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Lodging in Small Grains

N. I. Hancock
E. L. Smith
University of Tennessee Agricultural Experiment Station

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Lodging

IN

SMALL

GRAINS

by

N. I. Hancock and E. L. Smith

Investigations On Certain Characters Associated With Lodging In Small Grains And A New Technique For Measuring Breaking Strength Of Straw

THE UNIVERSITY OF TENNESSEE
AGRICULTURAL EXPERIMENT STATION
JOHN A. EWING, DIRECTOR
KNOXVILLE
THE WATER CONTENT of small grain stems is relatively high at the soft-dough stage of maturity. The stems lose water rapidly between this stage and full maturity. Since resiliency of the stems is conditioned by water content, lodging evaluations based on resiliency are affected by the stage of maturity at which the measurements are made and should be interpreted with caution.

- The stems of small grain tillers taper from the lower-most internode to the internode subtending the head. Wheat stems, in general, do not taper as much as the stems of oats and barley. The component internodes of a small grain stem vary in length, weight, diameter, and wall thickness, depending upon their position in the stem. Observations on lodging made in Tennessee over a number of years have shown that stem breakage usually takes place in the third or fourth internode. Very little breakage has been observed in the first internode above the ground.

- Nodding angles of the heads of lodging susceptible strains were appreciably larger than nodding angles of lodging-resistant strains. The nodding angle is undoubtedly a factor contributing to lodging.

- A new technique for measuring the breaking strength of small grains culms was described. This technique appears to be both rapid and accurate. The data indicate that the leaf-sheaths should be removed from the stem for the best results with this technique.

- It was found that one break made in the middle of one internode per stem was sufficient in evaluating the breaking strength of one tiller. In this respect, the third or fourth internode above the ground level should be the ones for breaking strength evaluation, since lodging appears to occur most frequently in these internodes.

- The breaking strength of oats and wheat was more closely associated with wall thickness than with culm diameter. This association was particularly striking for wheat. Breaking strength of barley internodes, on the other hand, was more closely associated with culm diameter than with wall thickness, although the difference was not great. The product of values for wall thickness and diameter gave highest association with breaking strength.

- To be of much value, any technique of evaluating lodging resistance must be correlated with natural lodging. While direct correlations were not available between breaking strength results and field lodging, it was found that breaking-strength values obtained from lodging-resistant strains were consistently higher than the values obtained from lodging-susceptible strains.
ACKNOWLEDGMENTS

Marshall Sartain assisted primarily in various aspects of data collection and technical operations. A. D. Rutledge, Dee Miller, and Kyle Overton assisted with the statistical analyses. Smith Worley, Phillip Hoskinson, and Z. A. Henry offered helpful suggestions in working out the breaking-strength techniques. The loan of Zeiss micrometer by Department of Plant Pathology is gratefully acknowledged.
# CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary and Conclusions</td>
<td>2</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>3</td>
</tr>
<tr>
<td>Introduction</td>
<td>5</td>
</tr>
<tr>
<td>Results and Discussion</td>
<td>7</td>
</tr>
<tr>
<td>Some Characteristics That May be Related to Lodging</td>
<td>7</td>
</tr>
<tr>
<td>Water Content of Tillers</td>
<td>7</td>
</tr>
<tr>
<td>Length and Weight of Internodes</td>
<td>9</td>
</tr>
<tr>
<td>Nodding Angles</td>
<td>10</td>
</tr>
<tr>
<td>Culm Diameter and Wall Thickness</td>
<td>15</td>
</tr>
<tr>
<td>A New Technique for Measuring Breaking Strength of Straw</td>
<td>17</td>
</tr>
<tr>
<td>Breaking Strength Procedure</td>
<td>17</td>
</tr>
<tr>
<td>Effect of Leaf-Sheaths on This Technique</td>
<td>18</td>
</tr>
<tr>
<td>The Position of the Break</td>
<td>19</td>
</tr>
<tr>
<td>Association Between Breaking Strength and Lodging</td>
<td>20</td>
</tr>
<tr>
<td>Associations Between Breaking Strength, Culm Diameter, and Wall Thickness</td>
<td>21</td>
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Lodging in Small Grains

Investigations on Certain Characters Associated with Lodging in Small Grains and a New Technique for Measuring Breaking Strength of Straw

by

N. I. Hancock and E. L. Smith

INTRODUCTION

It has long been recognized that lodging in small grains is a problem of considerable importance. Its effects on yield, test weight, seed quality, and other characteristics have been investigated (6, 18, 22, 26). With the advent of combine harvesting plus the use of higher levels of fertilization and better management, the need for lodging resistant varieties is becoming more urgent.

Much of the basic information on lodging that is obtained from any one of the small grain crops—oats, barley, wheat, or rye—should be applicable to the others, since the small grain crops are very similar in their patterns of growth and development (3, 9, 12).

