Tree Pulling Tests of Large Shade Trees in the Genus Acer

Brian Kane and Peggi Clouston

Abstract. Shade trees provide many benefits but can cause damage if they fail. Despite the potential for costly litigation that sometimes arises when damage occurs, there are no investigations of bending moments and stresses involved in failure of shade trees. Twenty-four shade trees of three species in the genus Acer were pulled to failure at a suburban property in Massachusetts, U.S. The maximum load and distance to failure were used to calculate maximum bending moment; stress at the point of failure was calculated from bending moment and stem cross-sectional dimensions. No trees uprooted, and failures were categorized as either stem at a lateral branch(es) or the attachment of codominant stems. Failures of codominant stems required one-half of the stress of stem failures. Similarly, failures of codominant stems occurred at only 45% of wood strength, whereas stem failures occurred at 79% of wood strength. Prediction of maximum bending moment from tree morphometric data was more reliable than prediction of maximum stress from tree morphometric data. Prediction of maximum bending moment and stress was more reliable for stem failures than codominant failures. Results are compared with similar tests on conifers. Implications of findings are discussed with respect to risk assessment of shade trees.

Key Words. Codominant stems; tree failure; tree pulling; trunk stress.
uprooting, compromised root systems were deemed to be irrelevant during testing. All trees were semimature to mature, but none was in declining health. Trees were chosen primarily according to practical considerations of the test procedure. Great care was needed when breaking large trees so that buildings, roads, aboveground utilities, and existing trees and shrubs on the property were not damaged. The availability of appropriate sites to conduct tests and the practical limitations of breaking large shade trees in situ naturally limited the scope of the study and the sample size. Before testing, tree height and diameter at breast height (dbh) were measured. Crown height and width were measured for 16 and 13 trees, respectively. Table 1 presents morphometric data for each species.

### Field Tests

Tests were conducted in the summers of 2002, 2003, and 2005; site constraints limited the number of days available to conduct tests each year. Trees were pulled to failure using a cable winch skidder (John Deere model 440D [Moline, IL], hydraulic winch capacity 90 kN); the cable was run from the spool of the winch to the skidder anchor was less than 2 m. The angle was necessary to incorporate a codominant stem when one existed in a tree. In such situations, the load was applied perpendicular to the attachment between the codominant stems. The distance from the skidder to the tree, the height of the winch spool and anchor point, and the horizontal distance between the spool and the anchor point were measured to determine the angle between the cable and the ground. The angle was necessary to resolve the applied load into components parallel and normal to the ground.

Tension in the cable was measured by placing a load cell (111 kN capacity, accurate to 111 N; Futek Advanced Sensor Technology, Inc., Irvine, CA) between the anchor point on the skidder and the cable after it was passed around the sheave of the block. Tension in the cable was measured by placing a load cell (111 kN capacity, accurate to 111 N; Futek Advanced Sensor Technology, Inc., Irvine, CA) between the anchor point on the skidder and the cable after it was passed around the sheave of the block. M etrology, Inc., Logic Beach, Inc., La Mesa, CA) that also recorded temperature and relative humidity. Trees were pulled until failure without stopping, which generally occurred within 15 sec of applying the load (the maximum time to failure was 30 sec).

Tests during the summers of 2003 and 2005 were videotaped to quantify the amount of deflection of the crown during tests. Video images were scaled and the distance traveled by the block attached to the trunk was measured on the video image. The horizontal deflection of the crown adds a bending moment as a result of the offset mass of the crown. Crown mass was not measured, which means that the reported stress values underestimate the actual breaking stress. Because the horizontal deflection of the block did not exceed 2 m (6.6 ft) for any tree, the bending moment resulting from the offset mass of the crown was likely negligible relative to the applied load.

After failure, a clean cross-section adjacent to the point of failure was cut with a chainsaw and the dimensions of the cross-section were measured parallel and normal to the direction of the applied load. The distance between the block and the point of failure was also measured. Decay and other defects on the trunk and cross-section were also noted and quantified with a digital image. Failure was categorized by its location either along the trunk (stem failures) or at the attachment between codominant stems (codominant failures).

### Stress Analysis

Compressive stress ($\sigma$) at the point of failure was calculated by adding the bending stress (the first fraction in Equation 1) and axial stress (the second fraction in Equation 1) resulting from the applied load:

$$\sigma = \frac{32P\cos\alpha}{\pi ab^2} + \frac{4P\sin\alpha}{\pi ab}$$  \[1\]

Table 1. Mean (standard deviation) morphometric data for trees of each species.

