# ASSESSING INTERNAL HURRICANE DAMAGE TO STANDING PINE POLETIMBER

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## ABSTRACT

Two test methods were used to assess type, location, and degree of internal stem damage to standing pine poletimber (5.0–8.9 in. diameter at breast height, DBH) caused by Hurricane Hugo. A total of sixty trees [15 from each of the four Forest Inventory Analysis (FIA) damage classes] were taken from three sites in the Francis Marion National Forest. Internal damage was expected in the form of ring shake and compression failure. Five stem sections (A through E) were taken from each tree at different heights. From each section, specimens were cut from four quadrants (Tension, Compression, Left, and Right) relative to the wind direction during the storm for toughness and tension perpendicular to the grain testing. A total of 2,147 toughness specimens were tested. A total of 273 specimens were tested in tension perpendicular to the grain. The dependent variables analyzed were toughness, tension strength, and specific gravity with FIA damage class as the whole plot factor.

Although there was an increasing trend in toughness from Damage Class 1 through 4, analysis of variance showed damage class not to be a significant effect on toughness. Stem section and quadrant were found to be significant on toughness. Much of the variation in toughness due to stem section may be attributed to the effects of juvenile wood differences with tree height. Also a high occurrence of reaction wood in Quadrant C (side of the tree away from the wind) would contribute to lower toughness strength. Similarly, specific gravity (SG) values showed an overall increase from Damage Class 1 through 4. Specific gravity of Damage Classes 1 and 4 was found to be significantly different. Statistical analysis showed no apparent relationship between damage class and tension strength perpendicular to the grain.

The lack of evidence for internal damage is relatively unimportant compared to the evidence of change in the wood properties from the formation of reaction wood. In leaning stems (FIA Damage Classes 2, 3, 4), reaction wood should continue to form. In straight trees, reaction wood formed in

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the two growth seasons following the storm, but it is unclear whether it will continue to form. The results lead to the conclusion that stands with leaning stems should be harvested and replanted.

*Keywords:* Storm damage, poletimber, toughness, tension strength, FIA damage class.

## INTRODUCTION

On September 22, 1989, Hurricane Hugo struck the South Carolina coast with sustained winds of 135 mph and gusts up to 175 mph. In the fall of 1989 the Forest Inventory and Analysis (FIA) Research Work Unit at the Southeastern Forest Experiment Station began a special inventory of the areas damaged by Hugo. A classification system was needed that would assign hurricane-damaged trees to discrete categories based on the amount of inflicted damage. The objective was to "provide a reasonable description of damage severity" and estimate the probability of mortality in the near future (Sheffield and Thompson 1992). The criteria for damage class were empirically derived, and a system of four damage classes emerged (Table 1).

Hugo caused extensive immediate damage to the Francis Marion National Forest with an estimated 75% of all marketable trees (DBH > 5.0) on the ground (Ehinger 1990). The FIA damage class system was devised and implemented in an effort to quantify the damage inflicted on the forest resource and to help foresters decide on the proper management strategies for the remaining stands. However, there were questions still unanswered. What possible long-range effects did Hugo have on the remaining 25%? In the case of poletimber (5.0–8.9 DBH), a question that naturally arose was "Should storm damaged poletimber be allowed to mature into sawtimber?" Internal damage to the stem in the form of ring shake and compression failures could reduce the utility of these trees for high-value products such as structural lumber. Such damage may not be evident until processing of the lumber is completed, adding further to the costs of utilizing these trees. Also, if stems with internal damage do enter the market, a significant liability risk

TABLE 1. *Summary of study variables.*

| Variable | Levels |
|---|---|
| Wind Damage Class (FIA) | 1—High risk of mortality in the near future. Tree lean is greater than 45°.<br>2—Moderate risk of mortality, damage may degrade value for use as sawlogs or plylogs. Tree lean 15° to 44°.<br>3—High probability of survival, risk of reduced growth and value degrade is minimal. Tree lean is less than 15°.<br>4—No obvious wind damage. Tree is essentially straight. |
| Quadrant | T—Side of tree facing the wind during the storm (under tension stress).<br>C—Side of tree opposite the wind direction (under compression stress).<br>L—Left side of tree facing the wind (under shear stress).<br>R—Right side of tree facing the wind (under shear stress). |
| Section (tree height) | A—Breast height<br>B—3 feet below critical stress point<br>C—Critical stress point (CSP)<br>D—3 feet above critical stress point<br>E—One foot below base of crown |
| Replicates | 15 trees per damage class |
| Response variable | Procedure |
| Mechanical Testing | Toughness (ASTM D143-93)<br>Tension perpendicular to the grain (ASTM D143-93) |
| Reaction Wood | Present or absent |

