent wind speeds, sail areas and wind forces are given in Table 1.

Stiffening the stem with steel T-bars

Reinforced sections of the stem should be alternated with non-modified sections in order to best distinguish the expected effect of reduced diameter increment in the

Fig. 1. Estimating the crown sail area by overlaying a fitted triangle

[1] Data downloadable at: www.uni.gaffrey.de (see Demos/Downloads)

Table 1. Height-dependent wind speed, sail areas and wind forces

Height (m)	$v(z)$ (m/s)	A (m^2)	Wind forces (N)
5.5	18.0	2.6	140
6.5	19.0	2.3	132
7.5	19.8	2.1	126
8.5	20.5	1.8	115
9.5	21.2	1.6	109
10.5	21.9	1.4	102
11.5	22.5	1.1	84
12.5	23.1	0.8	64
13.5	23.6	0.6	51
14.5	24.1	0.4	35
15.5	24.6	0.3	27
16.5	25.1	0.2	19
17.5	25.5	0.1	10
		15.3	**1,014**

reinforced parts from the growth pattern in the untreated sections.

As no previous experience of how many T-bars and of which size should be applied, basic considerations were necessary at the beginning. On the one hand, the stiffened stem parts should be sufficiently rigid, on the other hand, it was unclear whether this minimized flexibility could cause dangerous high stress in the non-stiffened parts and thus, an unintentional stem breakage.

The ideal material for stiffening the stem were T-shaped steel bars (dimensions: 50 × 50 × 6 mm, Fig. 2). They were cut into lengths of 3 m and each was fixed with four pairs of wood screws (8 × 60 mm) at both ends and at distances of one meter from each end. Three sections of the stem were reinforced (0.5 to 3.5 m, 4.7 to 7.7 m, 8.0 to 11.0 m) with different numbers of bars (4, 3 and 2) accounting for the upward decreasing size of the stem (Fig. 3). A regular horizontal positioning could not be realized due to hindering branches. At the position of the screws, little plates of wood were underlaid to prevent that the complete bar lay directly on the stem surface. This free space between stem and bar was to guarantee that despite the fast diameter growth, some stem sections would not be subjected to pressure from the bars and thus, without deformation and disturbed growth pattern even at the close of the experiment.

The only possibility to carry out the work was to use a truck equipped with a lift platform. The principal problem was the impossibility of securely positioning the sup-