<table>
<thead>
<tr>
<th>Measure</th>
<th>n</th>
<th>AP</th>
<th>n</th>
<th>AR</th>
<th>n</th>
<th>AS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree height (m)</td>
<td>7</td>
<td>16.8 (3.08)</td>
<td>6</td>
<td>18.5 (3.63)</td>
<td>10</td>
<td>16.7 (7.45)</td>
</tr>
<tr>
<td>dbh (m)</td>
<td>7</td>
<td>0.45 (0.11)</td>
<td>7</td>
<td>0.71 (0.15)</td>
<td>10</td>
<td>0.71 (0.13)</td>
</tr>
<tr>
<td>Slenderness (height/dbh)</td>
<td>7</td>
<td>38.0 (6.30)</td>
<td>6</td>
<td>28.6 (7.88)</td>
<td>10</td>
<td>24.1 (11.4)</td>
</tr>
<tr>
<td>Crown height (m)</td>
<td>7</td>
<td>13.8 (2.26)</td>
<td>3</td>
<td>nm</td>
<td>6</td>
<td>17.2 (2.42)</td>
</tr>
<tr>
<td>Crown width (m)</td>
<td>5</td>
<td>12.6 (4.39)</td>
<td>2</td>
<td>nm</td>
<td>6</td>
<td>15.7 (4.10)</td>
</tr>
</tbody>
</table>

*AP = Norway maple, AR = red maple, AS = sugar maple; dbh = diameter measured at breast height (1.4 m aboveground).

*nm indicates that there were too few samples to include in the analysis.

Figure 1. Diagram of tree-pulling setup. The dashed lines represent the cable with arrowheads indicating the tension. $D_1$ is the distance between the skidder and the tree, $H_B$ is the height of the tree, and $H_N$ is the height of the block. The angle ($\alpha$) between the cable and the ground was calculated as $\tan^{-1}(H_B/D_1)$. The distance between the winch and the skidder anchor was less than 2 m.
A bolt of wood was removed from the stem, adjacent to the point of failure, and four wood samples (one from each compass direction, assuming North was the direction in which the load was applied) were machined from each bolt. Samples (2.54 cm [1.02 in] × 2.54 cm [1.02 in] × 40.64 cm [16.26 in]) were tested in a three-point bending test as described in the American Society of Testing Materials D-143 Standard (ASTM 2000) to determine MOR and Young’s modulus (MOE) of the samples. Samples from trees pulled in 2005 were loaded at twice the speed specified by the D-143 Standard, but this was assumed not to influence results because a 10% increase in MOR requires an increase of 10 times the loading rate (Green et al. 1999). The average MOR and MOE were calculated from the four samples of each tree; in cases in which a specimen failed at a knot or other defect, that value was excluded from the average.

MOE of the trunk at breast height was determined by fitting a straight line to the plot of stress versus strain at breast height for each tree. The slope of the line is MOE. Strain at breast height was linear for every tree, indicating that fibers in the trunk at breast height did not go beyond the elastic range.

To compare stresses measured during tree-pulling tests with stresses endured during wind loading, trunk strains (ε) on a sugar maple (85 cm [33 in] dbh) and a sycamore maple (Acer pseudoplatanus L.) (70 cm [27 in] dbh) were each measured for 2 hr on a windy day using the method described by James et al. (2006).

Both trees were dormant and leafless during data collection. Previously, trunk strain had been measured while each tree was loaded with a winch at the height of the approximate center of pressure. The load was converted to trunk stress using Equation 1 and MOE of the trunk was calculated using Hooke’s Law:

\[ \text{MOE} = \epsilon \sigma = \text{MOE} \times \epsilon \]  

Hooke’s Law only applies when the stress/strain relationship is linear, and because the relationship was linear for all trees pulled to failure, it was safe to assume that the relationship was linear for all measured wind speeds (11.9 m/s [27 mph] or less). The maximum strain measured on the windy day was converted into a stress using Equation 2 and this value was compared with stresses at the point of failure and at breast height for trees pulled to failure.