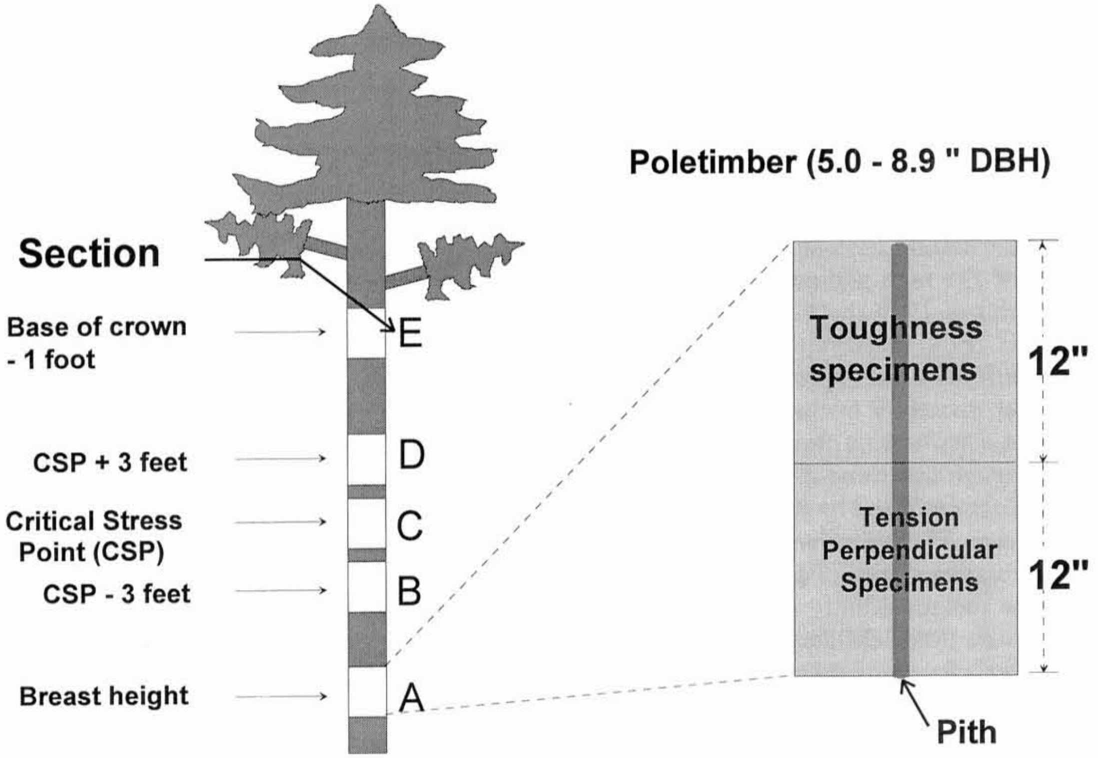

FIG. 1. Location of sections within the tree stem.

due to increased failure rates will occur. Thus, sawtimber from internally damaged stems should be sold for pulp chips, a lower value product.

Traditionally storm damage has been classified in terms of visual damage such as snapping of the trunk, uprooting, and bending (Webb 1988). Similarly, Mayer (1988) defined four types of storm damage as: stem breakage, stock (base of stem) breakage, root breakage, and tree throw. There have been other studies that differentiate only between tree throw and stem breakage. Although it is apparent that high winds could cause internal damage to tree stems, little information is available on the subject. The FIA damage class system that provides tree classification in terms of apparent storm damage and potential mortality allows only for conjecture as to the degree of internal stem damage. Although the FIA damage class system is only approximate, it is a very practical classification system, which brings us a step closer to understanding the nature of storm-damaged timber. What is needed is correlation between this visual damage classification system and actual internal damage as measured by mechanical testing and visual observation.

## OBJECTIVE

The objective of this study was to assess type, location, and degree of internal stem damage to standing pine poletimber and to relate this damage to the FIA damage classes. Internal damage in the form of compression failures, ring shake, and reaction wood were examined by toughness tests, tension perpendicular to the grain tests, and visual observation of reaction wood formation, respectively. Wood specific gravity was measured at each location within the tree and analyzed with the mechanical properties. A summary of the study variables is presented in Table 1.

