International Journal of Reliability and Applications
Vol. 8, No. 2, pp.153-173, 2007

Exploring Reliability of Wood-Plastic Composites: Stiffness and Flexural Strengths

Diane G. Perhac
Department of Statistics, Operations, and Management Science
337 Stokely Management Center
University of Tennessee, Knoxville, TN 37996-0532 USA

Timothy M. Young[1]
Tennessee Forest Products Center, 2506 Jacob Drive,
University of Tennessee, Knoxville, TN 37996-4570 USA

Frank M. Guess and Ramón V. León
Department of Statistics, Operations, and Management Science
337 Stokely Management Center
University of Tennessee, Knoxville, TN 37996-0532 USA

Abstract. Wood-plastic composites (WPC) are gaining market share in the building industry because of durability/maintenance advantages of WPC over traditional wood products and because of the removal of chromated copper arsenate (CCA) pressure-treated wood from the market. In order to ensure continued market share growth, WPC manufacturers need greater focus on reliability, quality, and cost. The reliability methods outlined in this paper can be used to improve the quality of WPC and lower manufacturing costs by reducing raw material inputs and minimizing WPC waste. Statistical methods are described for analyzing stiffness (tangent modulus of elasticity: MOE) and flexural strength (modulus of rupture: MOR) test results on sampled WPC panels. Descriptive statistics, graphs, and reliability plots from these test data are presented and interpreted. Sources of variability in the MOE and MOR of WPC are suggested. The methods outlined may directly benefit WPC manufacturers through a better understanding of strength and stiffness measures, which can lead to process improvements and, ultimately, a superior WPC product with improved reliability, thereby creating greater customer satisfaction.

Keywords: *exploring reliability graphically and statistically, reliability, tangent modulus of elasticity, modulus of rupture, flexural strength, stiffness, wood-plastic composites, smallest extreme value, Weibull, normal, logistic.*

---

[1] Corresponding author.
E-mail address: *tmyoung1@utk.edu*

1. INTRODUCTION

Wood-plastic composites (WPC) are gaining market share in the building industry as a result of chromated copper arsenate (CCA) pressure-treated wood being removed from the market, perceived durability advantages over traditional wood products, and forest conservation concerns, compare Clemmons (2002). Smith and Wolcott (2005a, 2005b, 2006) indicate that demand for WPC decking and railings, which accounted for approximately two-thirds of the United States $1 billion extruded WPC market in 2005, has been growing since 2002 at an annual rate of 16 percent. As a percentage of all decking, WPC decking is expected to grow from 19 percent in 2002 to 42 percent in 2010, see Anon. (2006b). Other WPC applications experiencing a high growth (between 16 and 20 percent annually) include window profiles, patio furniture, shingles, and siding, see Anon. (2003). Increased WPC decking demand will be driven by increased consumer and contractor familiarity, a growing distribution network, and substantial product improvements in terms of durability, stiffness, strength, cost, light sensitivity, and appearance, see Anon. (2006a).

Wood-plastic composite lumber refers to a material comprised of wood fiber within a thermoplastic matrix. Recycled plastics, such as the thermoplastics HDPE, LDPE, PP, and PVC, in addition to wood waste materials (e.g., 20 – 60 mesh wood flour from pine, oak, or maple) are normally used in WPC production. Other wood fiber types are being investigated for use in WPC, e.g., Kim et al. (2005) discuss how ash fibers from trees infested by emerald ash borers have been successfully tested. In the production process, wood flour is dried then mixed with plastic and additives that include lubricants, pigments, coupling agents, stabilizers, reinforcing agents, blowing agents, and foaming agents. Processing technologies used to manufacture WPC include extrusion, and injection or compression molding. Wood-plastic composites typically contain 30 to 60 percent wood fibers and 70 to 40 percent plastic. They are rigid and usually pigmented to look like natural wood.

Advantages of WPC over natural wood include utilization of recycled materials, low maintenance, dimensional stability, low moisture absorption, increased rot resistance, consistent and uniform shapes, splinter resistance, as well as not requiring periodic painting. Disadvantages include initial higher costs, lower stiffness than wood, thermal expansion, creep (increase in deformation over time while subjected to a sustained load), along with sensitivity to staining and light sensitivity, which allow notable color changes and color variations within the composites.

