Arboriculture & Urban Forestry 2007. 33(4):283–291.

ARBORICULTURE & URBAN FORESTRY
Scientific Journal of the International Society of Arboriculture

Branch Strength of Bradford Pear (*Pyrus calleryana* var. 'Bradford')

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Abstract. Previously planted extensively as a street tree, Bradford pear (*Pyrus calleryana* var. 'Bradford') has fallen out of favor because of its reputation for branch breakage. Despite this reputation, Bradford pear branch strength has never been tested. Prior studies on branch breaking have discounted the influence of branch attachment angle, suggesting that the ratio of branch to trunk diameter, or aspect ratio, is a better predictor of branch attachment strength. Twenty-six Bradford pear branches from 10 trees were broken by pulling them with a winch. To assess the effect of branch cross-sectional dimensions, breaking stress was calculated considering the branch cross-section as either an ellipse or a circle. Breaking stress was normalized by dividing it by the modulus of rupture measured on wood samples from each broken branch. The location of failure, either in the branch itself or at the branch/trunk attachment, did not affect breaking stress. Aspect ratio was a better predictor of branch attachment strength than branch attachment angle. Breaking stress calculated considering the branch cross-section as an ellipse was greater than when stress was calculated assuming the branch cross-section was a circle. Results are compared with previous studies and the importance of measuring branch cross-sectional dimensions is discussed.

Key Words. Branch attachment strength; branch breakage; mechanical stress.

A commonly planted street tree in the past, Bradford pear (*Pyrus calleryana* var. 'Bradford') is now discouraged as an ornamental and street tree because of its tendency to break apart in storms (Dirr 1990). This tendency is usually attributed to narrow branch attachment angles (Hauer et al. 1993; Sisinni et al. 1995). Despite the commonly held belief that Bradford pears are susceptible to storm damage, there is some evidence to the contrary (Gerhold and McElroy 1994; Gerhold 2000). Several studies have investigated branch attachment strength (MacDaniels 1923, 1932; Miller 1959; Lilly and Sydnor 1995; Gilman 2003), but none has considered Bradford pear.

Although MacDaniels (1923) considered the relative size of a lateral branch to its parent stem, "[a]nother very important factor in the strength of crotches . . ." (p. 8), he did not consider it as important as the angle of attachment for predicting strength of the attachment. Since that publication, branch attachment strength has often been attributed to attachment angle in tree risk assessment guides (Robbins 1986; Albers and Hayes 1993; Matheny and Clark 1994). Subsequent reports (MacDaniels 1932; Miller 1959; Lilly and Sydnor 1995; Gilman 2003), however, have not supported MacDaniels' (1923) conclusions. The idea that narrow branch attachments per se cause weakness in Bradford pear branch attachments appears not to be entirely justified. The presence of included bark between branch and trunk has been shown to reduce the strength of the attachment (MacDaniels 1923; Farrell 2003; Smiley 2003), and bark is often included on codominant stems or branch attachments with narrow angles (Shigo 1985). It has alternatively been suggested that branches that grow too large relative to the trunk are not as strongly attached as branches that are relatively small compared with the trunk regardless of whether included bark is present (Miller 1959; Shigo 1985; Farrell 2003; Gilman 2003). Miller (1959) noted that breaking stress was better correlated with the ratio of branch diameter to trunk diameter (an inverse relationship) than with angle of attachment. He also observed that the size of the branch relative to the trunk increased as the angle of attachment decreased.

Previous studies of branch breaking strength (MacDaniels 1923; Miller 1959; Lilly and Sydnor 1995; Smiley et al. 2000; Farrell 2003; Gilman 2003; Dahle et al. 2006) have all assumed the branch cross-section was circular. This assumption would not be appropriate when the branch cross-section is not perfectly circular (Niklas 1992).

The point at which a breaking load has been applied in previous studies has varied. Some researchers applied the breaking load a short distance from the branch attachment point (MacDaniels 1923; Farrell 2003; Gilman 2003). Although others (Miller 1959; Lilly and Sydnor 1995; Smiley et al. 2000) applied the breaking load farther from the branch attachment point, it appears that all of these studies applied the load in such a way as to ensure that either the attachment or a section of the branch just beyond it would fail. Lateral branches of similar size to the parent branch presumably introduce the same problems of weak attachment that arise when a branch grows relatively large compared with the trunk (Shigo 1985). Thus, large lateral branches may serve as a point of weakness along the length of a parent branch.

Although there is evidence to support (Putz et al. 1983; Jim and Liu 1997; Francis 2000) and reject (Hauer et al. 1993; Lilly and Sydnor 1995; Smiley et al. 2000; Farrell 2003) the notion that wood properties affect the likelihood of tree or branch failure, none of the branch breaking studies has measured wood properties other than specific gravity from branches that were broken. Although specific gravity can predict wood strength, modulus of rupture (MOR) is still quite variable (USDA 1999). There is merit in measuring wood properties directly from the broken branches as opposed to using an average test value from the Wood Handbook (USDA 1999).