## METHODS AND MATERIALS

A total of sixty poletimber-sized trees consisting of longleaf pine (*Pinus palustris,* Dim.) and loblolly pine (*Pinus taeda,* L.) was taken from natural stands in the Francis Marion National Forest near McClellanville, South Carolina, in August of 1991. To avoid the possibility of site bias, the trees were taken from three different sites. A member of the FIA research work unit helped to select the trees for the study, which consisted of 15 trees in each FIA damage class. Five stem sections were cut from each selected tree, as described below, and brought to the laboratory for further processing. In an attempt to obtain the best group of samples from each stem, it was first necessary to determine the point along the stem most likely to sustain wind damage—the critical stress point (CSP). Observations in the field were used to determine the critical stress point as the average height of broken poletimber-sized stems in close proximity to the sample tree. Using this value of critical stress point, the five 24-in. stem sections (Fig. 1) were cut on center at:

A— breast height
B— 3 feet below critical stress point
C— critical stress point (CSP)
D— 3 feet above critical stress point
E— one foot below base of crown

It was expected that internal damage to the trees was in the form of compression failures, ring shake, and reaction wood. Compression failures would be indicated by toughness testing as specified in ASTM D-143-93. Ring shake would be indicated by tension perpendicular to grain tests as specified in ASTM D-143-93, while the presence of reaction wood was determined by visual inspection of the outer 2 growth rings.

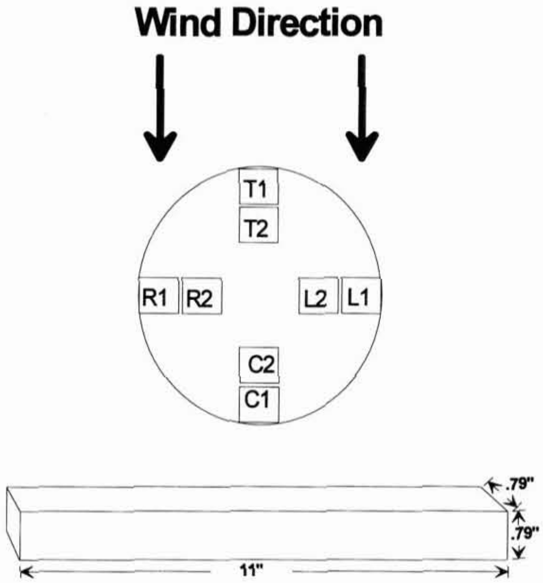

FIG. 2. Orientation of Toughness specimens in the tree stem.

The five stem sections were cross-cut into two 12-in. sections. Toughness specimens were taken from one of these 12-in. sections and tension perpendicular specimens from the other. Each section was divided into 4 quadrants on the cross-sectional plane such that 2 quadrants were parallel to the wind direction during the storm and the other 2 were consequently perpendicular to the wind direction. The quadrants parallel to the wind direction experienced the severest tension stress on the side of the tree facing the wind and severest compression stress on the side away from the wind. Toughness and tension perpendicular specimens were cut from each quadrant. Only straight-grained specimens free of knots were kept for testing. Reaction wood was present in many of the Position 1 (specimen closest to cambium and bark) toughness specimens. Care was taken during processing to remove as little wood from the bark side of the specimens as possible. Occurrence of reaction wood was visually observed in the outer 2 growth rings and recorded for each quadrant and section of each tree.

Toughness specimens were taken from Position 1 and 2, except in the higher sections of some stems from smaller diameter trees, where it was not possible to obtain both specimens (see Fig. 2). The toughness testing was done on 1,821 samples with a Wiedemann-Baldwin Impact machine. Specific gravity was calculated by measuring the volume prior to testing and the oven-dry weight of the specimen after testing.

To test for ring shake, it was necessary to stress the entire length of the tension perpendicular to the grain specimen since the location of the ring shake was unknown. The position and orientation of the specimens are shown in Fig. 3. Since the traditional throated tension perpendicular specimen described by ASTM D143 (ASTM 1993) does not stress the entire length of the specimen, the specimen was modified by using high strength epoxy to bond hard maple blocks to the bark and pith faces of the tension perpendicular to the grain specimens. Appropriate hardware was bolted to the maple blocks and tested as per ASTM standards. Only sections at DBH and critical stress point were tested since there was a higher probability of ring separation due to shear stress in these specimens. The tension perpendicular testing was done on 273 specimens with a Tinius Olsen 5000 universal testing machine.