Wood-plastic composites have an advantage over natural wood in outdoor uses such as residential decks (Figure 1.1), fences, landscape tiers, railroad ties, road noise barriers, boat docks, window and door profiles, residential furniture such as patio furniture and bathroom and kitchen cabinets, exterior and interior trim, playground equipment, picnic tables, benches, gazebos and walkways, in addition to naval pier decking. Zawlocki and Hermanson (2004) indicate that non-residential uses of WPC, such as heavy structural applications and use in marine structures, appears to be growing. New applications include roofing materials, siding, column foundation connection elements, and sill plates.

Improvements in durability and service life of WPC are needed to enhance performance in existing uses and accommodate new outdoor applications. Clemons (2002) discusses various research efforts focusing on WPC concerns such as increasing insect and fungal attack resistance, fire performance, ultraviolet light degradation, and creep performance. In addition, new and modified processing methods are being explored to eliminate some of the undesirable characteristics of WPC. For example, new wood-plastic composites utilizing superior compatibilizers are under development. Geng et al. (2005) discuss how these new composites could result in cost reductions, superior stiffness, and increased strength characteristics. Another example is the inclusion of a copolymer-coupling agent, maleinated polypropylene (maleic anhydride modified polypropylene or MAPP) in the production process. Harper and Wolcott (2005) established that the MAPP copolymer migrates to the wood surfaces, altering the wood-plastic matrix of the composite by increasing the compatibility between the hydrophilic wood and hydrophobic plastic components, thereby increasing the long-term durability performance of WPC, e.g., creep potential is greatly reduced. This analysis, in fact, examines the reliability and survival function differences for WPC samples with and without this MAPP coupling agent.

In order to ensure continued market share growth, WPC manufacturers need to focus on reliability, quality, and cost. The reliability methods outlined in this paper can be used to improve the quality of WPC, as well as lower manufacturing costs by reducing raw material inputs and minimizing WPC waste. For discussions on various approaches to measuring and understanding reliability, see Guess and Proschan (1988), Guess, Hollander, and Proschan (1986), Guess, Walker, and Gallant (1992), Young and Guess (1994), Young and Guess (2002), Guess, León, Chen, and Young (2004), and Guess, Zhang, Young, and León (2005).

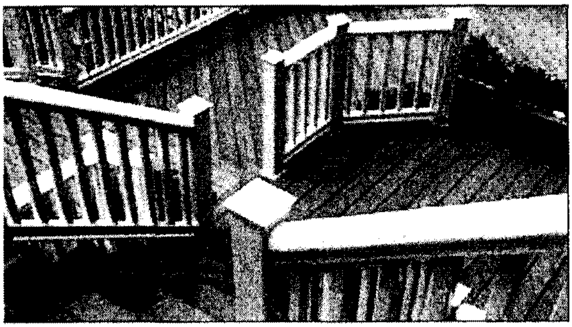


Figure 1.1. Illustration of WPC decking.

Improvements in product reliability hinge on the collection and interpretation of real-time destructive test data during the manufacturing process. Hence, data quality is an important issue for WPC manufacturers. In industrial settings, real-time and destructive data often will have outliers, missing values, or require sorting according to the final product type. Improving data quality will lead to improved statistical analysis and, ultimately, improved product quality. For guidance in this crucial area, see English (1999), Huang, Lee, and Wang (1999), and Redman (1996, 2001).

Product test data examined in this paper include strength (modulus of rupture) and stiffness (modulus of elasticity) of WPC. The modulus of rupture is defined as the maximum stress that can be applied to a beam in pure bending before permanent deformation occurs. The tangent modulus of elasticity is defined as the rate of change of strain as a function of stress. Sections 2 and 3 of this paper discuss WPC's bending tangent modulus of elasticity (MOE) and bending modulus of rupture (MOR), respectively. For each section the data are divided into two subsets, those WPC samples that incorporated the copolymer-coupling agent—malienated polypropylene (maleic anhydride modified polypropylene or MAPP) in the production process and those that did not. If an outlier was present, a third subset without the outlier was analyzed. A four-point loading system, or flexure test, is used to determine the flexural MOR, and bending MOE. Descriptions of testing methods and equations for these measures may be found in ASTM International standards, ASTM D 638-03 (2003) and ASTM D 6109-05 (2005). Section 4 provides concluding comments.