Lodging is affected by the environmental conditions attending the development of the plant as well as the genetic make-up of the plant itself. Therefore, when considering lodging, one should, as Mulder (19) has stressed, distinguish between the phenomenon itself and the inherent tendency of the plant to lodge. Even “resistant” varieties will lodge under adverse conditions, while “susceptible” varieties will withstand given favorable conditions.

Because natural environmental conditions favorable for differential lodging are sporadic and unpredictable, breeders have been forced to search for other methods of evaluating lodging resistance. These meth-

1Former Professor of Agronomy, now retired, and former Assistant Professor of Agronomy, now on the staff of Oklahoma State University, respectively.
methods seem to fall into three general categories: 1) inducing artificial lodging, 2) correlating various plant characteristics with lodging, and 3) evaluating lodging resistance by substitute methods.

Various factors have been studied with respect to lodging. The effects of shade, temperature, soil fertility, and other factors on lodging have been reported (19, 28). Overhead irrigation has been used to induce lodging (26). The effects of a wind machine have been reported (14). Lodging has been induced by altering the seeding rate and row spacings (16, 17, 26). The use of strings, wire mesh, boards, and hand-pinching have been used effectively to induce lodging in small grains (18, 22, 26).

The results of studies regarding the associations of morphological and anatomical stem characters with lodging have been inconsistent. Garber and Olson (9) found little or no relationship between lodging resistance and stem diameter, culm wall thickness, and certain anatomical characters. Other investigators (4, 12, 13) reached different conclusions regarding the associations between lodging and various stem characteristics. Jellum (17) reported that lodging-resistant varieties had larger stem diameters and thicker culm walls than did lodging-susceptible varieties. Hamilton (13) and Sechler (24) studied the relationship between lodging and root and crown characteristics.

A straw strength coefficient based on internode length, average cross-section of the culm, and average culm length was developed recently by Polish workers (23). They found a good agreement between their straw-strength coefficients and lodging results obtained in the field.

The search for techniques of evaluating lodging resistance in the absence of natural lodging has led to the development of substitute tests. Grafius and Brown (10) developed the clr test for evaluating lodging resistance in oats. Fairly good correlations were found between clr values obtained in the soft dough stage and subsequent lodging (10). The clr test was later modified to account for stem breakage in senescent stems (11). Frey and Norden (8) found the clr method useful in studying the inheritance of lodging resistance. It has been reported that the diameter of the stems was significantly correlated with clr values (17, 21).

Murphy et al. (20) developed the “snap” test for evaluating lodging resistance and studied the association between snap test scores, clr values and natural lodging. They obtained a good correlation between the
snap test and cLr values. The snap test, however, was more highly correlated with natural lodging than were the cLr values. A lodging index was proposed by Murphy et al. (20), based on percent lodging, percent stem curvature, snap test scores, and cLr values. Frey et al. (7) reported that the cLr method was effective for evaluating lodging resistance on a single plant, but that the snap test was preferred when a progeny row was involved.

The breaking strength of small grain culms as a measure of lodging resistance has been the subject of several investigations. As far back as 1915, Helmick (15) realized the possible importance of the breaking strength of the stem as a method of evaluating lodging resistance. Various methods for measuring breaking strength have since been proposed (5, 15, 24, 29).

Reports differ as to the merit of evaluating lodging resistance by means of breaking strength scores. Clark and Wilson (5), working with wheat, found good correlations between breaking strength and culm diameters, but there appeared to be no correlation between breaking strength and lodging. Salmon (24) reported that although the correlation between breaking strength and lodging was not statistically significant, lodging-resistant types were harder to break than were lodging-susceptible types. Atkins (1) studied the association of breaking strength and various morphological characters and found culm weight to be highly correlated with breaking strength. Atkins (2) also reported that breaking strength values were fairly constant from year to year, whereas lodging was not. He concluded that the relationship between breaking strength and the tendency to lodge was good enough to justify the use of breaking strength techniques in evaluating new varieties for lodging resistance.

RESULTS AND DISCUSSION

Some Characteristics that May be Related to Lodging

**Water Content of Tillers**

The tillers of small grain crops normally contain a relatively high percentage of water until the ripening process sets in, thus enabling the stems to maintain a certain amount of resiliency. The plants, however, must stand in the field until the moisture content of the kernels decreases to about 16% before
combining can begin. It would seem, therefore, that the stage in which the stem loses water most rapidly would be the critical period as far as lodging is concerned.

The water contents of representative samples of barley heads and stems and leaves at three different stages of maturity are shown in Table 1. Moisture content of both early- and late-maturing strains was determined. The water content of the late strains was slightly higher at each stage of maturity, but since this trend appeared to be consistent, the values for both maturity groups were combined and are presented as an average value in the table.

These results show that the water content varied greatly from year to year. The 1962 season at Knoxville was unusually dry, and this is reflected in the results. The moisture content was relatively high in the soft dough stage. By the hard dough stage, the water content of the stems and leaves had decreased by about one-third, and it continued to decrease until the dead-ripe stage.