## EXPERIMENTAL DESIGN

This study was analyzed as a split-plot design where the whole-plot factor was the four tree damage classes each represented by a subsample of trees. Whole-plot replication was by means of blocks defined as the three sites. The subplot factor was a factorial combination of the five tree sections by four quadrants of each tree. The design was unbalanced, which led to a complicated analysis. At the whole-plot level, there were no trees in one damage class for one of the sites. This resulted in a missing cell and, hence, only 5 degrees of freedom for the site by damage class effect instead of the typical $2 \times 3 = 6$. In addition, the number of trees sub-sampled in each site by damage class was unequal. At the subplot level, there were several missing observations at various section by quadrant treatment combinations. Due to the unbalanced nature of this study, approximate F-tests were performed in the typical split-plot design fashion using the whole-plot and subplot error terms. The expected mean squares obtained from SAS (SAS Institute Inc. 1988) indicated that these tests were close to those in the typical balanced situation. Mean separation tests were performed on the main factor effects with Tukey's test. General mean comparisons were not performed since they would require synthesized error terms using Satterthwaite's procedure, which was not attempted because of the complexity of the design.

## RESULTS AND DISCUSSION

### *Toughness and specific gravity analysis*

Results from the analysis of variance on toughness and specific gravity are shown in Table 2, while treatment means and Tukey's multiple comparisons for all main effects are shown in Table 3. The analysis was performed on the Position 1 and Position 2 specimens both separately and combined.

The effect of juvenile wood is evidenced by the lower values of toughness and specific gravity of the Position 2 specimens as compared to the Position 1 specimens. The Position 2 specimens should exhibit more juvenile properties of lower toughness and specific gravity because of their closer proximity to the pith.

*FIA damage class effects.*—The damage class factor was not quite significant for toughness ($P = 0.07$). Generally, toughness decreased with increasing damage (i.e., highly damaged trees had lower toughness). Similarly, Tukey's comparison tests showed a trend of decreasing specific gravity with increasing degree of damage. Damage class effects on specific gravity were significant at the 0.05 level. This trend supports the conclusion that trees with higher specific gravity and hence higher strength were better able to survive the effects of the storm. Perhaps this trend is due to the development of root systems. A better root system provides better support for the tree stem and is important in resisting windthrow and root upheaval. It seems logical that they develop denser wood tissue, since better developed root systems provide more nutrient and moisture uptake.

The interaction of damage class quadrant and also had a significant effect on toughness ($P = 0.02$). Figure 4 illustrates this interaction. The highest toughness values are concentrated

TABLE 2. *Results from the analysis of variance (P-values)*[1] *based on a split-plot design.*

| | Positions 1 and 2 | | | Position 1 | | | Position 2 | | |
|---|---|---|---|---|---|---|---|---|---|
| Source | df[2] | Toughness | SG | df | Toughness | SG | df | Toughness | SG |
| Site | 2 | —[3] | — | 2 | — | — | 2 | — | — |
| Damage Class (DC) | 3 | 0.07 | 0.05 | 3 | 0.08 | 0.07 | 3 | 0.17 | 0.14 |
| Site × DC | 5 | — | — | 5 | — | — | 5 | — | — |
| Tree (Site × DC) | 49 | — | — | 49 | — | — | 49 | — | — |
| Sect | 4 | 0.00 | 0.00 | 4 | 0.00 | 0.00 | 3 | 0.00 | 0.00 |
| Quad | 3 | 0.00 | 0.00 | 3 | 0.00 | 0.00 | 3 | 0.00 | 0.26 |
| Sect × Quad | 12 | 0.42 | 0.06 | 12 | 0.07 | 0.66 | 9 | 0.06 | 0.95 |
| DC × Sect | 12 | 0.55 | 0.31 | 12 | 0.11 | 0.00 | 9 | 0.78 | 0.77 |
| DC × Quad | 9 | 0.02 | 0.59 | 9 | 0.00 | 0.11 | 9 | 0.98 | 0.04 |
| DC × Sect × Quad | 36 | 0.90 | 0.93 | 36 | 0.88 | 0.57 | 27 | 0.80 | 0.94 |
| Error (b) | 1,015 | — | — | 1,011 | — | — | 554 | — | — |
| Total (corrected) | 1,150 | | | 1,146 | | | 673 | | |

[1] Probability that main effect or interaction has no effect on the measured response.