The objectives of this study were to determine the breaking stress of branches of Bradford pears and to identify tree characteristics, including wood properties, that influence the strength of a branch attachment. A secondary objective was to determine the effect of assuming branch cross-sections as circular when calculating breaking stress of a tree branch.

METHODS AND MATERIALS

Bradford pear trees from two sites (Table 1) were tested: (1) the Virginia Tech campus in Blacksburg, Virginia, U.S., and (2) State Road 340 in Waynesboro, Virginia, U.S. Ten branches from three trees were tested from the site in Blacksburg and 17 branches from seven trees were tested from the site in Waynesboro. One branch from the site in Waynesboro was too large and did not break, so it was not included in the analysis. Branches were selected on ease of testing and measuring. For example, at each site, space limitations restricted where the winch to pull branches could be located. Trees from the site in Blacksburg were spaced ≈4 m (13.2 ft) apart growing on the south side of and ≈5 m (16.5 ft) from a brick building. There were no obvious root obstructions at the site. Trees from the site in Waynesboro were growing ≈10 m (33 ft) apart in a boulevard median ≈5 m (16.5 ft) wide and 500 m (1650 ft) long. Trees from the site in Waynesboro had been watered and pruned as part of routine town maintenance; at the site in Blacksburg, trees had not received the same level of care. Trees at both sites had previously lost branches as a result of storms.

Table 1. Dendrometric information for trees used in the current study.[z]

Site	Tree no.	Branches tested	Tree dbh (cm)	Range of branch diameter (cm)	Range of attachment angle (°)
LR	1	1	26.7	13.6	47
	2	3	32.0	7.1–11.6	26–36
	3	6	35.6	7.8–13.6	15–26
WB	1	2	30.7	14.6–17.8	38–58
	2	2[y]	29.1	16.6	15
	3	3	26.7	10.6–15.4	37–40
	4	3	32.8	11.3–13.7	30–40
	5	2	32.3	9.7–12.1	30–61
	6	3	29.1	9.7–13.7	13–50
	7	2	31.9	9.2–13.3	33–53

[z]Trees came from two sites in Virginia, on the Virginia Tech campus (LR) and in Waynesboro (WB).

[y]Only one branch is included in the analysis because the second branch did not fail.

A 2.5 cm (1 in) wide polyester webbing sling was girth-hitched to each branch to be tested. The sling was attached at least 1 m (3.3 ft) from the trunk and, in almost every case, distal of at least one lateral branch with a minimum diameter of one-third the diameter of the branch being pulled. A steel shackle connected the sling to a load cell (model L2356, 11,340 kg [24,948 lb] capacity; Futek Advanced Sensor Technology, Irvine, CA). The load cell was attached to another shackle that was connected to a 0.95 cm (0.38 in) steel cable. The cable was connected to a winch that applied the load at roughly 0.4 m/s (1.3 fps) (model # XD9000i; Warn Industries, Clackamas, OR). The winch was activated until the branch completely failed, usually within 5 to 10 seconds of applying the load. The load was always applied in a direction perpendicular to the branch bark ridge between the branch being tested and the trunk. The load cell measured tension in the cable two times per second; the data were collected by a data logger (ModuLogger™; Logic Beach, La Mesa, CA) and then downloaded into Microsoft Excel® for processing.

In addition to applied force (i.e., tension in the cable), the following measurements were recorded on each tree and branch: branch diameter at load point, branch diameter at trunk, trunk diameter above branch attachment, branch diameter at failure, inside bark branch depth (parallel to direction of applied load) and width (perpendicular to direction of applied load) at the point of failure, angle of attachment between the branch and the trunk, angle between the cable and the branch at failure, distance from applied load to the trunk, and distance from applied load to failure. Digital images were taken of the cross-sections of failed branches from the Waynesboro site but not the Virginia Tech site. Branch depth and width outside bark were measured from these images. Failure was categorized by type. If more than 50% of the failed fibers originated in the branch, it was categorized as a branch failure; if fewer than 50% of the failed fibers originated in the branch, it was categorized as an attachment failure (Figure 1). If an attachment failed, it was checked for the presence of included bark.