The results seem to be consistent with those reported by Riegewa and Muszyn'ska (23). They reported that the water content of wheat stems at the milk dough stage was between 59% and 66% and that the water content fell slightly at the waxy stage, then decreased rapidly to full maturity. These results, supported by general field observations, would seem to point up the importance of the stage of maturity at which lodging evaluations are made. In this connection, Jellum (17) found that cLr values obtained from lodging studies with oats decreased after anthesis. This decrease in the lodging score was undoubtedly related to a corresponding decrease in the water content of the stems.

Table 1—Water content of barley heads and stems from samples taken at Knoxville at varying stages of maturity

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soft dough</td>
<td>74.8</td>
<td>47.3</td>
<td>31.2</td>
<td>81.1</td>
<td>55.3</td>
<td>31.2</td>
</tr>
<tr>
<td>Hard dough</td>
<td>33.2</td>
<td>25.4</td>
<td>19.4</td>
<td>55.4</td>
<td>39.0</td>
<td>23.9</td>
</tr>
<tr>
<td>Dead ripe</td>
<td></td>
<td></td>
<td>13.2</td>
<td></td>
<td></td>
<td>10.0</td>
</tr>
</tbody>
</table>

8
Length and Weight of Internodes

Morphological and anatomical characteristics of the culm internodes have been the subject of several studies concerned with lodging in small grains. That stem breakage generally occurs in the internodes and not at the nodes has been well established. Observations over a number of years at this station have seldom shown any stem breakage at the nodes, and breaking strength tests have shown that nodes will withstand 15 to 20 times the force required to break an internode.

Representative tillers from several varieties of each crop were taken at the dead-ripe stage. The length and weight of different internodes and the heads of the three crops are shown in Table 2. The length of the respective internodes for all three crops, in general, increased from the lowest internode to the one subtending the head. The oat panicle is considerably longer, in proportion to the stem, than is the spike of either barley or wheat.

The internodes of oats and wheat show an increase in weight from the lowest internode to the uppermost. The weight of barley internodes on the other hand, does not vary greatly with position.

The ratio of heads to tillers by weight is approximately the same in the three crops, comprising about 45% of the weight of the tiller. The fact that the heads of small grain crops comprise about half the weight of the tiller is not directly related to lodging, since, as observed by Grafius and Brown (10), the stem is fully capable of supporting its own weight and the weight of the head under normal conditions. However, the weight of the heads taken together with the “nodding angle” of the head could be a factor in lodging.

Table 2—Average percentages for length and weight of various culm components of oats, barley and wheat at the dead-ripe stage

<table>
<thead>
<tr>
<th>Culm components</th>
<th>Length (Percent of total)</th>
<th>Weight</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>oats</td>
<td>barley</td>
<td>wheat</td>
<td>oats</td>
<td>barley</td>
</tr>
<tr>
<td>Internode</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5.1</td>
<td>6.5</td>
<td>5.5</td>
<td>3.5</td>
<td>7.8</td>
</tr>
<tr>
<td>2</td>
<td>10.9</td>
<td>12.1</td>
<td>11.5</td>
<td>8.8</td>
<td>8.8</td>
</tr>
<tr>
<td>3</td>
<td>12.5</td>
<td>14.8</td>
<td>11.9</td>
<td>9.4</td>
<td>9.8</td>
</tr>
<tr>
<td>4</td>
<td>15.4</td>
<td>19.4</td>
<td>13.7</td>
<td>9.9</td>
<td>9.5</td>
</tr>
<tr>
<td>5</td>
<td>18.4</td>
<td>23.2</td>
<td>21.2</td>
<td>11.0</td>
<td>8.8</td>
</tr>
<tr>
<td>6</td>
<td>23.1</td>
<td>20.3</td>
<td>26.9</td>
<td>13.9</td>
<td>7.8</td>
</tr>
<tr>
<td>Panicle or spike</td>
<td>14.6</td>
<td>3.8</td>
<td>9.3</td>
<td>43.6</td>
<td>47.5</td>
</tr>
</tbody>
</table>

1 Internode No. 1 is the basal internode.
Plant height is also a factor that has been discussed in connection with lodging. A fairly high correlation (r = 0.61), obtained from over 200 measurements was found between height and lodging in oats. However, height alone does not appear to be responsible for lodging, since several very short strains of oats have been observed to lodge as frequently as the taller varieties. It seems more logical that characteristics of the culm in addition to total length are of paramount importance in conditioning lodging resistance.

**Nodding Angles**

The relation of nodding angle of the small grain head to lodging is not clearly understood. However, the moment of force of a given mass is a function of the distance of the mass from the vertical axis. Thus, the moment of force acting on a small grain culm increases as the nodding angle increases. This relationship may be of some importance in lodging resistance studies.