[2] Degrees of freedom.

[3] —Not of interest or cannot be calculated.

near the tension (T) quadrant, the lowest values near the compression quadrant, and intermediate values are predominantly associated with the left and right quadrants. The trend is increasing toughness from Damage Class 1 to 4. The tension quadrant at Damage Class 4 caused the interaction effect by not having higher toughness than the other quadrants. This may be explained by the low occurrence of reaction wood and higher specific gravity in this combination of damage class and quadrant.

The purpose of the toughness test was to detect compression failures occurring on the transverse axis of the wood. While a trend in toughness with damage class was observed, it was probably due to the significant trend in specific gravity rather than the detection of internal damage. Compression failures were observed in several samples that were tested. However, these compression failures were extremely localized and their effects lost in the large sample of specimens.

*Section and quadrant effects.*—The section

TABLE 3. *Means for toughness and specific gravity with Tukey's mean separation.*[1]

| | | Positions 1 and 2 | | Position 1 | | Position 2 | |
|---|---|---|---|---|---|---|---|
| Factor | | Toughness (in-lb) | SG | Toughness (in-lb) | SG | Toughness (in-lb) | SG |
| Damage Class | 1 | 278a | 0.526b | 295a | 0.556b | 246a | 0.471a |
| | 2 | 313a | 0.557ab | 322a | 0.582ab | 296a | 0.518a |
| | 3 | 306a | 0.560ab | 322a | 0.586ab | 286a | 0.517a |
| | 4 | 321a | 0.589a | 329a | 0.605a | 307a | 0.565a |
| Section | A | 347a | 0.599a | 358a | 0.630a | 331a | 0.551a |
| | B | 305b | 0.574b | 323b | 0.604b | 280b | 0.524b |
| | C | 301bc | 0.558c | 314bc | 0.588c | 275b | 0.507c |
| | D | 284cd | 0.537d | 304c | 0.566d | 242c | 0.485d |
| | E | 283d | 0.516e | 283d | 0.516e | — | — |
| Quadrant | T | 354a | 0.547c | 383a | 0.577c | 315a | 0.512b |
| | L | 308b | 0.569a | 314b | 0.584ab | 296ab | 0.531a |
| | R | 296b | 0.562b | 301b | 0.579bc | 281b | 0.526a |
| | C | 261c | 0.556b | 270c | 0.590a | 251c | 0.515b |

[1] Means in the same Factor for a given variable not followed by the same letter are significantly different at the $\alpha = 0.05$ level using Tukey's test.

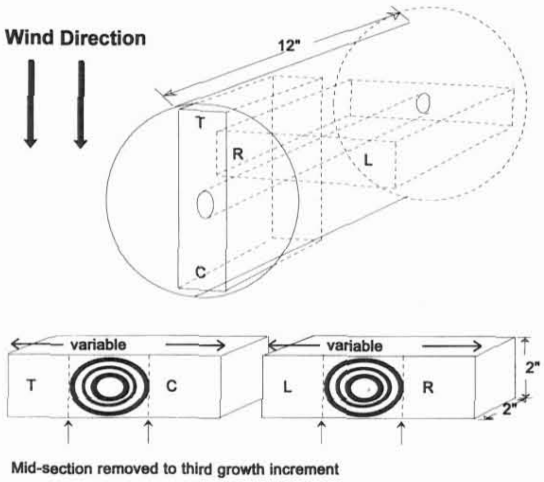

FIG. 3. Orientation of tension perpendicular specimens in the tree stem.

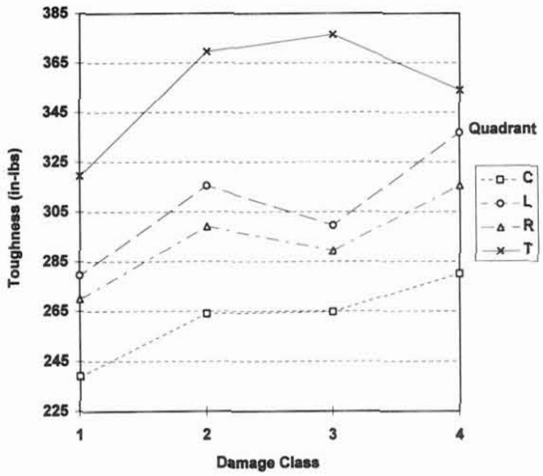

FIG. 4. Interaction of Damage Class and Quadrant.

variable reflects tree height and shows significant effects on toughness as expected ($P = 0.00$). The lower toughness associated with juvenile wood is evidenced by decreasing toughness with increasing section height. Toughness specimens become closer to the pith and tree crown higher up the stem. These specimens have wood tissue with more juvenile characteristics. The trend is identical for specific gravity, which is a primary measure of juvenility.