After breaking each branch, a short section immediately adjacent to the point of failure was removed. The cut ends of each section were coated with a wax emulsion sealant (Anchor-seal; U-C coatings Corp., Buffalo, NY) to reduce moisture loss, and the sections were stored in plastic bags at 4°C (39.2°F) for several weeks. Sections were machined into two clear, defect-free samples from the top and bottom of the branch, with respect to the direction of the applied load, as close to the outer growth rings as possible. Sample dimensions were 2.5 cm × 2.5 cm × 35.6 cm (1 in × 1 in × 14.2 in). Samples were tested in the green condition on a universal testing machine (MTS, Eden Prairie, MN) in a three-point bending test similar to the standard test (ASTM 2000), although the dimensions of each sample were smaller than specified by the standard. Modulus of rupture and modulus of elasticity (MOE) were measured during the test. After testing, a small piece was cut from the sample; it was weighed, oven-dried at 104°C (219.2°F) for 4 days, and then its volume was measured to determine its specific gravity (GS) and moisture content. The average value from the two samples was used in data analysis. For one tree, one of the samples failed prematurely at a defect in the sample; only the remaining sample was used in the analysis of wood properties.

Bending stress (σ_B), axial stress (σ_A), shear stress (τ), bending stress in tension (σ_T), bending stress in compression (σ_C), and "stress ratio" (SR) were calculated from the measurements. Bending stress was calculated at the point of failure in three ways. First, the branch cross-section was considered as an ellipse of inside bark depth (y) and width (x):

$$\sigma_{BE(IB)} = 32Pl\cos\theta/(\pi xy^2) \quad (1)$$

where the subscript E indicates ellipse, the subscript (IB) indicates measurements were taken inside bark, P is the applied load, l is the distance from the loading point to the failure point, and θ is the angle between the cable and the branch. Second, equation 1 was repeated using branch outside bark depth and width measurements (this was only possible for trees from Waynesboro because branch outside bark depth and width were not measured on the branches from trees at Virginia Tech). The subscript (IB) from equation 1 changed to (OB) for this calculation. The third bending stress calculation considered the branch cross-section as a circle of outside bark diameter (d):

$$\sigma_{BC} = 32Pl\cos\theta/(\pi d^3) \quad (2)$$

where the subscript C indicates circle. Shear stress was calculated at the point of failure considering the branch cross-section as an ellipse of inside bark depth (y) and width (x):

$$\tau = 16P\cos\theta/(3\pi xy) \quad (3)$$

Axial stress was calculated in two ways. First, the branch cross-section was considered as an ellipse (indicated by the subscript E) of inside bark depth (y) and width (x):

$$\sigma_{AE} = 4P\sin\theta/(\pi xy) \quad (4)$$

Second, the branch cross-section was considered a circle (indicated by the subscript C) of outside bark diameter (d):

$$\sigma_{AC} = 4P\sin\theta/(\pi d^2) \quad (5)$$

Bending stress is tensile on the top of the branch (side opposite of the direction of the applied load) and compressive on the bottom of the branch (side in the direction of the applied load). By convention, tensile and compressive stresses are taken to be positive and negative, respectively. To calculate the total tensile (T) and compressive (C) stress in the branch:

$$\sigma_{Ti} \quad \text{or} \quad \sigma_{Ci} = \sigma_{Ai} + \sigma_{Bi} \quad (6)$$

where the subscript i indicates that the calculations were made considering the branch as both an elliptical and a circular cross-section. If the angle between the winch cable and the branch exceeded 90°, σ_{Ai} was tensile (and positive). For such branches, the magnitude of tensile stress exceeds that of compressive stress by equation 6. If the angle between the winch cable and the branch was less than 90°, σ_{Ai} was compressive (and negative). For these branches, the magnitude of compressive stress exceeds that of tensile stress by equation 6. To normalize branch breaking stress by the inherent wood strength, a stress ratio (SR_i) was calculated by dividing the

Figure 1. Failures were categorized as either branch (left) in which more than 50% of the failed fibers originated in the branch or attachment (right) in which fewer than 50% of the failed fibers originated in the branch.

larger (based on absolute magnitude) of σ_{Ti} or σ_{Ci} by MOR. Thus, three stress ratios were calculated, one based on the elliptical cross-section dimensions measured inside bark [$SR_{E(IB)}$], one based on the elliptical cross-section dimensions measured outside bark [$SR_{E(OB)}$], and one based on the circular cross-section calculations (SR_C).

Branch taper was calculated as described by Leiser and Kemper (1973):

$$\text{Taper} = -(R - r)/(RL) \quad (7)$$

where R is the radius of the branch at the point of failure, r is the radius of the branch at the loading point, and L is the distance between the loading point and the failure point. Aspect ratio was calculated as described by Eisner et al. (2002):

$$\text{aspect ratio} = d/D \quad (8)$$

where d is the diameter of the branch measured at the point of failure and D is the diameter of the trunk, or, if the branch failed at a lateral branch, the diameter of the lateral branch measured above the point of attachment of the branch to which the load was applied.