As a result of the small sample size and similarity among species with respect to tree morphometric data (Table 1), data from all species were pooled for analysis. Data were tested for normality using the Kolmogorov-Smirnov test and were found to be normally distributed. Within each failure type (stem or codominants), a paired t-test was used to compare 1) stress at the point of failure and at breast height; 2) bending moment at the point of failure and at breast height; and 3) stress at the point of failure with MOR of wood samples. MOE of whole trees was not compared with MOE of wood samples because samples were not taken from the height at which the strain gauge was placed on the trunk. A t-test was used to determine whether stress and bending moment at the point of failure, maximum tension in the cable, and MOR of wood samples differed between stem failures and codominant failures.

The relationship between tree morphometric data and both trunk stress and bending moment at the point of failure was investigated for all trees and within each failure type using linear regression analysis. All analyses were conducted in SAS (version 9.1; SAS Institute, Cary, NC).

RESULTS

There were 13 codominant failures and 11 stem failures. No trees with codominant stems below the height of attachment of the block exhibited stem failure, and all of the stem failures occurred at a lateral branch(es) along the main trunk. No trees uprooted during the tests; one additional tree was intentionally uprooted, however, by applying the load sufficiently close to the ground for the sake of comparison with stem and codominant failures.

There were many similarities between stem failures and codominant failures (Table 2). Trees from both categories were
Table 2. Means (standard deviation) for tree morphometric data, stress ($\sigma$), bending moment (M), cable tension (P), and modulus of rupture of wood samples (MOR) for stem and codominant failures.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Stem failures</th>
<th>Codominant failures</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean (SD)</td>
<td>n</td>
</tr>
<tr>
<td>dbh (m)</td>
<td>11</td>
<td>0.57 (0.16)</td>
<td>13</td>
</tr>
<tr>
<td>Tree height (m)</td>
<td>11</td>
<td>18.0 (5.72)</td>
<td>12</td>
</tr>
<tr>
<td>Slenderness (height/dbh)</td>
<td>11</td>
<td>31.8 (7.62)</td>
<td>12</td>
</tr>
<tr>
<td>Crown height (m)</td>
<td>9</td>
<td>14.6 (3.00)</td>
<td>7</td>
</tr>
<tr>
<td>Crown width (m)</td>
<td>7</td>
<td>16.2 (3.87)</td>
<td>6</td>
</tr>
<tr>
<td>Block height/tree height</td>
<td>11</td>
<td>0.53 (0.11)</td>
<td>12</td>
</tr>
<tr>
<td>Stem volume (m$^3$)</td>
<td>11</td>
<td>6.90 (4.79)</td>
<td>12</td>
</tr>
<tr>
<td>P (kN)</td>
<td>11</td>
<td>18.0 (11.6)</td>
<td>13</td>
</tr>
<tr>
<td>$M_y$ (kN*m)</td>
<td>11</td>
<td>110 (103)</td>
<td>13</td>
</tr>
<tr>
<td>$M_y*$ (kN*m)</td>
<td>11</td>
<td>278 (209)</td>
<td>13</td>
</tr>
<tr>
<td>$\sigma_{by}$ (kPa)</td>
<td>11</td>
<td>51.193 (20.521)</td>
<td>13</td>
</tr>
<tr>
<td>$\sigma_{by*}$ (kPa)</td>
<td>11</td>
<td>12.117 (5.816)</td>
<td>13</td>
</tr>
<tr>
<td>MOR (kPa)</td>
<td>10</td>
<td>62.596 (11.287)</td>
<td>11</td>
</tr>
<tr>
<td>Stress at failure (m)</td>
<td>11</td>
<td>3.12 (1.55)</td>
<td>13</td>
</tr>
<tr>
<td>Diameter at failure (m)</td>
<td>11</td>
<td>0.30 (0.15)</td>
<td>13</td>
</tr>
<tr>
<td>Height of failure (m)</td>
<td>11</td>
<td>6.00 (2.15)</td>
<td>12</td>
</tr>
<tr>
<td>Distance to failure (m)</td>
<td>11</td>
<td>0.53 (0.20)</td>
<td>13</td>
</tr>
</tbody>
</table>

*P value refers to the probability that the given variable for both failure types is the same.

The subscript "F" indicates that the measurement pertains to the point of failure; the subscript "BH" indicates that the measurement refers to breast height (1.4 m (4.6 ft) aboveground).

SD = standard deviation; dbh = diameter at breast height.

similar in size: there were no significant differences in tree height, slenderness, crown height and width, stem volume, or cable tension. There was weak evidence that dbh of stem failures was less than codominant failures. MOR of samples was similar for both types of failure.