In an attempt to characterize oats, barley, and wheat with respect to nodding angles, the tillers were harvested at the dead-ripe stage and brought into the laboratory for analyses. Each head with the subtending internode attached was placed on a heavy white paper sheet. A line representing the vertical axis was then drawn parallel to the internode, and a point corresponding to the peduncle node was marked. The point where the center of the head terminated its position in the prescribed arc, in relation to the vertical axis, was then marked. A line was then drawn between the two points, giving an angle which was then measured by a large protractor. Approximately 300 such measurements were made for each crop.

Mean values for nodding angles of upright strains were contrasted with those of nodding strains for each crop (Table 3). As one would expect, the nodding angles of the upright types were appreciably smaller than the angles for the nodding types. The oat varieties, in general, had smaller nodding angles than wheat, and the nodding angles of wheat were, in general, less than those of barley. Possibly the angles presented for the oat strains are not truly representative, since the nodding types measured did not represent the extreme nodding situation. Representative nodding angles for oats, barley, and wheat are shown in figures 1-4.
Representative Nodding Angles of Small Grain Crops

Figure 1. Small angles measured on oats, barley, and wheat.
Representative Nodding Angles of Small Grain Crops

Medium Angles

Figure 2. Medium angles.
Figure 3. Large angles.
Figure 4. Very large angles. Internode continues to bend outward from axis of culm resulting in more than 90-degree angle.
It has been shown that the tiller must support approximately 45% of its total weight as the head and since the nodding angle may be a factor in lodging, the selection for an upright type of standing habit may be of some importance in breeding for lodging resistance.

**Culm Diameter and Wall Thickness**

In addition to length and weight, the internodes of small grain crops were characterized for culm diameter and the thickness of the culm wall. Mean values of length, weight, culm diameter, and wall thickness for various internodes are presented in Table 4. Measurements were made on culms harvested in the dead-ripe stage, and each value in Table 4 represents the mean of 60 measurements made on several varieties of each crop. The results with length and weight of the internodes are similar to those presented in Table 2, and will not be discussed further. Culm diameter and wall thickness were measured with a Zeiss micrometer as shown in figures 5 and 6. The culm diameters for the three crops decrease as one proceeds from the lowest to the uppermost internode. As shown in the table, the wall thicknesses of the lower internodes of wheat is greater than those of oats and barley.

![Figure 5](image1.png) **Figure 5.** This is the procedure used in measuring the culm diameter with a micrometer.

![Figure 6](image2.png) **Figure 6.** Here is the procedure that is used in measuring wall thickness with a micrometer.
Table 3—Nodding angles subtended by heads of oats, barley and wheat; contrasting upright strains with nodding strains

<table>
<thead>
<tr>
<th>Character</th>
<th>Upright Strains</th>
<th>Nodding Strains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Strain No.</td>
<td>Strain No.</td>
</tr>
<tr>
<td>Average</td>
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<td>2</td>
</tr>
<tr>
<td>Oats</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle</td>
<td>7.5</td>
<td>6.7</td>
</tr>
<tr>
<td>S. E. mean</td>
<td>0.52</td>
<td>0.49</td>
</tr>
<tr>
<td>Barley</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle</td>
<td>24.4</td>
<td>39.4</td>
</tr>
<tr>
<td>S. E. mean</td>
<td>1.89</td>
<td>2.24</td>
</tr>
<tr>
<td>Wheat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle</td>
<td>18.0</td>
<td>24.1</td>
</tr>
<tr>
<td>S. E. mean</td>
<td>0.74</td>
<td>1.05</td>
</tr>
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</table>

No direct comparisons between any of these characters and lodging were obtained, but Jellum (17) found in oats, that cLr scores were significantly correlated with culm diameter. It would appear from these data, however, that in wheat, wall thickness might be more important than culm diameter in conditioning lodging resistance.

Table 4—Means and standard errors of the mean for internode length, weight, diameter and wall thickness obtained from representative samples of oats, barley and wheat

<table>
<thead>
<tr>
<th>Internode No.</th>
<th>Character</th>
<th>Length (inches)</th>
<th>Weight (grams)</th>
<th>Diameter (mm)</th>
<th>Wall Thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Mean</td>
<td>S.E.M.</td>
<td>Mean</td>
<td>S.E.M.</td>
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<tr>
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<td>0.18</td>
<td>0.18</td>
<td>0.005</td>
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<tr>
<td>2</td>
<td></td>
<td>5.07</td>
<td>0.12</td>
<td>0.39</td>
<td>0.017</td>
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<td>0.16</td>
<td>0.40</td>
<td>0.027</td>
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<tr>
<td>4</td>
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<td>6.55</td>
<td>0.46</td>
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<td></td>
<td>10.36</td>
<td>0.61</td>
<td>0.40</td>
<td>0.023</td>
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<tr>
<td>Barley</td>
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<td>0.015</td>
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<td>5.96</td>
<td>0.11</td>
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<td>10.86</td>
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<td>13.85</td>
<td>0.92</td>
<td>0.34</td>
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<td>Wheat</td>
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<td>0.82</td>
<td>0.52</td>
<td>0.041</td>
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<tr>
<td>6</td>
<td></td>
<td>12.00</td>
<td>0.63</td>
<td>0.54</td>
<td>0.051</td>
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</table>