Quadrant had a significant effect on toughness and specific gravity ($P = 0.00$). Quadrant indicates the location of the specimen around the tree stem relative to the wind direction during the storm. The windward side of the stem (T) shows the highest toughness, while the side of the stem undergoing compression (C) showed the lowest toughness. The L and R quadrants were always intermediate in toughness and closest in actual value. This observation is logical since the L and R quadrants experienced similar stresses. The trends are more complex for specific gravity with quadrant. It would be logical that specific gravity would be constant around the tree stem at a specific tree height. Therefore, we would not expect the quadrant to have a significant effect on specific gravity. The T quadrant of the section was significantly lower in specific gravity than the other quadrants at Position 1 and 2. This is contrary to accepted relationships between wood strength and specific gravity. However the occurrence of reaction wood offers some explanation of why this trend occurs. Reaction wood has higher specific gravity but lower strength.

### *Occurrence of reaction wood*

Low average toughness values of the compression side specimens may be attributed to the high occurrence of reaction wood. Figure 5 illustrates the frequency of reaction wood occurrence in damage class by quadrant. The C quadrant had highest occurrence of reaction wood as would be expected. However, extensive reaction wood was occurring on Damage Class 4 trees, which were standing straight. Residual stress from the storm must have triggered reaction wood formation in the following growing season. Considering toughness values with quadrant as a factor, compression side toughness values were considerably lower than all others due to partial rings of reaction wood, which in many cases had been growing since the storm. In some cases reaction wood extended into the left and right quadrants. The overall effect of reaction wood in the left and right quadrants, however, was less pronounced for two reasons. There were fewer occurrences of reaction wood in these quadrants since the

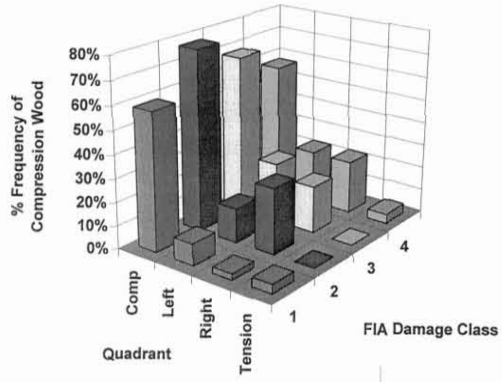

FIG. 5. Reaction wood frequency for quadrant by damage class.

reaction wood bands did not always extend into the left and right quadrants. Secondly, the reaction wood bands generally became thinner as they proceeded away from the compression quadrant, so the strength reduction due to the reaction wood band was diminished in the left and right quadrants.

Perhaps more importantly, reaction wood was observed in trees of all four damage classes. This is significant since even trees appearing to have no wind damage (i.e., not leaning), those of Damage Class 4, have a frequency of reaction wood as high as Damage Class 1. Stress from the wind has caused formation of reaction wood in the two growing seasons after the storm even in trees that are straight and have no visible damage. The formation of reaction wood in leaning stems should continue until harvesting; however it is unknown how long reaction wood will continue to form in Damage Class 4 trees that are essentially straight. The formation of reaction wood occurred almost uniformly over all tree heights as shown in Fig. 6.

TABLE 4. *Mean tension strength values for Damage Class by stem section.*

| Damage class | Section | | Damage class means[1] |
|---|---|---|---|
| | A | C | |
| 1 | 500.9 | 480.6 | 488.8 |
| 2 | 518.4 | 514.9 | 516.3 |
| 3 | 519.9 | 457.4 | 485.4 |
| 4 | 504.5 | 490.8 | 496.8 |
| Section means[2] | 511.5 | 485.5 | 496.5 |

[1] Damage class means were not significantly different at the 0.05 level.
[2] Section means were significantly different at the 0.05 level.