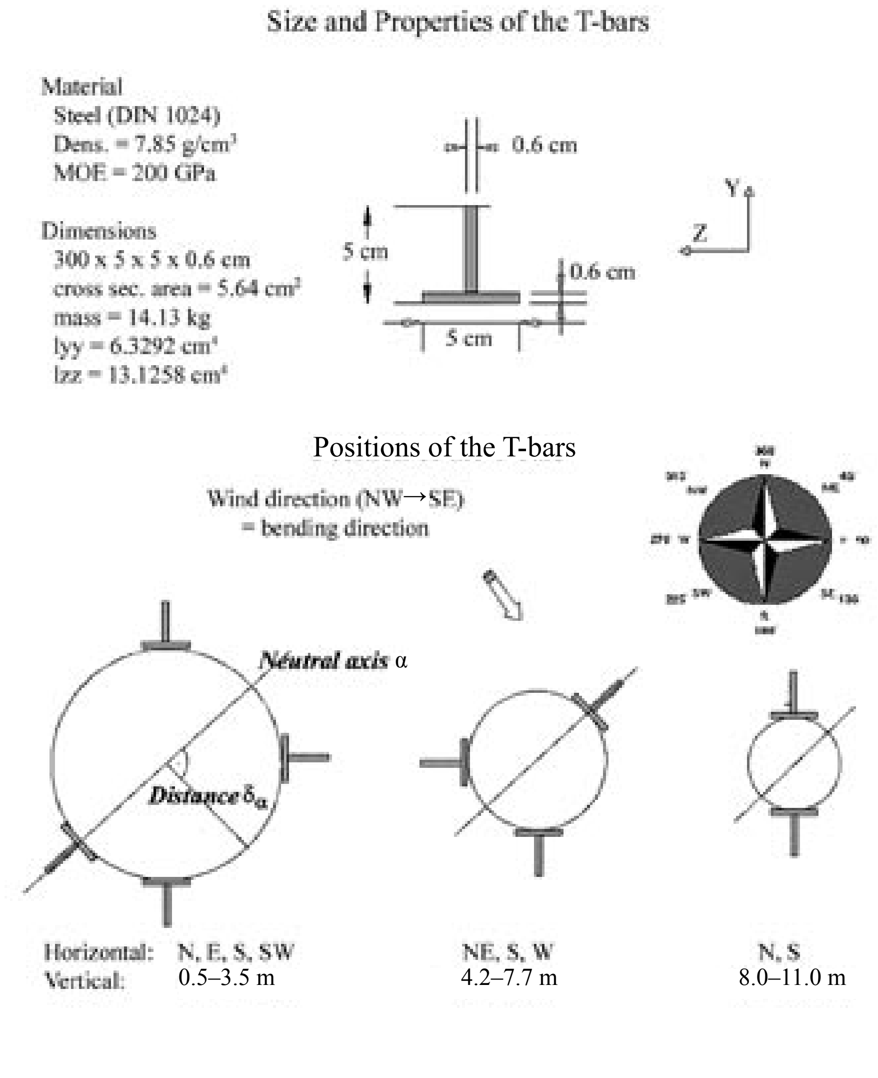


Fig. 2. Size and properties of the T-bars and their position at the stem surface

Fig. 3. Stiffening of the stem within three sections: 0.5–3.5 m (left), 4.7–7.7 m (lower right), 8.0–11.0 m (upper right)

port arms on the soft ground in the stand. Therefore, the truck remained on the packed trail and trees were chosen within the range of the jib. Nonetheless, as the weight of each bar was over 14 kg, the fixing turned out to be very difficult.

To estimate the influence of attached T-bars on the bending of the stem under heavy wind loads and thus, of the experienced fiber stress, the tree model had to be supplemented by a model for stem reinforcement. Unfortunately, the software used for modeling was not suited to handle cross sections of a stem-steel system and to calculate the resulting axial second moments of area, and its flexural stiffness. Therefore, the effect of the T-bars on the elasto-mechanical behavior of the stem was estimated otherwise by applying several simplifications. This is a first rough approach which surely cannot lay claim to being a very accurate model.

A single MOE value for each cross section, the so-called structural YOUNG's modulus E_{st} was calculated for the non-reinforced stem. This is the mean MOE weighted with the axial second moments of area I of the contributing tissues (SPECK et al. 1996), i.e., in this case the stem cross-section was considered to be inhomogeneous with differing material properties for each year ring. As said before, as we do not know the geometry of the inner tree rings, nor the exact shape of the stem cross sections of the fir trees, the cross sections were assumed to be circular. The structural MOE then does not depend on the bending direction and thus, on the orientation of the neutral axis.

The resistance of a cross section of the stem against bending is defined by its flexural stiffness S

$$S = \sum_{i=1}^{n} E_i \cdot I_i$$

which is the sum of $E_i \cdot I_i$ of all n contributing layers (year rings). The maximum stress σ in the peripheral fibers, i.e., of the last, n-th year ring at a distance r (the stem radius) is then

$$\sigma = \frac{E_n \cdot M_{ext} \cdot r}{S}$$

M_{ext} is the sum of all acting external bending moments derived from wind forces and gravitational forces. If calculating the strain ε is of interest, because it is estimated to be a more reliable measure for, e.g., safety factors, we obtain

$$\varepsilon = \frac{M_{ext} \cdot r}{S}$$

In respect to a stem with a circular cross section, the axial second moment of area is simply given by $I_s = \pi/4 \cdot r^4$ and thus, the bending stiffness of the stem is

$$S_S = E_{st} \cdot I_S$$

If steel bars are rigidly fixed at the stem, the flexural stiffness is increased by the number amount of the T-bars and by a value accounting for their distance from the neutral axis.

The material properties of steel are given according to the standard specification (DIN 1024) with MOE = 200 GPa and density = 7.85 g/cm^3. Bars of the dimensions 50 × 50 × 6 mm were used in the experiment. Unfortunately, all calculations were based on bars of 50 × 56 × 6 mm which were to be used in the initial planning. Therefore, we will receive a slight overestimation for cross-sectional area, axial second moment of area and thus, the reinforcement effect.