1Internode No. 1 is the basal internode.
A New Technique for Measuring Breaking Strength of Straw

Breaking Strength Procedure

Investigations with lodging resistance, conducted at this station over a number of years, have led to the development of a rapid technique for measuring the breaking strength of small grain culms. The procedure is as follows: A wire hook, 3 inches in length, is fastened to the pan on a Toledo scale, Model 4030, which has a dial graduated in tenths of a pound. Weights are placed on the counter-balance to compensate for the weight of the hook. An internode of a single stem is then centered over the wire hook. Another hook of 20 gauge metal, with a 1 inch gap for breaking space, is placed over the culm. The operator then pulls down on the internode with this hook while watching the dial of the scale. In this manner, the operator is able to read directly the pounds of force necessary for breaking the internode. The breaking strength technique is shown in Figure 7.

It can be seen that this operation is both efficient and rapid. With a little experience, the operator can ascertain within a tenth of a pound the force at the instant of breaking. One individual can measure the breaking strength of more than

Figure 7. This technique was used to measure the breaking strength of small grain culms.
60 culms in an hour. The culms to be measured for breaking strength are harvested in the dead-ripe stage of maturity or harvested a few days before this stage and allowed to air-dry for a number of days.

This new technique of measuring the breaking strength of small grain culms appears to be more rapid than the methods previously described (5, 15, 24, 29). The value of this method as well as any other method of measuring breaking strength, however, depends on the correlation between breaking strength and natural lodging.

**Effect of Leaf-Sheaths on This Technique**

The effects of adhering leaf-sheaths on breaking strength were studied in order to determine whether leaf sheaths differentially affected breaking strength. Measurements of oats, barley, wheat, and rye culms both with and without adhering leaf-sheaths were made. Four internodes of each culm from eight different plants of six different strains of each crop were involved. As shown in Table 5, adhering leaf sheaths resulted in higher breaking strength scores, but the differences between culms with and without sheaths were inconsistent.

The analysis of variance comparing the effects of leaf-sheaths on breaking strength is shown in Table 6. There is a significant difference among strains. The effect of sheaths on breaking strength was significant in the four crops as were the differences among internodes. The interaction of sheaths X internodes is the critical point here and as shown in Table 6, this interaction was significant in oats, barley, and wheat but not for rye. This indicates that sheaths should probably be removed from the culm when testing for breaking strength.

**Table 5—Breaking strength results of small grains culms; with and without adhering leaf sheaths**

(Values represent means of eight breaks for each of six strains of species)

<table>
<thead>
<tr>
<th>Internode number</th>
<th>Oats</th>
<th>Barley</th>
<th>Wheat</th>
<th>Rye¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pounds per inch break</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2.59</td>
<td>2.65</td>
<td>2.16</td>
<td>1.87</td>
</tr>
<tr>
<td>2</td>
<td>2.32</td>
<td>2.21</td>
<td>1.11</td>
<td>1.66</td>
</tr>
<tr>
<td>3</td>
<td>2.96</td>
<td>1.84</td>
<td>1.12</td>
<td>1.20</td>
</tr>
<tr>
<td>4</td>
<td>1.80</td>
<td>0.98</td>
<td>.82</td>
<td>0.94</td>
</tr>
</tbody>
</table>

¹The 6 strains of rye represent different selections from an F₅ tetraploid cross.
²Leaf sheaths intact.
³Leaf sheaths removed.
Table 6—Analysis of variance of breaking strength of small grain culms with and without adhering leaf sheaths

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Oats Mean squares</th>
<th>Barley Mean squares</th>
<th>Wheat Mean squares</th>
<th>Rye Mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strains</td>
<td>5</td>
<td>74.12**</td>
<td>147.21**</td>
<td>125.33**</td>
<td>162.41**</td>
</tr>
<tr>
<td>Sheaths</td>
<td>1</td>
<td>52.08**</td>
<td>96.10**</td>
<td>64.21**</td>
<td>168.20**</td>
</tr>
<tr>
<td>Internodes</td>
<td>3</td>
<td>116.95**</td>
<td>195.43**</td>
<td>155.18**</td>
<td>210.42**</td>
</tr>
<tr>
<td>Strains X Sheaths</td>
<td>5</td>
<td>2.31 ns</td>
<td>2.61 ns</td>
<td>1.24 ns</td>
<td>33.30**</td>
</tr>
<tr>
<td>Strains X Internodes</td>
<td>15</td>
<td>1.84 ns</td>
<td>11.76**</td>
<td>3.37**</td>
<td>65.45**</td>
</tr>
<tr>
<td>Sheaths X Internodes</td>
<td>3</td>
<td>20.15**</td>
<td>3.98*</td>
<td>6.65**</td>
<td>2.19 ns</td>
</tr>
<tr>
<td>Error</td>
<td>15</td>
<td>.0314</td>
<td>.0076</td>
<td>.0091</td>
<td>.0073</td>
</tr>
<tr>
<td>Total</td>
<td>47</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1The 6 strains of rye represent different selections from an F1 tetraploid cross.