Linear regression was used to investigate the effect of attachment angle, aspect ratio, and taper on $\sigma_{BE(IB)}$, σ_{BC}, $SR_{E(IB)}$, and SR_C. Linear regression was also used to investigate the effect of GS, MOE, and MOR on $\sigma_{BE(IB)}$ and σ_{BC}. Analysis of variance (ANOVA) was used to investigate whether σ_{BE}, σ_{BC}, $SR_{E(IB)}$, SR_C, attachment angle, aspect ratio, taper, GS, MOE, and MOR differed by the type of failure (branch or attachment). ANOVA was also used to investigate the difference between $\sigma_{BE(IB)}$, $\sigma_{BE(OB)}$, and σ_{BC} and between $SR_{E(IB)}$, $SR_{E(OB)}$, and SR_C. Means were separated using Tukey's highly significant difference test. A preliminary analysis indicated that there was no effect resulting from individual trees, so tree was not included as an independent variable. All analyses were conducted using SAS version 9.3 (SAS Institute, Cary, NC).

To compare results for Bradford pear, values from previous studies were converted to SI units where necessary. Because MacDaniels (1923) did not calculate stress, his data were used to calculate stress values instead of the normalized force measurements that he presented.

RESULTS

Of the failures that occurred at an attachment, only one showed any included bark, and it did not constitute a substantial portion (less than 5%) of the exposed surface area of the broken attachment. Its values for $SR_{E(IB)}$ and $\sigma_{BE(IB)}$ were slightly higher than, but within one standard deviation of, the mean $SR_{E(IB)}$ and $\sigma_{BE(IB)}$ for all attachment failures.

Both $\sigma_{BE(IB)}$ and $SR_{E(IB)}$ were inversely proportional to aspect ratio, although the relationships were somewhat weak (Figures 2 and 3). Similar and slightly more robust relationships emerged for plots of σ_{BC} and SR_C against aspect ratio (Figures 2 and 3). Neither the angle of attachment nor branch taper influenced $\sigma_{BE(IB)}$, σ_{BC}, $SR_{E(IB)}$, or SR_C (*P* values all greater than 0.20). None of the measured wood properties (GS, MOR, MOE) influenced $\sigma_{BE(IB)}$ or σ_{BC} (*P* values all greater than 0.10).

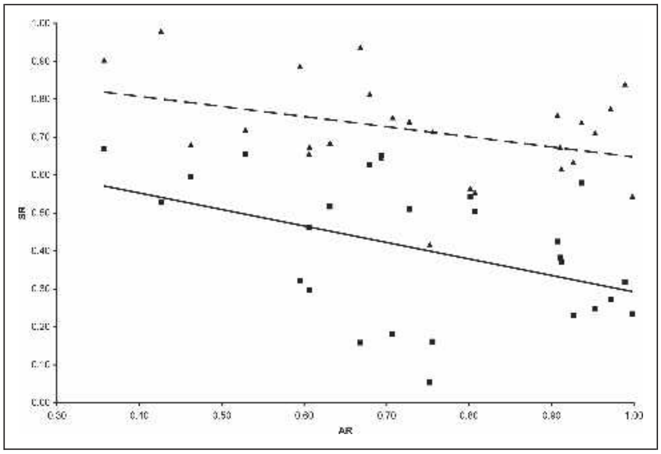

Figure 2. Scatterplot and best fit line between stress ratio (SR) and aspect ratio (AR). Stress ratio was calculated using inside bark branch depth and width ($SR_{E(IB)}$ (▲)) and outside bark branch diameter (SR_C (■)). Both fits are linear; $SR_{E(IB)} = -0.2829 * AR + 0.9298$; $R^2 = 0.16$, $p = 0.04$); $SR_C = -0.4347 * AR + 0.7266$; $R^2 = 0.20$, $p = 0.0227$).

Mean values for $\sigma_{BE(IB)}$, σ_{BC}, $SR_{E(IB)}$, SR_C, aspect ratio, GS, MOR, MOE, angle of attachment, and taper were not different between branch and attachment failures (Table 2). Reanalyzing MacDaniels' (1923) data produced a weak but significant positive relationship between breaking stress and angle of attachment (Figure 4). There was no relationship