The axial second moment of area I_T of the T-bar depends on the location of the neutral axis. In formularies, calculations are usually given for the two main axes going through the bar's center of gravity. In a T-shaped bar, these values differ considerably from each other (6.34E-08 m^4 vs. 18.1E-08 m^4 for bars of the size described above). As the bars are fixed at different azimuthal positions at the stem, we have to take into account their rotation of 0°, 45° and 90° with respect to the neutral axis of the bending tree. If, theoretically, a bar would lie inside the stem with the neutral axis going through the bar's center of gravity, the axial second moment would be the minimum, maximum or an intermediate value. Here we simplified and assumed always the lowest value, independent from bar orientations. However, the bars are rigidly attached at the stem's surface at distance δ from the neutral axis. Therefore, STEINER's theorem must be applied to calculate the effective axial second moment of area $I^*_T = I_T + A \cdot \delta^2$, with the cross-sectional area $A = 6.0$ cm^2. We neglected the slight shift of position in the neutral stem axis by adding the T-bars, as well as the distance from the stem surface to the bar's center of gravity. Thus, the vertical distance δ is only defined by the diameter r.

If the given bending direction of the tree is south-east, STEINER's addends of T-bars in north-west and south-east are $A \cdot r^2$, of those in the northern and southern positions $A \cdot r^2/2$, and the north-eastern and south-western bars have no additional term because their center of gravity is intersected by the neutral axis. For the three stem sections with four, three and two attached bars respectively, the contribution of the bars to the total flexural stiffness S_{tot} of the stem-steel system is as follows:

In the first section from 0.5 to 3.5 m height, where the four bars are directed to the north, east, south and south-west

$$S_{tot} = S_S + 4 \cdot S_T + 3/2 \cdot r^2 \,.\, A_T \,.\, E_T$$

in the second section, from 4.7 to 7.7 m with orientation of the three bars to the north-east, south and west

$$S_{tot} = S_S + 3 \cdot S_T + r^2 \,.\, A_T \,.\, E_T$$

and in the last, from 8.0 to 11 m with directions to the north and south

$$S_{tot} = S_S + 2 \cdot S_T + r^2 \,.\, A_T \,.\, E_T$$

The technically easiest way to change the elastic properties of the stem-steel system was to add a constant, averaged flexural stiffness value for each of the three reinforced sections. Of course, this approach ignores that within each section the share of stiffness of the T-bars increases upwards and underestimates at the base and overestimates at the top end.

Table 2. Flexural stiffness of stem and T-bars, and the reinforcement effect

Height (m)	Radius (cm)	S_S (MNm^2)	S_T (MNm^2)	Reinforcement (%)
0.8	11.3	1.29	2.30	179
1.2	11.1	1.21	2.24	184
1.8	10.6	1.00	2.03	203
2.4	10.3	0.90	1.93	214
3.0	10.0	0.79	1.81	228
4.8	9.7	0.71	1.14	161
5.4	9.2	0.57	1.02	180
6.0	9.1	0.55	1.00	183
6.6	8.5	0.42	0.87	210
7.2	8.3	0.37	0.83	222
8.4	7.8	0.30	0.74	248
9.0	7.5	0.25	0.67	273
9.6	7.8	0.30	0.74	249
10.2	7.0	0.18	0.58	315
10.8	6.8	0.17	0.56	329

The data of the flexural stiffness values for stem and bars are shown in Table 2. For the first section, a roughly rounded mean addend was chosen with 2 MNm^2, for the second part 1.5 MNm^2 and 0.75 MNm^2 for the last section.

Lastly, it shall be noted that the bar masses of 14.13 kg each were taken into account by adding proportionate dead weight forces at the four screwing positions of the bars. The unknown masses of the fine and regular branches, which were estimated to be of minor influence, were neglected.

Destabilizing the stem with sand bags

The second tree of comparable, but not exactly the same size, was treated in a way to generally increase its flexure under wind forces and thus, to stimulate the diameter increment. Sand bags with a mass of about 1.5 kg each were hung at the base of each branch with the exception of the top-most branches (Fig. 4). Unfortunately, an exact measurement of number, vertical and azimuthal position of the branches could not be carried out during the installation. Therefore, the added masses and their distribution were guessed and due to the uncertainty, two variants were calculated (Table 3). In both cases, the total masses applied to the whirls were reduced in three steps and instead of simulating bags with a mass of 1.5 kg each and oriented to a multitude of horizontal directions, only the four main cardinal points and masses summed up were chosen. For this tree, too, the branch masses were not taken into account.