* = Significant at the 5% level of probability.

** = Significant at the 1% level of probability.

The Position of the Break

Table 7 shows the mean values for breaking strength at three different positions on each internode for oats, barley, wheat, and rye. The values represent the means of 10 breaks for each of three strains per species. The position of the breaks were as follows: one break was made near the lower node, the second break was made near the center of the internode, and the third break was made near the upper node.

The analysis of variance (Table 8) shows significant differences among break position for oats, barley, and rye, but not for wheat.

There was no significant interaction of strains X break-positions nor break positions X internodes. It appears then that one break in the center of the internode is sufficient for evaluating the breaking strength of the particular internode.

Table 7—Breaking strength results of small grain culms comparing breaks made at 3 different points on each internode (Values represent means of ten breaks for each of three strains per species)

<table>
<thead>
<tr>
<th>Internode number</th>
<th>Oats Break position1</th>
<th>Barley Break position</th>
<th>Wheat Break position</th>
<th>Rye Break position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A        B        C</td>
<td>A        B        C</td>
<td>A        B        C</td>
<td>A        B        C</td>
</tr>
<tr>
<td>1</td>
<td>0.94     1.03     1.11</td>
<td>2.34     2.35     2.42</td>
<td>1.69     1.63     1.82</td>
<td>2.28     2.25     2.18</td>
</tr>
<tr>
<td>2</td>
<td>0.51     0.65     0.79</td>
<td>1.59     1.72     1.69</td>
<td>1.26     1.33     1.27</td>
<td>1.65     1.57     1.42</td>
</tr>
<tr>
<td>3</td>
<td>0.31     0.43     0.54</td>
<td>0.88     0.96     1.08</td>
<td>1.06     1.11     1.14</td>
<td>1.23     0.95     0.75</td>
</tr>
<tr>
<td>4</td>
<td>0.23     0.32     0.36</td>
<td>0.67     0.72     0.81</td>
<td>0.63     0.58     0.71</td>
<td>0.74     0.72     0.49</td>
</tr>
</tbody>
</table>

1Break positions: A = near lower node; B = at the center of the internode; C = near the upper node.
Table 8—Analysis of variance of breaking strength of small grain culms involving three different break positions per internode (Calculations were based on means of ten breaks)

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Oats Mean squares</th>
<th>Barley Mean squares</th>
<th>Wheat Mean squares</th>
<th>Rye Mean squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strains</td>
<td>2</td>
<td>41.85**</td>
<td>48.40**</td>
<td>15.74**</td>
<td>20.64**</td>
</tr>
<tr>
<td>Break positions</td>
<td>2</td>
<td>27.65**</td>
<td>11.85**</td>
<td>3.17ns</td>
<td>11.79**</td>
</tr>
<tr>
<td>Internodes</td>
<td>3</td>
<td>111.70**</td>
<td>54.70**</td>
<td>170.63**</td>
<td>49.33**</td>
</tr>
<tr>
<td>Strains X Break pos.</td>
<td>4</td>
<td>0.27ns</td>
<td>1.36ns</td>
<td>1.04ns</td>
<td>1.49ns</td>
</tr>
<tr>
<td>Strains X Internodes</td>
<td>6</td>
<td>1.97ns</td>
<td>17.40**</td>
<td>1.89ns</td>
<td>7.22**</td>
</tr>
<tr>
<td>Break pos. X Internodes</td>
<td>6</td>
<td>0.08ns</td>
<td>1.59ns</td>
<td>1.93ns</td>
<td>1.84ns</td>
</tr>
<tr>
<td>Error</td>
<td>12</td>
<td>.0041</td>
<td>.0115</td>
<td>.0078</td>
<td>.0030</td>
</tr>
<tr>
<td>Total</td>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

144 degrees of freedom for barley because of 5 internodes.