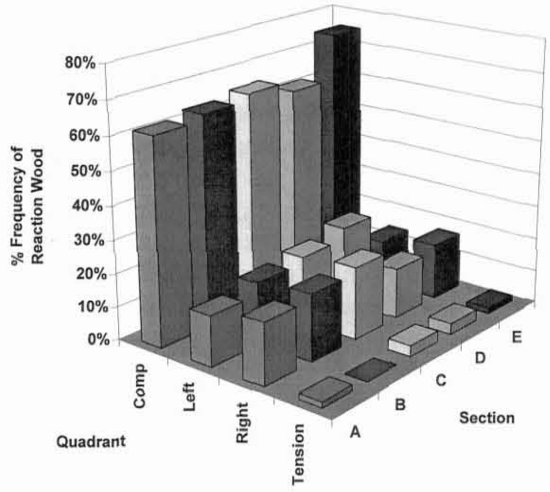

FIG. 6. Reaction wood frequency for quadrant by stem section.

### *Evidence of ring shake*

Observations of failures in tension perpendicular to the grain showed no evidence of ring shake, which was confirmed by the test results of tension strength perpendicular to the grain. There were no significant differences found in tension strength for damage class or quadrant. The section variable was significant with Section A significantly higher in tensile strength than Section C (see Table 4). This trend is consistent with observations of decreasing toughness with tree height. Table 5 shows tension strength means for damage class by quadrant. It is noted that these average tension strength values are consistent with the literature (Wood Handbook 1987).

TABLE 5. *Mean tension strength values for Damage Class by Quadrant.*

| Damage class | Quadrant | | | | Damage class means |
|---|---|---|---|---|---|
| | C | T | L | R | |
| 1 | 505.9 | 509.9 | 487.7 | 456.3 | 488.8 |
| 2 | 491.7 | 503.4 | 557.0 | 511.8 | 516.3 |
| 3 | 471.2 | 499.2 | 488.0 | 483.3 | 485.4 |
| 4 | 499.4 | 490.3 | 517.4 | 486.5 | 496.8 |
| Quadrant means[1] | 490.7 | 500.2 | 512.1 | 483.1 | 496.5 |

[1] Quadrant means were not significantly different at the 0.05 level.

## SUMMARY AND CONCLUSIONS

The results of the study offer inconclusive evidence that the FIA damage classes are indicative of internal damage to storm-stressed trees. It was expected that compression failures and micro-fractures would be found to have a varying effect on toughness and that ring shake would have a similar effect on tension perpendicular to the grain in a manner consistent with the FIA damage classes; but this relationship was marginally significant for toughness strength and nonexistent for tension strength perpendicular to the grain. Several interesting patterns did arise however. Specific gravity was a factor in determining the extent of damage. The specific gravity measurements made on the toughness specimens do offer some explanation as to the nature of wind damage. In particular, with damage class as the whole plot factor, the specific gravity values of Position 1 specimens fall into a pattern. Here again we consider only the Position 1 specimens to avoid the highly variable juvenile wood present in most Position 2 specimens. Moving from Damage Class 1 to 4 specific gravity shows an increasing trend and significantly different means between Damage Classes 1 and 4 at the 0.05 level using Tukey's test. The trees most resistant to wind damage, those classified in Damage Class 4, were found to have the highest average specific gravity. Thus there is a negative relationship between wind damage, as defined by the FIA damage class system, and wood density. Other studies (Foster 1988 and Studholme 1989 for instance) have shown this negative relationship between sustained wind damage and specific gravity. The variation of toughness and specific gravity could be explained in part by the occurrence and extent of reaction wood observed. The relatively higher specific gravity and lower strength of reaction wood will impact the utilization of these trees.

In conclusion, with dwindling timber resources, it will become more important to correctly determine the short-term as well as long-term effects of catastrophic storms on our timber resources. While the FIA visual damage classification system was developed to predict risk of mortality, it has been shown not to be an indicator of internal damage as measured by loss of mechanical properties. FIA damage class was a good indicator of the wood quality in the tree as measured by specific gravity.

The high occurrence of reaction wood as measured in this study indicates that residual stress from the storm caused reaction wood in all damage classes. It is likely that reaction wood formation will continue in leaning stems (Damage Classes 1 to 3). Further study is needed to determine if non-leaning trees will continue reaction wood formation. The formation of reaction wood appears to be the major damage to trees still standing after the storm.

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