There were a few statistical differences between stem and codominant failures, however, and these were important (Table 2). They did not appear to be related to the experimental procedure because the ratio of block height to tree height was similar for both types of failure. Although stem and codominant failures experienced similar bending moments at the point of failure, stem failures required more than twice the stress of codominant failures. The distance to failure from the block was 2.4 m (7.9 ft) longer for codominant failures, which made diameter at the point of failure 0.14 m (0.5 ft) greater for codominant failures. Stem failures occurred twice as high in the crown as codominant failures, and all but one stem failure occurred above the base of the crown. In contrast, two-thirds of codominant failures occurred at the base of the crown.

For both failure types, stress at the point of failure was greater than stress at breast height, but the mean difference was more than twice as great for stem failures as codominant failures (Table 3). Stress at the point of failure was less than MOR of wood samples for codominant failures and there was some evidence that this was also true of stem failures, but the difference was not nearly as large. Bending moment at the point of failure was consistently less than at breast height regardless of the location of failure.

Only diameter at breast height and diameter at breast height cubed produced statistically significant predictions of stress at the point of failure for all trees, but neither variable explained more than 17% of the variance of stress at the point of failure (Table 4). For stem failures, there was some evidence that stress at the point of failure was inversely proportional to crown width. Although there were no statistically significant predictors of stress at the point of failure when trees were separated by the type of failure, correlation coefficients were generally greater for stem failures than codominant failures (Table 4).

When grouping all trees, bending moment at the point of failure was directly and linearly proportional to dbh, dbh cubed, and stem volume (Table 5). These relationships were the same when considering only stem failures, but not for codominant failures, which were independent of stem properties. Correlation coefficients were greater for regressions of bending moment at the point of failure, which was less than twice as great for stem failures as codominant failures.

A bending moment at the root flare of 801 kN*m, somewhat greater than the largest bending moment of any other tree, which was 741 kN*m. Both of these trees were sugar maples, approximately 85 cm (33 in) dbh. Stress at breast height was 12,690 kPa for the uprooted tree and 15,400 kPa for the other sugar maple; stress at the point of failure was 24,380 kPa for the other sugar maple.

DISCUSSION

Failure Type

The lack of root failures in the current study does not agree with observations of failed trees after storms (Gibbs and Greg 1990; Duryea et al. 1996; Jim and Liu 1997), but root failures are likely the result of the presence of defects such as decay that compromised root systems before wind loading (Gibbs and Greg 1990; Jim and Liu 1997). For forest trees, stem failure was more likely to be followed by root failure, which is consistent with the results of this study.

Table 3. Mean difference (standard deviation) and P value between paired comparisons for each failure type.

<table>
<thead>
<tr>
<th>Paired comparison</th>
<th>Stem failures</th>
<th>Codominant failures</th>
<th>Difference*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean (SD)</td>
<td>n</td>
</tr>
<tr>
<td>Stress at failure point – stress at breast height* (kPa)</td>
<td>11</td>
<td>39.076 (20.812)</td>
<td>13</td>
</tr>
<tr>
<td>Stress at failure point – MOR* (kPa)</td>
<td>10</td>
<td>-12.674 (19.862)</td>
<td>11</td>
</tr>
<tr>
<td>Bending moment at failure point – bending moment at breast height (kN*m)</td>
<td>11</td>
<td>-169 (119)</td>
<td>13</td>
</tr>
</tbody>
</table>

*Breast height is 1.4 m (4.6 ft) aboveground.

©2008 International Society of Arboriculture
when roots were not decayed or restricted by soil conditions (Fraser 1962; Somerville 1979; Moore 2000; Peltola et al. 2000). More than half of the maples considered hazardous in Helsinki, Finland, were deemed hazardous by virtue of poor branch attachments, including codominant stems (Terho and Hallaksa 2005). A frequency analysis of the International Tree Failure Database (ITFD; data downloaded in March 2007 from http://ftcweb.fs.fed.us/natfdb/) shows that 36% of 1627 trunk failures were codominant failures.

Although it was not part of this investigation to determine the cause of weakness of codominant stems, two explanations offer some insight. One codominant failure was observed not to have bark occluded among the stems, unlike every other codominant failure. The failure stress for this tree was 74% greater than the next largest value for a codominant failure. Although our study supports the idea that the presence of occluded bark reduces tree strength, the influence of bark occlusions with respect to failure stress is not entirely clear in the literature. Smiley (2003) found that bark occlusions reduced the strength of the attachment among codominant branches of small red maples, but others suggested that the most reliable predictor of branch attachment

Table 5. Predictions of bending moment at the point of failure from tree morphometric data and wood strength (MOR) for all trees, stem failures, and codominant failures.