Association Between Breaking Strength and Lodging

The use of a breaking strength technique as an effective means of evaluating lodging resistance demands that the breaking strength scores be closely correlated with lodging. Although direct correlations between breaking strength and lodging resistance were not available, an indirect comparison was made. Breaking strength values were obtained from a lodging-resistant and a lodging-susceptible strain for the four crops (Table 9). It is readily apparent that the lodging-resistant strains required considerably more breaking force than did the lodging-susceptible strains. The

Table 9—Breaking strength, wall thickness, and culm diameter comparisons between a lodging resistant strain and a lodging susceptible strain of each of the 4 small grain species (Values represent means of ten measurements)

<table>
<thead>
<tr>
<th>Internode number</th>
<th>Oats B.S.</th>
<th>W.T.</th>
<th>C.D.</th>
<th>Barley B.S.</th>
<th>W.T.</th>
<th>C.D.</th>
<th>Wheat B.S.</th>
<th>W.T.</th>
<th>C.D.</th>
<th>Rye B.S.</th>
<th>W.T.</th>
<th>C.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>lbs.</td>
<td>mm</td>
<td>mm</td>
<td>lbs.</td>
<td>mm</td>
<td>mm</td>
<td>lbs.</td>
<td>mm</td>
<td>mm</td>
<td>lbs.</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>Lodging-resistant</td>
<td></td>
<td></td>
<td></td>
<td>Lodging-susceptible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.82</td>
<td>0.36</td>
<td>3.91</td>
<td>2.15</td>
<td>0.39</td>
<td>4.51</td>
<td>1.98</td>
<td>0.53</td>
<td>3.42</td>
<td>3.31</td>
<td>0.57</td>
<td>3.07</td>
</tr>
<tr>
<td>2</td>
<td>1.35</td>
<td>0.29</td>
<td>3.81</td>
<td>1.48</td>
<td>0.34</td>
<td>4.62</td>
<td>1.63</td>
<td>0.43</td>
<td>3.69</td>
<td>2.80</td>
<td>0.52</td>
<td>5.12</td>
</tr>
<tr>
<td>3</td>
<td>0.99</td>
<td>0.23</td>
<td>3.64</td>
<td>0.96</td>
<td>0.31</td>
<td>4.05</td>
<td>1.29</td>
<td>0.39</td>
<td>4.07</td>
<td>2.16</td>
<td>0.45</td>
<td>4.79</td>
</tr>
<tr>
<td>4</td>
<td>0.58</td>
<td>0.21</td>
<td>2.94</td>
<td>0.79</td>
<td>0.28</td>
<td>3.97</td>
<td>0.75</td>
<td>0.33</td>
<td>3.35</td>
<td>1.17</td>
<td>0.41</td>
<td>2.56</td>
</tr>
<tr>
<td>Avg.</td>
<td>1.19</td>
<td>0.27</td>
<td>3.53</td>
<td>1.35</td>
<td>0.33</td>
<td>4.29</td>
<td>1.41</td>
<td>0.42</td>
<td>3.63</td>
<td>2.36</td>
<td>0.49</td>
<td>3.89</td>
</tr>
<tr>
<td>Lodging-susceptible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.11</td>
<td>0.33</td>
<td>4.02</td>
<td>1.21</td>
<td>0.34</td>
<td>3.88</td>
<td>1.33</td>
<td>0.39</td>
<td>2.90</td>
<td>1.77</td>
<td>0.33</td>
<td>3.79</td>
</tr>
<tr>
<td>2</td>
<td>0.73</td>
<td>0.24</td>
<td>3.96</td>
<td>0.88</td>
<td>0.29</td>
<td>3.94</td>
<td>0.92</td>
<td>0.35</td>
<td>3.19</td>
<td>1.31</td>
<td>0.29</td>
<td>3.82</td>
</tr>
<tr>
<td>3</td>
<td>0.65</td>
<td>0.25</td>
<td>3.71</td>
<td>0.68</td>
<td>0.28</td>
<td>2.73</td>
<td>0.72</td>
<td>0.30</td>
<td>3.29</td>
<td>0.92</td>
<td>0.24</td>
<td>3.03</td>
</tr>
<tr>
<td>4</td>
<td>0.48</td>
<td>0.23</td>
<td>2.61</td>
<td>0.53</td>
<td>0.26</td>
<td>3.12</td>
<td>0.39</td>
<td>0.26</td>
<td>2.79</td>
<td>0.58</td>
<td>0.25</td>
<td>1.94</td>
</tr>
<tr>
<td>Avg.</td>
<td>0.74</td>
<td>0.26</td>
<td>3.58</td>
<td>0.83</td>
<td>0.29</td>
<td>3.42</td>
<td>0.84</td>
<td>0.33</td>
<td>3.04</td>
<td>1.15</td>
<td>0.28</td>
<td>3.15</td>
</tr>
</tbody>
</table>

1Breaking strength in pounds per inch break.

Wall thickness in millimeters.

3Culm diameter in millimeters.
analysis of variance (Table 10) shows that breaking strength differences between lodging-susceptible and lodging-resistant strains are highly significant. It is also shown in Table 10 that the internode X culm interaction is not significant for any of the four crops. This indicates that a test of one internode can be used reliably to represent the breaking strength of an entire culm.