The data are analyzed graphically and statistically using S-PLUS, along with SPLIDA. For information on the statistical software, S-PLUS, see http://www.insightful.com/products/default.asp. For information on the freeware add-on, SPLIDA, developed by Professor William Meeker, visit his web site: http://www.public.iastate.edu/~splida/, along with Meeker and Escobar (1998). SAS's JMP, statistical discovery software: http://www.jmp.com, is also used in this analysis. Tutorials on the use of these software packages for reliability applications can be found at Professor Ramón León's course webpage at http://web.utk.edu/~leon/.

2. EXPLORING GRAPHICALLY AND STATISTICALLY THE RELIABILITY OF BENDING TANGENT MODULUS OF ELASTICITY (MOE) IN WOOD-PLASTIC COMPOSITES

The test data used in this analysis were obtained from the University of Maine, Advanced Engineering Wood Composites Center (AEWC), http://www.aewc.umaine.edu./. WPC using five different polymer resins and two pine species, *Pinus resinosa* and *Pinus strobes*, were tested. Bending strength MOE descriptive statistics were generated for two subsets of data: WPC samples with and without MAPP. These descriptive statistics include the mean, median, standard deviation, coefficient of variation, interquartile range (IQR), minimum (Min), maximum (Max), skewness, and kurtosis.

The box plot and histogram for the MOE data are also evaluated. In addition to these descriptive measures, probability plots, information criteria, and reliability/survival functions are utilized in order to better understand the data. See, for example, Guess, Walker, and Gallant (1992), and Walker and Guess (2003) for how different measures of reliability can be used. Compare Guess, Edwards, Pickrell, and Young (2003) for graphical and statistical analysis of medium density fiberboard.

Descriptive statistics of the bending MOE data are summarized in Table 2.1; they characterize the location, variability, and shape of these data. Location statistics include the mean and median, while variability statistics include standard deviation, coefficient of variation, and interquartile range (IQR). The shape of the data is expressed by the skewness and kurtosis values. Skewness measures the direction and degree of asymmetry. It is represented graphically by a longer tail in the skewness direction. A positive numerical value indicates skewness to the right while a negative value indicates skewness to the left. Table 2.1 shows skewness values of -0.251 and -0.272 for the bending MOE without MAPP and the bending MOE with MAPP, respectively. These negative values indicate that the distributions for both subsets are slightly left skewed.

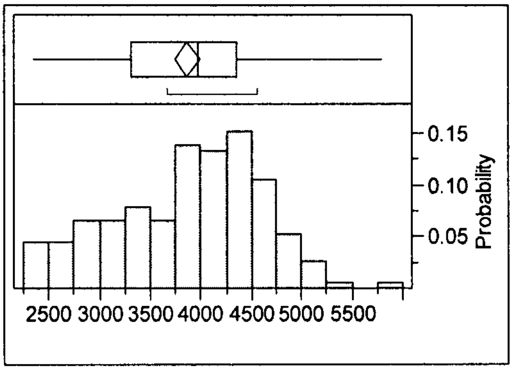
Kurtosis is a measurement of the peakedness (narrow or broad) of a distribution. It is a measure of the extent to which the probability is concentrated around the mean and in the tails rather than in the midrange relative to a normal distribution. The kurtosis value for a normal distribution is zero. A kurtosis value less than zero is obtained for a distribution with a wide midrange, on either side of the mean, and a low peak (referred to as platykurtic) while a kurtosis value greater than zero indicates a high peak, a thin midrange, and fat tails (referred to as leptokurtic). Distributions with kurtosis values of approximately zero are referred to as mesokurtic. Higher kurtosis values indicate that more of the variance is attributed to infrequent extreme deviations, in contrast to frequent modest-sized deviations. The kurtosis values of -0.539 and -0.882, shown in Table 2.1, for both the without MAPP and with MAPP subsets indicate that the distributions are platykurtic. This is further supported by viewing the shapes of the histograms in Figure 2.1 for the MOE data.

Table 2.1. Wood-plastic composites bending tangent modulus of elasticity (MOE) without coupling agent (MAPP) and with coupling agent (MAPP) descriptive statistics.