Table 3. Attachment of sand bags. Two variants for the distribution of the added masses

Height (m)	A – Added masses		B – Added masses	
	per position (kg)	in total (kg)	per position (kg)	in total (kg)
5.00	2.0	8	4	16
5.75	2.0	8	4	16
6.50	2.0	8	4	16
7.25	2.0	8	4	16
8.00	1.5	6	3	12
8.75	1.5	6	3	12
9.50	1.5	6	3	12
10.25	1.5	6	3	12
11.00	1.0	4	2	8
11.75	1.0	4	2	8
12.50	1.0	4	2	8
13.25	1.0	4	2	8
	18.0	72	36	144

Affecting the supply of assimilates by girdling one half of the crown

The mechanical behavior of the third tree remained unaffected, as only the influence of suppressed assimilate import into the stem was to show its effect. All branches of one half of the symmetrically shaped crown were girdled at their base. Shaded northern branches as well as southern, fully sun-lit branches were treated equally. The branches were not cut off so as not to change the mass distribution and thus, the wind forces received by the crown. This way of treatment should prevent a possible additional, mechanically based growth effect, which would overlay the one of the assimilate concentration.

RESULTS

As the experiment is still running, the presentable results are restrained to descriptions of the visible development of the firs and to calculations of the effects the treatments will have on the elasto-mechanical behavior of the trees.

Stiffening the stem with steel T-bars

According to the models described above, for the tree just before and after the stem reinforcement, the stress at the surface of the bending stem is calculated under wind load (Table 4). Fig. 4 shows very illustratively that fixing with T-bars will enormously reduce the stress in these sections by about 75 to 90%. The stress in the non-reinforced parts remains high but, nevertheless, shows also a distinct decrease of about 7%. Obviously, as the flexing of the steel-supported parts is extremely reduced, this causes a minor deflection of the stem masses, with the consequence of much lower gravity-induced bending moments. As the above-made assumptions for calculating the reinforcement of the T-bars are rather underestimating, it is likely that the real stiffening effect will be significantly greater.

The deduction of the stress estimation was that this treatment does not increase (or, if at all, not considerably) the risk of stem breakage. This is, in a way

Fig. 4. Attachment of sand bags

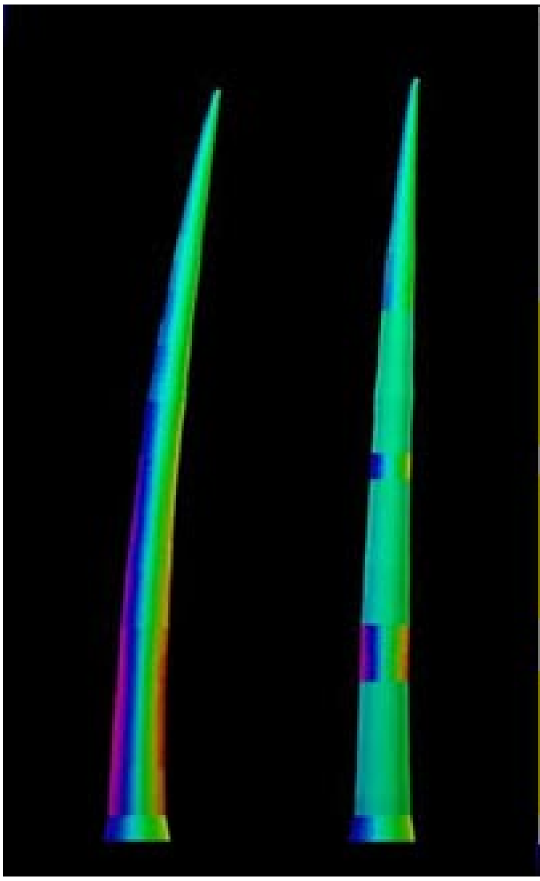
Fig. 5. Tree with branches girdled on one crown half