<table>
<thead>
<tr>
<th>Variable^a</th>
<th>All trees</th>
<th>Stem failures</th>
<th>Codominant failures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n Estimate (SE)</td>
<td>P</td>
<td>RMSE/R^2</td>
</tr>
<tr>
<td>MOR (kPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>21</td>
<td>169 (77.8)</td>
<td>0.0430</td>
</tr>
<tr>
<td>β</td>
<td>-0.0004 (0.0011)</td>
<td>0.7013</td>
<td>-0.0007 (0.0033)</td>
</tr>
<tr>
<td>Tree height (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>23</td>
<td>75.6 (70.2)</td>
<td>0.2936</td>
</tr>
<tr>
<td>β</td>
<td>2.65 (3.91)</td>
<td>0.5056</td>
<td>5.29 (5.97)</td>
</tr>
<tr>
<td>dbh (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>24</td>
<td>53.2 (66.6)</td>
<td>0.4334</td>
</tr>
<tr>
<td>β</td>
<td>-1.716 (1233)</td>
<td>0.1786</td>
<td>-9.27 (1274)</td>
</tr>
<tr>
<td>Crown height (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>16</td>
<td>88.2 (97.0)</td>
<td>0.3468</td>
</tr>
<tr>
<td>β</td>
<td>15.76 (204)</td>
<td>0.1113</td>
<td>464 (158)</td>
</tr>
<tr>
<td>Crown width (m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>13</td>
<td>42.0 (90.8)</td>
<td>0.6527</td>
</tr>
<tr>
<td>β</td>
<td>23</td>
<td>12.8 (60.1)</td>
<td>0.0092</td>
</tr>
<tr>
<td>Slenderness</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>23</td>
<td>26.0 (36.9)</td>
<td>0.0794</td>
</tr>
<tr>
<td>β</td>
<td>13.5 (4.63)</td>
<td>0.0085</td>
<td>13.5 (5.60)</td>
</tr>
<tr>
<td>Stem volume (m^3)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B^β</td>
<td>24</td>
<td>56.9 (28.9)</td>
<td>0.0067</td>
</tr>
<tr>
<td>β</td>
<td>217.75 (715)</td>
<td>0.0084</td>
<td>370 (130)</td>
</tr>
</tbody>
</table>

^a dbh = diameter at breast height; slenderness = tree height/dbh; stem volume = tree height^2(dbh)^2.

^β, β = intercept and slope, respectively, of best fit line for the plot of bending moment at the point of failure and the variable listed in the first column.

SE = standard error; RMSE = root mean square error.
strength was the ratio of branch diameter to trunk diameter at the point of attachment, regardless of whether bark occlusions were present (Miller 1959; Gilman 2003). Bark occlusions were present for 21% of 1627 trunk failures recorded in the ITFD (data downloaded in March 2007 from http://ftcweb.fs.fed.us/natfdb/).

A second explanation considered the orientation of wood fibers and the corresponding initial mode of failure of codominant stems. Video footage revealed that failure initiated in a complex combined stress state at the attachment: through combined shear and tension. Both shear and tension perpendicular to the grain were significantly weaker failure modes of wood than tension parallel to the grain (Green et al. 1999) and therefore more likely the governing factors. A crack was then observed to have formed pulling the fibers apart parallel to the long axis of the trunk and effectively splitting it in two. Supporting this speculation, the mean stress at the point of failure of codominant failures was approximately one-half of stress for stem failures—the value expected if the cross-section that resisted bending were one-half of the measured cross-section. In some cases, there was obvious splintering of fibers (typical of tensile parallel-to-grain failure) in the side of the trunk expected to be under compressive stress if the entire trunk were stressed, i.e., proximal to the applied load. Furthermore, for six of the nine codominant failures that occurred within 2.5 m (8.3 ft) of the ground, no trunk strains were recorded, indicating that that side of the trunk was separate and did not contribute to tree strength. The effect of shear and tension perpendicular to the grain should be considered more carefully in future investigations of codominant stems and branch attachments.