Statistics	Bending MOE (MPa) without MAPP	Bending MOE (MPa) with MAPP
Mean	3868.168	3901.520
Median	3971.372	4010.012
Standard Deviation	736.152	615.116
Coefficient of Variation	19.031	15.766
IQR	1045.483	977.456
Min	2340.300	2583.728
Max	5790.445	5133.649
Skewness	-0.251	-0.272
Kurtosis	-0.539	-0.882
N	150	120

The histogram is useful for showing both the skewness and kurtosis of the data set. The histograms in Figure 2.1 indicate that the bending MOE data, with and without MAPP, distributions are slightly left skewed and platykurtic. Boxplots are shown alongside the histograms. Boxplots are valuable tools for summarizing interval data. They show the shape of the distribution, the median, the lower and upper quartiles, the minimum and maximum data values, and possible outliers. The diamond shape within each boxplot represented in this paper indicates the 95% confidence interval for the mean of the data. The vertical bar within each boxplot represents the median of the data. The mean is less robust with respect to the distribution of the data than is the median. Thus, the boxplot of a left-skewed distribution will show the 95% confidence interval for the mean to the left of the median, while a right-skewed distribution will have the mean interval to the right of the median. Outliers, if present, are represented as points outside the ends of the whiskers (lines seen extending from the sides of the box). The boxplots shown in Figure 2.1 indicate the left-skewness of the distributions. No outliers are indicated for either distribution.

(a)



(b)

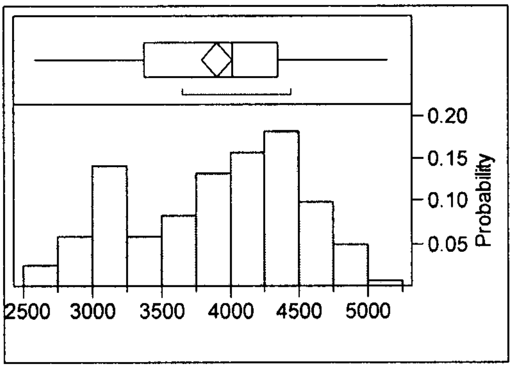


Figure 2.1. Boxplots and histograms of wood-plastic composites bending tangent modulus of elasticity (MOE) (a) without coupling agent (MAPP) and (b) with coupling agent (MAPP).

Probability plots are commonly used in the analysis of reliability data, because they graphically illustrate the conformity of a particular data set to a variety of distributions. The data are ordered and plotted against the theoretical order statistics for selected distributions. If the data set is consistent with a specific distribution, the data values will fall on, or close to, a straight line for the probability plot of that specific distribution. Simultaneous confidence bands with pointwise confidence intervals provide objective assessments of deviations from this straight line. Data points falling outside the confidence bands indicate that the data do not adequately fit the candidate probability distribution. Refer to Chapter 6 of Meeker and Escobar (1998) for additional information. Smallest extreme value (SEV), Weibull, normal, lognormal, largest extreme value (LEV), and Frechet probability plots were produced for the bending strength MOE data using S-PLUS and SPLIDA.