(even if not scientifically), confirmed by the fact that until now the tree has survived three winters with some severe storms. Secondly, if diameter growth depends on fiber stress, significant effects are to be expected because within the stiffened stem sections, the diameter growth should decrease remarkably. In regards the non-reinforced parts, predicting how growth will be affected is uncertain. On the one hand, there is a (minor) stress reduction, too, which could be followed by a decrease of diameter increment. But on the other hand, the opposite is also thinkable. This would be the case if the partition of photosynthesates that is available for stem wood production does not change its total amount. Then shares which will not be used for diameter growth in the reinforced parts might be available for the other stem sections. An answer will only be obtained through stem analysis, because an external measurement of stem circumference development during the past three years gives no visible indication.

Destabilizing the stem with sand bags

According to the two variants, weights totaling 72 kg and 144 kg are added and the calculated stress increases by about 4% and 9%, maximum (Table 5).

The calculated stress increase might not be enough to produce a significant change in diameter increment – if the estimations are correct. Indeed, they are doubtful because directly after hanging the sand bags on the branches, the tree showed a fairly different, less stable behavior: when the tree was pulled horizontally with a certain force, after the loading the deflection was greater and the swaying lasted much longer. This indicates errors in either the assumptions of the mass distribution or the tree model itself, or both. However, the destabilization of the tree could not have been critical because this tree, too, weathered out the winter storms without any damage.



Height (m)	Without Stiffening (MPa)	With Stiffening (MPa)	Diff.
16.2	6.3	6.3	1.0%
15.6	3.1	3.2	0.0%
15.0	2.9	2.9	-1.0%
14.4	2.8	2.7	-2.0%
13.8	2.7	2.6	-3.0%
13.2	2.7	2.6	-4.0%
12.6	2.3	2.2	-5.0%
12.0	2.9	2.7	-6.0%
11.4	3.5	3.2	-7.0%
10.8	3.5	0.4	-89.0%
10.2	4.2	0.4	-89.0%
9.6	3.7	0.6	-84.0%
9.0	5.4	0.7	-87.0%
8.4	5.6	0.9	-84.0%
7.9	6.3	5.7	-9.0%
7.2	6.8	1.0	-86.0%
6.6	7.4	1.2	-84.0%
6.0	7.0	1.5	-78.0%
5.4	7.8	1.6	-79.0%
4.8	7.6	1.9	-75.0%
4.2	8.8	8.1	-7.0%
3.6	9.5	8.8	-7.0%
3.0	9.5	1.6	-83.0%
2.4	9.5	1.6	-83.0%
1.8	9.5	1.8	-82.0%
1.2	8.8	1.8	-80.0%
0.8	8.8	2.1	-76.0%
0.2	5.5	5.2	-6.0%

Fig. 6. Distribution of stresses at the stem surface for the stem without reinforcement (left) and with reinforcement (right)

Table 4. Estimated maximum tensile stresses under wind load for the stem, with stiffening and without stiffening

Table 5. Estimated maximum tensile stresses under wind load for the stem, with and without attached masses (variant A: 72 kg; variant B: 144 kg)

Height (m)	Without added masses (MPa)	A – Added masses		B – Added masses	
		(MPa)	differences (%)	(MPa)	differences (%)
0.2	5.5	5.7	3	5.8	6
0.8	8.8	9.1	3	9.4	6
1.2	8.8	9.1	3	9.4	6
1.8	9.5	9.8	3	10.1	7
2.4	9.5	9.8	3	10.1	7
3.0	9.5	9.9	3	10.2	7
3.6	9.5	9.8	4	10.2	8
4.2	8.8	9.1	4	9.4	8
4.8	7.6	7.9	4	8.2	8
5.4	7.8	8.2	4	8.5	8
6.0	7.0	7.3	4	7.6	8
6.6	7.4	7.7	4	8.0	8
7.2	6.8	7.1	4	7.4	9
7.9	6.3	6.5	4	6.8	9
8.4	5.6	5.9	4	6.1	8
9.0	5.4	5.6	4	5.8	8
9.6	3.7	3.9	4	4.0	8
10.2	4.2	4.4	4	4.5	7
10.8	3.5	3.6	3	3.7	7
11.4	3.5	3.6	3	3.7	6
12.0	2.9	3.0	2	3.0	5
12.6	2.3	2.3	1	2.3	3
13.2	2.7	2.8	1	2.8	2
13.8	2.7	2.7	0	2.7	0
14.4	2.8	2.8	0	2.8	0
15.0	2.9	2.9	0	2.9	0
15.6	3.1	3.1	0	3.1	0
16.2	6.3	6.3	0	6.3	0