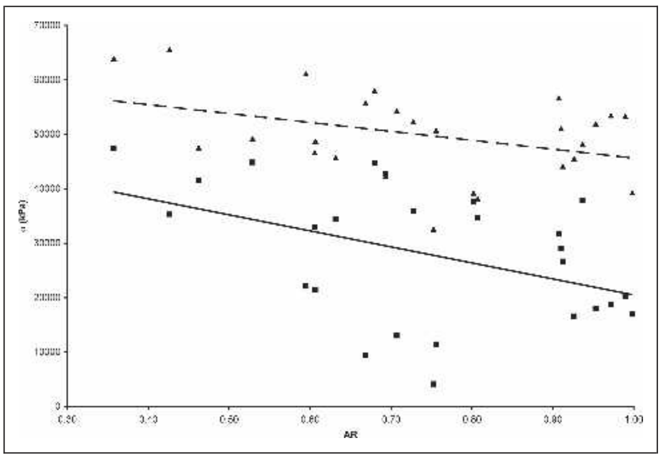

Figure 3. Scatterplot and best fit line between stress (σ) and aspect ratio (AR). Stress was calculated using inside bark branch depth and width ($\sigma_{BE(IB)}$ (▲)) and outside bark branch diameter (σ_{BC} (■)). Both relationships are linear; $\sigma_{BE(IB)} = -17541 * AR + 63{,}122$ ($R^2 = 0.16$, $P = 0.04$); $\sigma_{BC} = -29430 * AR + 49{,}927$ ($R^2 = 0.19$, $P = 0.0242$).

Table 2. Means (standard errors in parentheses) for dependent variables tested by failure type (branch or attachment).[z]

Failure type	Aspect ratio	$\sigma_{BE(IB)}$ (kPa)	σ_{BC} (kPa)	$SR_{E(IB)}$	SR_C	Angle (°)	Taper	MOE (MPa)	MOR (kPa)	GS
Branch	0.72	50,671	25,703	0.73	0.37	37	−0.11	4,792	70,116	0.67
(n = 12)	(0.054) a	(2339) a	(3,552) a	(0.038) a	(0.052) a	(3.75) a	(0.015) a	(217) a	(1147) a	(0.015) a
Attachment	0.76	49,600	30,093	0.71	0.43	33	−0.15	7,047	69,804	0.69
(n = 14)	(0.050) a	(2166) a	(3,289) a	(0.051) a	(0.048) a	(3.47) a	(0.014) a	(201) a	(1062) a	(0.014) a

[z]Abbreviations are described in the text. Means read down a column followed by the same letter are not significantly different at P = 0.05 (Tukey highly significant difference).

between breaking stress and aspect ratio using the reanalyzed data.

Whether calculated considering the branch cross-section as elliptical (equation 1) or circular (equation 2), branch stress was considerably smaller than MOR from the wood samples (Table 3). Using branch outside bark measurements of branch diameter and branch depth and width significantly reduced stress compared with branch stress calculated using inside bark depth and width measurements (Table 3). Similarly, the greatest stress ratio was calculated using branch inside bark depth and width dimensions (Table 3). The average absolute difference between depth and width of branches was 7%. Shear and axial stresses constituted 0.7% and 1.1% of $\sigma_{BE(IB)}$.

DISCUSSION

Table 4 summarizes results from previous work on branch breaking for six species (MacDaniels 1923; Miller 1959; Lilly and Sydnor 1995; Farrell 2003; Gilman 2003).

Previous studies have found that stress is inversely proportional to aspect ratio (Miller 1959; Farrell 2003; Gilman 2003), which is a better predictor of stress than branch angle. It is likely that aspect ratio was a less reliable predictor of stress in Bradford pears than in previous studies because of the smaller sample size. A contributing factor may be that aspect ratio was based on branch diameter as was the stress calculation in previous studies (Miller 1959; Farrell 2003; Gilman 2003), so there is a common measurement in both calculations. The higher correlation coefficient for σ_{BC} than $\sigma_{BE(IB)}$ supports this notion, because the $\sigma_{BE(IB)}$ calculation was not based on branch diameter.

Contrary to the current study, previous studies found that breaking stress of branches was greater than breaking stress of attachments (Miller 1959; Lilly and Sydnor 1995; Farrell 2003; Gilman 2003). One reason branch and attachment failure stresses of Bradford pears did not differ was that half of the branch failures occurred at large laterals. In four of the branch failures, the load acted parallel to the branch bark ridge between the branch and the lateral. In those cases, the attachment that failed was not loaded in the same manner as branches that failed at the attachment to the trunk. Presumably, the fiber orientations that cause branch to trunk attachments to be weaker when aspect ratios are large (Farrell 2003; Gilman 2003) also exist when the aspect ratio between two branches is large. Farrell (2003) found that attachments between lateral branches were significantly weaker than branch–trunk attachments for red maple (*Acer rubrum*), callery pear, and sawtooth oak (*Quercus acutissima*).