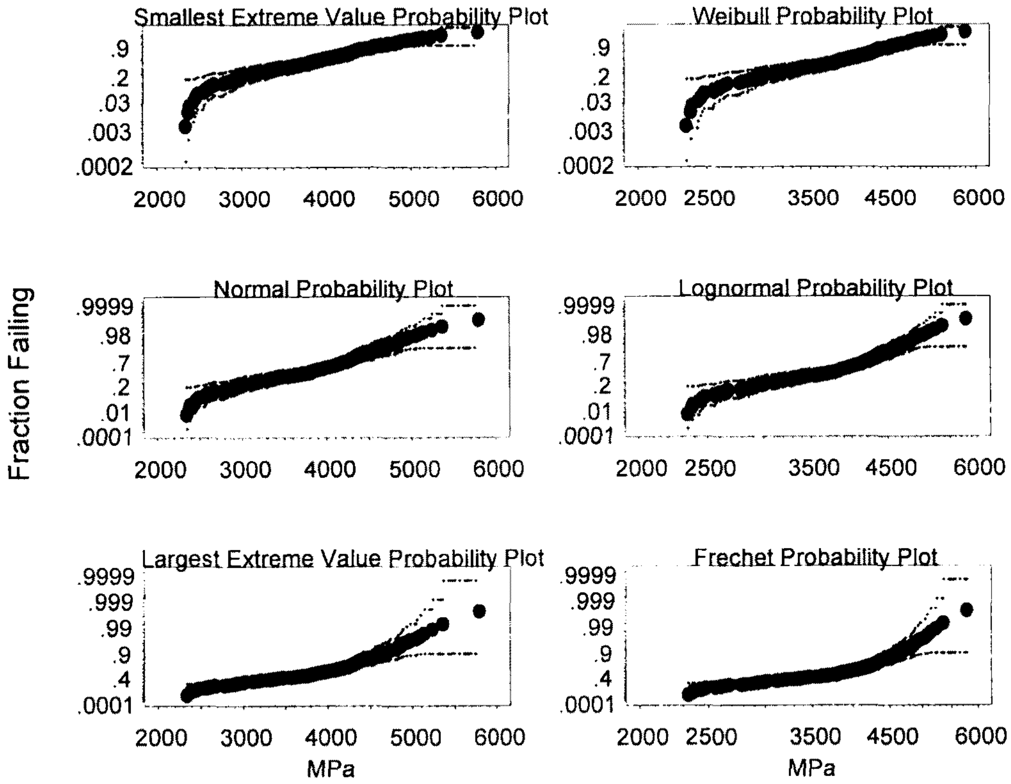


Figure 2.2. Wood-plastic composites bending tangent modulus of elasticity (MOE) with no coupling agent (MAPP) probability plots from S-PLUS and SPLIDA.

Probability plots for the smallest extreme value (SEV), Weibull, normal, lognormal, largest extreme value (LEV), and Frechet distributions for the WPC MOE without MAPP data are shown in Figure 2.2. It appears that the data are best represented by the Weibull, normal, and smallest extreme value probability plots. Additional curvature is seen at either tail or both tails with the remaining three distributions. Figure 2.3 shows the probability plots for the WPC MOE with MAPP data. The best distributional representations for the MAPP data are also the Weibull, normal, and smallest extreme value distributions. These probability plot results are further supported by the results obtained from Akaike's Information Criterion (AIC).

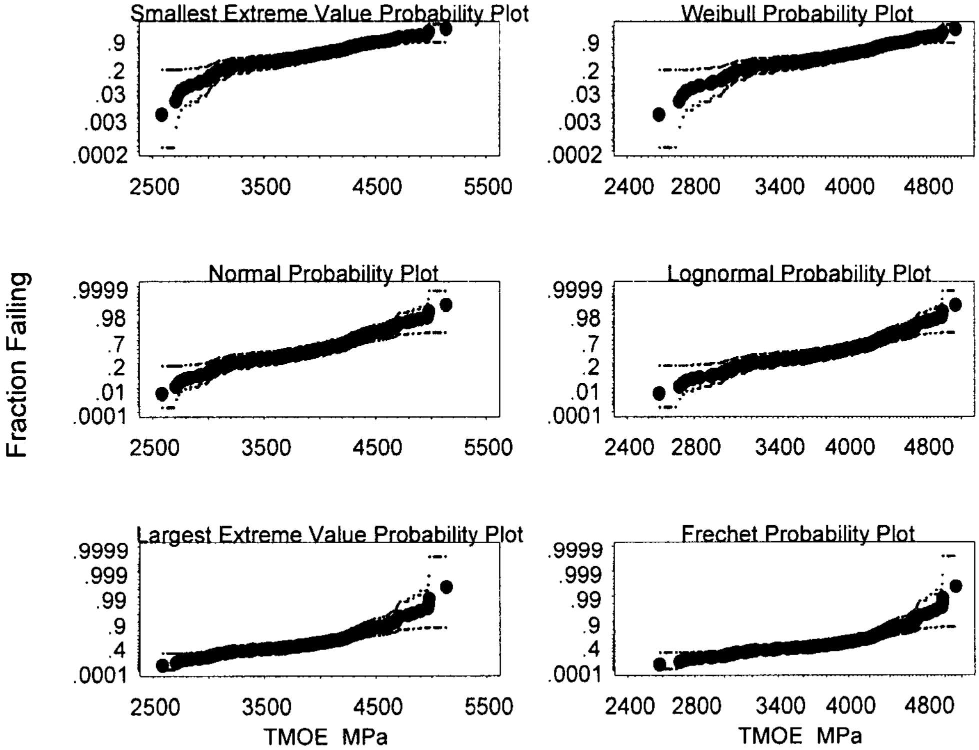


Figure 2.3. Wood-plastic composites bending tangent modulus of elasticity (MOE) with coupling agent (MAPP) probability plots from S-PLUS and SPLIDA.