**Associations Between Breaking Strength, Culm Diameter, and Wall Thickness**

The data presented in Table 11 are based on results from both lodging-resistant and lodging-susceptible strains of each species. Breaking strength was more closely correlated with wall thickness in oats, wheat, and rye, while in barley the correlation between breaking strength and culm diameter was highest. Scatter diagrams showing the association between breaking strength and wall thickness of the four crops are presented in figures 8-11. Atkins (2) found a good relationship between internode weight and breaking strength. As shown in Table 11, internode

**Table 10—Analysis of variance of breaking strength of small grain culms involving a lodging-resistant strain and a lodging-susceptible strain for each species**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Oats</th>
<th>Barley</th>
<th>Wheat</th>
<th>Rye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strains</td>
<td>1</td>
<td>10.24**</td>
<td>10.69**</td>
<td>16.32**</td>
<td>30.61**</td>
</tr>
<tr>
<td>Internodes</td>
<td>3</td>
<td>76.40**</td>
<td>54.90**</td>
<td>28.46**</td>
<td>120.24</td>
</tr>
<tr>
<td>Culms</td>
<td>9</td>
<td>1.72</td>
<td>3.30*</td>
<td>1.58*</td>
<td>2.47*</td>
</tr>
<tr>
<td>Strains X Internodes</td>
<td>3</td>
<td>19.36**</td>
<td>9.74*</td>
<td>3.94*</td>
<td>20.02**</td>
</tr>
<tr>
<td>Strains X Culms</td>
<td>9</td>
<td>17.17*</td>
<td>4.97ns</td>
<td>0.07ns</td>
<td>7.07ns</td>
</tr>
<tr>
<td>Internodes X Culms</td>
<td>27</td>
<td>1.33ns</td>
<td>0.43ns</td>
<td>0.77ns</td>
<td>1.83ns</td>
</tr>
<tr>
<td>Error</td>
<td>27</td>
<td>0.0196</td>
<td>0.0792</td>
<td>0.310</td>
<td>0.0483</td>
</tr>
<tr>
<td>Total</td>
<td>79</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 11—Simple correlation coefficients between several culm characters in each of 4 small grain species (118 degrees of freedom for each correlation coefficient)**

<table>
<thead>
<tr>
<th>Characters correlated</th>
<th>Oats</th>
<th>Barley</th>
<th>Wheat</th>
<th>Rye</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breaking strength X Wall thickness</td>
<td>0.780</td>
<td>0.601</td>
<td>0.979</td>
<td>0.874</td>
</tr>
<tr>
<td>Breaking strength X Culm diameter</td>
<td>0.727</td>
<td>0.658</td>
<td>0.702</td>
<td>0.852</td>
</tr>
<tr>
<td>Wall thickness X Culm diameter</td>
<td>0.673</td>
<td>0.550</td>
<td>0.519</td>
<td>0.593</td>
</tr>
<tr>
<td>Internode weight X Wall thickness</td>
<td>0.738</td>
<td>0.412</td>
<td>0.726</td>
<td>—</td>
</tr>
<tr>
<td>Internode weight X Culm diameter</td>
<td>0.742</td>
<td>0.574</td>
<td>0.744</td>
<td>—</td>
</tr>
</tbody>
</table>

Note: At 118 degrees of freedom all of the above correlation coefficients are significant at the 1% level of probability.
Figure 8. Oats: Association of breaking strength (pounds per inch) with wall thickness (tenths of millimeter).

Figure 9. Barley: Association of breaking strength (pounds per inch) with wall thickness (tenths of millimeter).
Figure 10. Wheat: Association of breaking strength (pounds per inch) with wall thickness (tenths of millimeter).

Figure 11. Rye: Association of breaking strength (pounds per inch) with wall thickness (tenths of millimeter).
weight was fairly closely correlated with culm diameter and wall thickness in oats and wheat, but these correlations in barley were rather low. However, in the present study, culm diameter and wall thickness were more highly correlated with breaking strength than was internode weight.

Standard partial regression coefficients of culm diameter and wall thickness with breaking strength were calculated according to the procedure outlined by Snedecor (27). These are presented in Table 12. The results from this analysis support the previously-discussed correlation results. These data indicate that wall thickness has much more influence on breaking strength in oats, wheat, and rye than does culm diameter. It appears to be especially important in wheat. The breaking strength of barley internodes appeared to be influenced more by culm diameter than wall thickness.

Table 12—The influence of wall thickness ($X_1$) and culm diameter ($X_2$) on breaking strength ($Y$) of small grains as estimated by standard partial regression coefficients

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Oats</th>
<th>Barley</th>
<th>Wheat</th>
<th>Rye</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b'y1.2$ (Wall thickness)</td>
<td>0.5414</td>
<td>0.3808</td>
<td>0.8279</td>
<td>0.5674</td>
</tr>
<tr>
<td>$b'y2.1$ (Culm diameter)</td>
<td>0.2794</td>
<td>0.4870</td>
<td>0.2917</td>
<td>0.3275</td>
</tr>
</tbody>
</table>