Including lateral branches along the length of Bradford pear branches that were broken may have produced unreal-

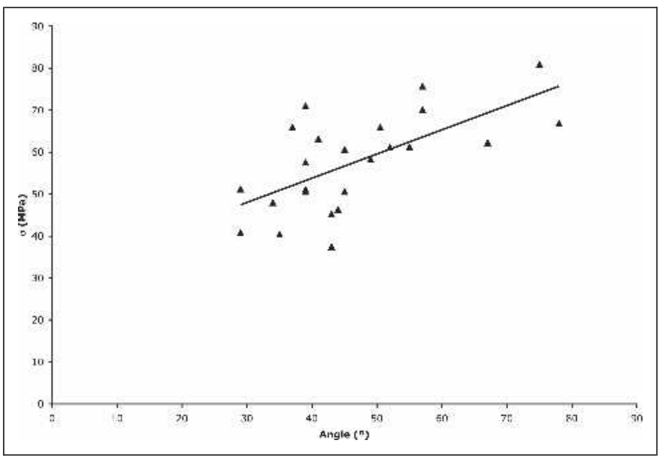

Figure 4. Scatterplot for stress (σ) and angle of attachment from a reanalysis of MacDaniels' (1923) data. The fit is linear and the equation for the line is, $\sigma = 0.5774 * \text{angle} + 30.645$ (R^2 = 0.42, P = 0.006).

Table 3. Means (standard errors in parentheses) for stress (σ) and stress ratio (σ/MOR).[z]

Calculation	n	σ (kPa)	Stress ratio
MOR	26	69948 (764) a	N/A
Ellipse (IB)	26	50094 (1561) b	0.72 (0.036) a
Ellipse (OB)	16	38603 (1525) c	0.55 (0.024) b
Circle (OB)	26	28067 (2405) d	0.40 (0.035) c

[z]The modulus of rupture (MOR) comes from wood sample tests. Stress calculations were made considering the branch cross-section as either an ellipse or a circle (see equations 1 and 2, respectively) and measuring branch dimensions inside (IB) or outside (OB) bark. Means down a column followed by the same letter are not significantly different at P = 0.01 (Tukey highly significant difference).

Table 4. Stress and branch diameter values from previous studies.[z]

Species	Stress range or mean (MPa)	Branch diameter range or mean (cm)	Study
Acer platanoides	24.5	5–30	Lilly and Sydnor 1995
Acer saccharinum	29.7	5–30	Lilly and Sydnor 1995
Acer rubrum	1.0–11.0	0.5–2	Gilman 2003
Acer rubrum	22.4–60.6	1.8–7.8	Farrell 2003
Malus spp.	30.5–75.2	7.0	Miller 1959
Malus spp.	37.5–81.0	2.2–3.2	MacDaniels 1923
Pyrus calleryana	32.1–71.3	2.3–8.4	Farrell 2003
Pyrus calleryana 'Bradford' ($\sigma_{BE(IB)}$)	25.6–65.6	7.1–17.8	Present study
Pyrus calleryana 'Bradford' (σ_{BC})	4.2–44.7	7.1–17.8	Present study
Quercus acutissima	36.7–103.9	2.3–6.9	Farrell 2003

[z]A range or mean is provided depending on what was presented in each study. Stress range for Bradford pear (present study) is given when calculated based on the elliptical, inside-bark cross-section (σ_{BE}) and when calculated based on the circular, outside-bark cross-section (σ_{BC}). MacDaniels' (1923) data were reanalyzed to determine stress values.

istically high stresses in the branches. Especially for static loading such as ice accretion, the cumulative loading of all lateral branches must be borne by the attachment of the parent branch and the trunk. It may be that an individual lateral branch would never experience the stress endured in this study because of the location of the load application. Loading resulting from ice accretion, which is most similar to the applied load in this study, varies according to tree characteristics and climate factors and can increase branch weight up to 30 times (Hauer et al. 1993). It is difficult to predict the likelihood of a lateral branch failing before the attachment between the main branch and the trunk.

Another explanation for the discrepancy may be the categories themselves, because several failures appeared to initiate at the attachment but had a substantial number of branch fibers that failed below the attachment (Figure 5). A final contributing factor may be the small sample size. The highest stress value was only 2.6 times as large as the smallest stress value, which is smaller than the range presented by Gilman (2003, Figure 1, p. 292). The lack of a relationship between stress and aspect ratio in MacDaniels' (1923) reanalyzed data may similarly be attributable to a small sample size ($n = 26$). It might also be the result of the fact that his data set included only one attachment with an aspect ratio less than 0.60.