Table 2.1 displays the log likelihood and AIC scores of select models. These scores provide a quantitative measure for choosing the best-fitting distributional model. Akaike (1973) and Bozdogan (2000) define the AIC for model selection. This criterion provides scores for each of the selected models of a particular data set, and is represented as:

$$\mathrm{AIC} = -2 \log L(\hat{\vartheta}) + 2k \qquad (2.1)$$

where $L(\hat{\vartheta})$ is the maximized likelihood function for a particular population parameter ϑ (either scalar or vector values) and k is the number of parameters evaluated in the model, e.g., $k = 2$ for the normal model with the parameters μ and σ^2. The model with the lowest AIC score is selected as the best model for the data. For the bending MOE without MAPP data, the lowest score is obtained for the Weibull distribution followed by the normal, SEV, and logistic distributions. This result is consistent with the probability plots shown in Figure 2.2. For the bending MOE with MAPP data, the lowest score is obtained for the Weibull distribution followed by the normal, SEV, and lognormal distributions. The Weibull distribution clearly represents the best-fitting model for both data subsets.

Table 2.1. Selected model scores for the wood-plastic composites bending modulus of elasticity (MOE) without coupling agent (MAPP) and with coupling agent (MAPP).

Model Fit	Bending MOE without MAPP		Bending MOE with MAPP	
	Log Likelihood	AIC	Log Likelihood	AIC
Exponential	-1389	2782	-1112.0	2228.0
Frechet	-1230	2464	-958.1	1920.2
LEV	-1216	2436	-950.1	1904.2
Logistic	-1206	2416	-944.4	1892.8
Loglogistic	-1211	2426	-947.3	1898.6
Lognormal	-1209	2422	-943.9	1891.8
Normal	-1203	2410	-940.4	1884.8
SEV	-1206	2416	-940.4	1884.8
Weibull	-1201	**2406**	-938.3	**1880.6**

The reliability/survival function is used to determine the probability that the product will survive beyond a specified "time" or "pressure." With the MOE data, pressure to failure is measured. The Kaplan-Meier estimator (origin of Product Limit Estimator) estimates the survival function from life-time (or pressure to failure) data, see Kaplan and Meier (1958). Kaplan-Meier plots, also called Product Limit graphs, are commonly used and provide a simple means of estimating the survival curve when problematic data, such as censored data, occur. Figure 2.4 shows the combined plots for the bending MOE without MAPP and the bending MOE with MAPP. This figure shows the survival probabilities of WPC for increasing pressure. For example, the probability that the bending MOE without MAPP will be greater than 3968.63 MPa is 0.50, while the probability that the bending MOE is greater than 4728.37 MPa is 0.10. Statistically, 5% of WPC fails before reaching a pressure of 2480.15 MPa and 95% of WPC fails before attaining a pressure of 4882.73 MPa. The Kaplan-Meier plot for this WPC data set indicates that pressure to failure decreases at increasing rates between 2500 and 5250 MPa. For comparison, the probability that the bending MOE with MAPP will be greater than 3987.11 MPa is 0.50, while the probability that the bending MOE is greater than 4656.70 MPa is 0.10. Statistically, 5% of WPC fails before reaching a pressure of 2838.33 MPa and 95% of WPC fails before realizing a pressure of 4790.73 MPa. The Kaplan-Meier plot for this WPC data set indicates that pressure to failure decreases at increasing rates between 2583 and 4978 MPa. For this WPC bending MOE data, it appears that the addition of the MAPP coupling agent does not greatly alter or improve the stiffness or tangent modulus of elasticity of the product.