Affecting the supply of assimilates by girdling one half of the crown

The expectation was not fulfilled that by only girdling and thus, maintaining branches the mechanical behavior of the tree will not be changed. Though the branches still lived for a few months, they bent over at their base in the first winter under snow load (Fig. 6). Obviously the great wounds were very quickly infected by fungi causing a rapid decay. The branches did not break off completely, but are still hanging. Nonetheless, wind forces acting on the treated crown half are significantly reduced and the bending moments arising from the branch masses are decreased by the extremely shortened lever arms, as well as by the loss of weight due to dehydration. Therefore, the future analysis of the diameter growth pattern can be complicated in respect to a segregation into assimilate concentration-induced effects and stress-induced ones.

PROSPECTS

The experiment will close in the fall or the winter 2003, with extensive measurements in field and laboratory. Before the trees are cut, pulling tests combined with fiber strain measurements will be performed. In regards to the mechanically treated firs, these tests will be carried out before and after release from the T-bars and the sand bags. Thus, measured data will be available to check or respectively, to improve the elasto-mechanical tree models which are to be built for simulation studies. Further field work will be, among other things, registering branch size and spatial distribution with fresh

Fig. 7. Tree with branches of eastern crown half girdled

masses and growth during the experiment time, as well as measuring stem diameters and growth in length, including the extraction of stem discs with weighing their fresh masses. All year rings of the discs will be scanned in high resolution to reveal the spatial distribution of the secondary growth. Further wood samples will be used to measure the mechanical properties which are needed for the simulation model.

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Vliv změn v elastomechanice kmene a v hmotnosti jehličí na rozložení tloušťkového přírůstu: experiment na dvacetiletých stromech jedle obrovské *Abies grandis*

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ABSTRAKT: Na jaře roku 2000 byl v dvacetiletém porostu jedle obrovské (*Abies grandis*) zahájen experiment zaměřený na ovlivňování elastomechanických vlastností kmenů stromů a distribuce asimilátů. Cílem bylo analyzovat a následně popsat a modelovat očekávané změny v růstu kmene. Tři sekce kmene jedné z experimentálních jedlí byly vyztuženy přiložením ocelových tyčí v T-tvaru tak, aby byl redukován stres ohybem kmene. Předběžnými výpočty byl pomocí elastomechanického modelu (vyvinutého pro různé stromy, ale upraveného zahrnutím rozdílů v rozměrech experimentálního stromu do výpočtu) určen rámec experimentu zejména s ohledem na potřebný počet tyčí a jejich rozměry tak, aby byl sledovaný kmen dostatečně zpevněn a zajištěn proti ohybu. Simulace rovněž ukázala, že se v neposílené části kmene nezvýší riziko zlomu. Stabilita druhého kmene byla snížena pověšením zátěže (sáčky s pískem o definované hmotnosti) na větve. Hned po zavěšení zátěže bylo pozorováno, že se signifikantně změnilo kývání a ohýbání kmene, které způsobovalo odpovídající zvýšený stres v dřevních vláknech. Pro tuto zátěž bylo v simulacích prognózováno pouze nepatrné zvýšení stresu. Rámcově adaptovaný model použitý k simulacím zřejmě pro tento případ nepostačuje. Třetí experimentální strom byl upraven okroužkováním (odstraněním kůry na bázi) všech větví na východní polovině koruny tak, aby byl přerušen tok asimilátů z větví do kmene. Větve nebyly odstraněny, aby se rozložení hmotnosti koruny a následně mechanické chování kmene narušilo co nejméně. Experiment bude ukončen v zimě 2003 po čtyřech růstových sezonách. Kromě detailních kmenových analýz bude proveden rozbor struktury korun včetně distribuce hmotnosti jehličí a větví a budou změřeny mechanické vlastnosti dřeva.

Klíčová slova: *Abies grandis*, jedle obrovská; elastomechanika; stres; namáhání kmene; tloušťkový přírůst

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