In the absence of included bark, which often occurs when the angle of attachment is small, the angle of attachment appears to be a less reliable predictor of branch strength (MacDaniels 1932; Miller 1959; Gilman 2003), although MacDaniels' (1923) reanalyzed data suggest the opposite. Lilly and Sydnor (1995) noted that the angle of attachment was influenced by species. Norway maple (*Acer platanoides*) branches with wide angles of attachment were more likely to fail in the branch, whereas branches with narrow angles of attachment were more likely to fail at the attachment. However, wider angles of attachment in silver maple (*Acer saccharinum*) were considered "less stable" (p. 304). Results from the current study do not support their findings. This disparity may be attributed in part to the fact that Lilly and Sydnor (1995) did not investigate aspect ratio, which Miller

Figure 5. Failure that was difficult to categorize as branch or attachment based on the definitions presented in the text. The initial failure appears to occur at the apex of the attachment but below that most of the failed fibers are from the branch not the trunk.

(1959) noted was the underlying cause of reduced branch strength when the angle of attachment was small.

The absence of an effect of taper on failure type is unexpected because taper can influence the location of maximum bending stress (Leiser and Kemper 1973). The lack of influence, however, may be the result of the small range of measured branch tapers ($-0.25 \leq$ taper ≤ -0.02) or the superseding effect of aspect ratio. Strong taper, i.e., a large length to diameter ratio, is generally considered to increase tree stability (Petty and Swain 1985; Mattheck et al. 2002). That suggestion might not apply to branches because strong taper in a branch may increase aspect ratio and thus reduce branch attachment strength.

The unexpected lack of influence of GS, MOR, or MOE on $\sigma_{BE(IB)}$ and σ_{BC} is probably the result of the greater likelihood of juvenile and/or tension wood present in wood samples taken from each branch. Both juvenile and tension wood have highly variable strength properties compared with normal trunk wood (Haygreen and Bowyer 1996). Wood samples were not explicitly tested for tension wood, but 14 of the 16 images of branch cross-sections revealed an eccentric pith. Although it is not the best way to confirm the presence of tension wood (Koch et al. 1968), tension wood is often associated with an eccentric pith (Haygreen and Bowyer 1996).

The likelihood of reaction wood (tension wood in angiosperms, compression wood in gymnosperms) or juvenile wood in branches will vary by species and branch size. Using average values for MOR from a source such as the Wood Handbook (USDA 1999) may be misleading because those values are based on trunk wood samples. The ability to extrapolate wood properties' values from trunks to branches varies among species (Rozens 1969; Ueda and Tanaka 1997; Kothiyal et al. 1999) and even height within the tree (Rozens 1969).

The results also illuminate some fundamental considerations in biomechanics research. First, estimating branch or trunk cross-sections as circular is inappropriate without confirming that the cross-section closely resembles a circle. Measuring the cross-section of a branch or trunk as an ellipse would confirm (or reject) that the cross-section is essentially circular. Resistance to bending stress is determined by the moment of inertia, which, for a circle, increases as the fourth power of diameter (Kane et al. 2001). As a branch or trunk cross-section becomes more elliptical, the small dimensional disparities also increase in proportion to the fourth power. Such disparities are responsible for the dramatic differences between $\sigma_{BE(OB)}$ and σ_{BC} as well as between SR_E and SR_C despite relatively small differences in x and y measurements of each branch cross-section. Visual inspection of cross-sections is probably not sufficient to determine whether the x and y measurements differ enough to cause differences in moment of inertia calculations, because the x and y measurements in this study did not differ widely. Because of the constant unidirectional load from gravity, branches have a tendency to form elliptical cross-sections (Fegel 1955), so future examinations of branch failure should consider using equation 1 to calculate stress. It is interesting to speculate on the adaptive growth of elliptical branch cross-sections. Such cross-sections strengthen branches in the direction of static gravitational loads while facilitating lateral bending and swaying during wind loads.

It may be unwise to assume that branch strength will be less than MOR determined from wood samples. Previous studies have found this to be untrue of Japanese cedar (*Cryptomeria japonica*) and Hinoki cypress (*Chamaecyparis obtusa*) (Onwona-Agyeman et al. 1994).

Although shear stress did not contribute to Bradford pear failures, accounting for only 1% of bending stress, future studies should consider the effect of shear stress when the distance from the applied load to the point of failure is short. For a circular beam, the ratio of shear stress to bending stress is d/(6l), where d and l are the diameter and length of the beam, respectively. Thus, on long, slender beams, shear stress becomes less important relative to bending stress. Importantly, however, the shear strength of wood is on average only 12% of MOR (USDA 1999). If the distance from the applied load to the point of failure causes the ratio of shear to bending stress to exceed 12% (e.g., Farrell 2003; Gilman 2003), the effect of shear stress should be investigated.

Acknowledgments. The author thanks the following individuals for their valuable assistance collecting data: Caitie Hutter, Dwayne Jones, Joe Murray, Robert Hopper, and Chris Tooley; and machining test samples: David Jones, Dan Pepin, and Andrew Putnam. The author also thanks two anonymous reviewers for suggesting revisions to the manuscript. This study was funded in part by a Duling grant from the TREE Fund and a Santamour grant from ISA's Mid-Atlantic Chapter.