Bending moment was found to be statistically similar for stem and codominant failures, but distance to failure was significantly larger for codominant trees. This implies that failure load was lower, but that was not the case, presumably as a result of large variability among trees within each failure type. Such variability can be attributed to size differences among trees. It is also speculated that the difference in calculated stress at the point of failure between stem and codominant failures was partially the result of differences in cross-sectional dimension at the point of failure and the weaker failure mode of codominants. Differences in diameter at failure were the result of the greater height of failure of stem failures.

Although codominant stems constituted a significant structural defect, none appeared to be in imminent danger of failing. As a point of comparison, for a wind speed of 11.9 m/s (27 mph), the maximum stress measured on the sycamore maple was 510 kPa. On the sugar maple, the maximum stress was 2190 kPa when the maximum wind speed was 11.4 m/s (25 mph). Both of these values were much less than the average stress at breast height for all stem and codominant failures (Table 2), but the lack of foliage certainly reduced stress on the trees measured in the wind. It is also important to consider that stress determined by a static pull test will overestimate breaking stress endured during dynamic loading that occurs during windstorms (Oliver and Mayhead 1974).

Although stem failures occurred at greater stress than codominant failures, it was likely that lateral branches still constituted a trunk defect. The orientation of branch and trunk fibers at the point of branch attachment presumably causes the point of weakness. Moore (2000) also observed that stem failures often occurred at lateral branches. Fredericksen et al. (1993) noted that stem failures of winched loblolly pines (Pinus taeda L.) generally occurred closer to ground than trees damaged during a storm, an artifact of the height of the applied load. This was not the case for maples, presumably because defects (i.e., lateral branches and codominant stems) were incorporated below the height of applied load. The mean height of failure for all maples was 26% of tree height, which is almost identical to the mean of 25% from the ITFD (data downloaded in March 2007 from http://ftcweb.fs.fed.us/natfdb/).

The lack of stem failures close to the ground and the substantial smaller stress at breast height compared with the point of failure have important implications for practitioners, who often assess tree risk by investigating trunk decay within a few meters of the ground. For stress at breast height to have been equal to stress at the point of failure, maples would have to have been 82% hollow at breast height. This value is larger than the common guideline that a trunk that is 70% hollow constitutes a substantial defect (Kane et al. 2001). A assessing defects higher in the crown may be more useful in predicting failure.

**Bending Moment and Stress at the Point of Failure**

Elementary mechanical principles explain why stress and bending moment at the point of failure were greater than and less than, respectively, stress and bending moment at breast height. Bending moment is the product of the applied load and the lever arm. At the point of failure, the lever arm was the distance between the block and the point of failure; at breast height, it was the height of the block less 1.4 m (4.6 ft). For the maximum applied load, the greater lever arm at breast height caused the bending moment to be greater. Because stress was inversely proportional to the cube of diameter, and diameter at breast height was larger than at the point of failure, stress was expected to be less. This was true although the bending moment was greater at breast height because the inverse relationship between stress and diameter is nonlinear.

Stress at the point of failure for stem and codominant failures, respectively, was 79% and 45% of the MOR of wood samples. For stem failures, Fons and Pong (1957) reported that failure stress was 70% of published MOR values for ponderosa pine (Pinus ponderosa P&C Lawson), and Peltola et al. (1999) suggested that failure stress was 85% of published MOR values for
failure because such models use wood properties taken from
ultimate bending strength and therefore underestimate the risk of
models that use a static pulling test and Hooke
and Schaper 2003). It appears that shade tree risk assessment
were less than those from trees sampled in Germany (Hannover
(Green et al. 1999), whereas MOR values for Norway maples
width of wood that resists bending underestimates the actual
stress. MOR values for wood samples of red and sugar maples in
this study were similar to those published in the Wood Handbook
(Green et al. 1999), whereas MOR values for Norway maples
were less than those from trees sampled in Germany (Hanover
and Schaper 2003). It appears that shade tree risk assessment
models that use a static pulling test and Hooke’s Law to quantify
stem defects (e.g., Brudil and van Wassenhoven 2001) may overes-
timate bending strength and therefore underestimate the risk of
failure because such models use wood properties taken from
samples, not entire trees.