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Résumé. Autrefois plantés abondamment comme arbre de rue, le poirier Bradford (*Pyrus calleryana* var. 'Bradford') a perdu de son intérêt en raison de sa réputation aux bris de branches. En dépit de cette réputation, le degré de résistance des branches du poirier Bradford n'a jamais été testé. Les études antérieures sur les bris de branches ont écarté l'influence du facteur de l'angle d'attache de la branche au profit du ratio des diamètres entre celui de la branche et celui du tronc qui constituerait un meilleur indice de prédiction de la force d'attache de la branche. Trente-six branches provenant de 10 poiriers Bradford ont été brisées en tirant sur elles au moyen d'un treuil. Pour évaluer l'effet des dimensions de la section transversale de la branche, le stress lié au bris a été calculé en tenant compte de la coupe transversale de la branche par rapport à une ellipse ou un cercle. Le stress au bris a été normalisé en divisant ce dernier par le module de rupture mesuré sur les échantillons de bois provenant de chaque branche brisée. La localisation du bris, que ce soit sur la branche elle-même ou au point d'attache de la branche avec le tronc, n'affectait en rien le stress au bris. Le ratio des diamètres de la branche par rapport à celui du tronc était un meilleur indice de prédiction de la force d'attache de la branche que l'angle d'attache de la branche. Le stress au bris calculé en prenant en compte une coupe transversale de la branche en forme d'ellipse était supérieur à celui calculé à partir d'une coupe transversale où on assumait que la branche était en forme de cercle. Les résultats sont comparés avec des études antérieures et l'importance de mesurer les dimensions de la section transversale de la branche est discutée.

Zusammenfassung. Früher wurde die Bradford-Birne in großem Ausmaß als Straßenbaum gepflanzt, heute ist sie aus der Gunst gefallen wegen ihres Rufs, zu Kronenbruch zu neigen. Ungeachtet ihrer Reputation wurde die Stärke der Äste von Bradford-Birnen nie getestet. Frühere Studien über Astbruch haben den Einfluss des Astansatzwinkels eher unberücksichtigt gelassen unter der Annahme, dass das Verhältnis des Astes zum Stammdurchmesser, oder Aspekt-verhältnis, ein besserer Indikator für die Stärke der Astanbindung sei. 26 Äste von Bradford-Birnen an 10 Bäumen wurden mit dem Einsatz einer Seilwinde abgebrochen. Um den Einfluss der Dimensionierung der Astscheibe zu untersuchen, wurde der Bruchstress kalkuliert unter der Annahme, dass der Astquerschnitt entweder ellipsoid oder rund war. Der Bruchstress wurde ausgeglichen/normalisiert durch eine Division mit dem Unterbrechungsruptus (MOR), der an jedem gebrochenen Ast an Beispielen gemessen wurde. Das Astversagen, entweder im Ast selbst oder an der Anbindestelle hatte keine Einfluss auf das Brechverhalten. Das Aspekt-Verhältnis war ein besserer Indikator für die Haltekraft des Astes als der Astansatzwinkel. Unter der Annahme eines ellipsoiden Astquerschnitts war der kalkulierte Bruchmoment größer als bei einem unterstellten kreisrunden Astquerschnitts. Die Ergebnisse wurden mit früheren Studien verglichen und auf die Bedeutung der Messung der Astquerschnitte wurde hingewiesen.

Resumen. El peral Bradford *(Pyrus calleryana* var. 'Bradford'), plantado extensivamente como árbol urbano, ha perdido interés debido a su fama de rotura de ramas. A pesar de esta reputación, la resistencia de las ramas del peral Bradford no ha sido probada. Otros estudios han discutido la influencia del ángulo de unión con la rama, sugiriendo que la relación: rama - diámetro del tronco es un buen revelador de la resistencia de la unión. Con un malacate se rompieron 26 ramas de diez árboles de peral Bradford. Para evaluar el efecto de las dimensiones del corte trasversal de la rama, el estrés de rotura fue calculado considerando la sección bien sea como una elipse o como un círculo. El estrés de rotura fue normalizado dividiéndolo por el módulo de ruptura (MOR, por sus siglas en inglés) medido en muestras de madera de cada rama rota. La ubicación de la falla, bien sea en la rama en sí misma o en la unión rama/tronco, no afectó el estrés de rotura. El aspecto relación fue un mejor revelador de la resistencia de la unión de la rama que el ángulo de unión. El estrés de rotura, calculado considerando la sección trasversal de la rama como una elipse, fue mayor que cuando se calculó asumiéndola como un círculo. Los resultados son comparados con estudios previos y se discute la importancia de la medición de las dimensiones de la sección trasversal.