Prediction of Bending Moment and Stress at the
Point of Failure

The inverse relationship between stress and diameter cubed ex-
plains why diameter at breast height and diameter at breast
height cubed were somewhat reliable predictors of stress at the
point of failure. The relationships between bending moment at
the point of failure and measures of tree size were the result of the
fact that bending moment is directly proportional to the
fourth power of diameter (Lardner and Archer 1994). The fact
that bending moment at the point of failure for codominant fail-
ures was not reliably predicted by measures of tree size for
codominant failures supports the notion that codominant stems
were less than those from trees sampled in Germany (Hanover
et al. 1997; Moore 2000). Part of this disparity can be explained
by the difference in height of failure; the lever arm from which
bending moment was calculated was naturally longer for trees
that failed closer to the ground. The maximum bending moment
at breast height, however, was more than twice the values from
previous studies because maples tested in the current study were
larger. This finding further illustrates the importance of defects
(i.e., lateral branches and codominant stems) as a source of fail-
ure of shade trees.

CONCLUSIONS

This study was the first to test large shade trees by pulling them
to failure, providing much-needed empiric data. In light of po-
tential risk associated with failure of large shade trees and their
importance to urban and suburban communities, results of this
study are integral to developing better techniques to assess the
risk of failure of shade trees. Arborists and urban foresters can
use the results to quantify risk associated with codominant stems
and should cautiously predict tree strength based on MOR of
wood samples.

It was difficult to predict stress and slightly less difficult to
predict bending moment at the point of failure for maples, and
extrapolation from forest trees seems to be inappropriate given
the importance of defects as points of failure on shade trees.
Although species did not appear to influence results, the small
sample size may have affected the results. The differences between stem
failures and codominant failures merit further investigation.
In particular, the importance of included bark as a synergist
with codominant stems to weaken the structure of shade trees
should be examined as well as investigations to determine the
extent to which codominant stems are separate below the point
of attachment.

Acknowledgments. We gratefully ac-
knowledge the following individuals who
contributed to this project: Daniel Pepin,
Mike Gary, Charlie Burnham, Alan Snow,
Dawn Winkler, Ken Collette, Steve Orlik,
Phil Campo, Melanie Joy, Kirk Stephens,
Robert Rizzo, and Alex Schreyer. This project was funded in part by a
John Z. Duling grant from the TREE Fund.

LITERATURE CITED

2004. Modelling the vulnerability of balsam fir forests to wind dam-
individual tree based mechanical model to predict wind damage


transversale de la tige. Aucun arbre ne s’est déraciné; quant aux bris, ils ont été classés entre ceux provenant le long de la tige sur des branches latérales et ceux provenant du point d’attache entre des branches codominantes. Les bris de branches codominantes ont requis la moitié seulement de la valeur en stress par rapport aux bris de tiges elles-mêmes. De manière similaire, les bris de branches codominantes se produisaient à seulement 45% de la capacité de résistance du bois tandis que ceux des tiges se produisaient à 79% de la capacité. La prédiction du moment de flexion maximum à partir de données morphométriques de l’arbre était plus fiable que la prédiction du stress maximal. La prédiction du moment maximum de flexion et de stress a été comparée à des tests similaires sur des conifères forestiers. Ces découvertes ont des implications importantes en regard de l’évaluation du risque posé par un arbre.


Resumen. Los árboles de sombra, si fallan, pueden lastimar y dañar las propiedades. A pesar del potencial por los costosos litigios que algunas veces se elevan cuando el árbol causa daño, no hay estudios que tengan investigado empiricamente la falla de árboles de sombra. Veinticuatro árboles de sombra de tres especies del género Acer fueron probados en una propiedad suburbana en Massachusetts. Se usó la carga máxima y la distancia para calcular el máximo del momento de doblamiento; el estrés en el punto de falla fue calculado del momento de doblamiento y las dimensiones de la sección transversal del tallo. No se categorizaron los árboles dañados bien sea en la rama lateral o en la unión de las ramas codominantes. Las fallas de las ramas codominantes requirieron solamente la mitad del estrés de las fallas de los tallos. Similarmente, las fallas de las ramas codominantes ocurrieron en solamente 45% de resistencia de la madera, mientras que las fallas en los tallos ocurrieron en el 79% de la madera. La predicción del máximo momento de doblamiento de los datos morfométricos del árbol fue más real que la predicción del estrés máximo. La predicción del máximo momento de doblamiento y estrés fue más real para las fallas de los tallos que en las ramas codominantes. Los resultados son comparados a pruebas similares en bosques de coníferas. Los hallazgos tienen importantes implicaciones con respecto a la evaluación del riesgo en los árboles.