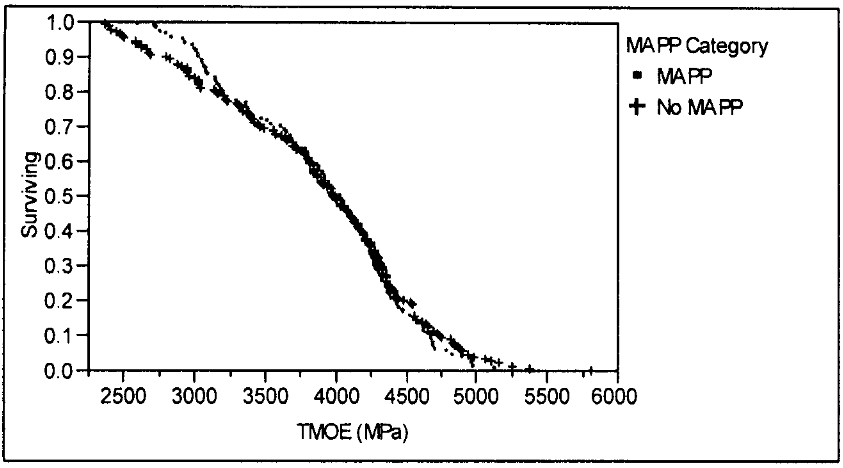


Figure 2.4. Reliability Kaplan-Meier Plot of wood-plastic composites bending tangent modulus of elasticity (MOE) without coupling agent (MAPP) and with coupling agent (MAPP).

The practitioner may use the Kaplan-Meier plots to explore the effects of different wood fibers, polymer resins, and various additives as well as whether or not a coupling agent has been added, for new product development by comparing plots for the different rates. These comparisons may provide an effective means for minimizing raw material usage and reducing sources of variation, while maintaining product reliability.

3. EXPLORING GRAPHICALLY AND STATISTICALLY THE RELIABILITY OF BENDING MODULUS OF RUPTURE (MOR) IN WOOD-PLASTIC COMPOSITES

Descriptive statistics for the bending modulus of rupture with and without MAPP are summarized in Table 3.1. This table also includes bending MOR with MAPP and one outlier removed since the presence of one outlier was determined in the bending MOR with MAPP subset. The skewness values of -0.619, -0.708, and -0.597 suggests mild left skewness for the bending MOR without MAPP, the bending MOR with MAPP and outlier, and the bending MOR with MAPP and outlier excluded, respectively. The kurtosis values of -0.660 and -0.123 for the bending MOR without MAPP and the bending MOR with MAPP excluding the outlier, respectively, indicate flat or platykurtic distributions. In contrast, the kurtosis value of 0.193 for the bending MOR with MAPP including the one outlier indicates a mesokurtic to mildly leptokurtic distribution. The non-peakedness or peakedness of these distributions is further supported by viewing the histogram shapes in Figure 3.1 for the MOR data.

Table 3.1. Wood-plastic composites bending tangent modulus of rupture (MOR) without coupling agent (MAPP) and with coupling agent (MAPP) descriptive statistics.

Statistics	Bending MOR (MPa) without MAPP	Bending MOR (MPa) with MAPP and one Outlier	Bending MOR (MPa) with MAPP and Outlier Removed
Mean	26.970	43.717	43.856
Median	27.651	44.621	44.856
Standard Deviation	5.384	5.344	5.145
Coefficient of Variation	19.964	12.225	11.731
IQR	6.027	7.985	7.936
Min	16.187	27.193	29.942
Max	35.217	53.233	53.233
Skewness	-0.619	-0.708	-0.597
Kurtosis	-0.660	0.193	-0.123
N	150.000	120.000	119.000

The histograms in Figure 3.1 indicate that the bending MOR distributions are slightly left skewed and that the distributions without an outlier are relatively flat. The boxplots in Figure 3.1 indicate the left skewness of the data for the three subsets and are in agreement with the skewness shown in the histograms. The WPC bending MOR with MAPP and one outlier boxplot also depicts the presence of the one outlier as a single point to the left of the left-sided whisker on the boxplot.

Probability plots for the smallest extreme value (SEV), Weibull, normal, lognormal, largest extreme value (LEV), and Frechet distributions for the WPC MOR data without MAPP and with MAPP including one outlier are shown in Figures 3.2 and 3.3, respectively. Figure 3.4 shows the four best, or most representative, probability plots for the WPC MOR with MAPP excluding the one outlier data. For all three subsets, it appears that the data are best represented by the smallest extreme value (SEV), Weibull, and normal probability plots. Additional curvature is seen at either tail or both tails with the remaining three distributions. These probability plot results are further supported by the results obtained from Akaike's Information Criterion.

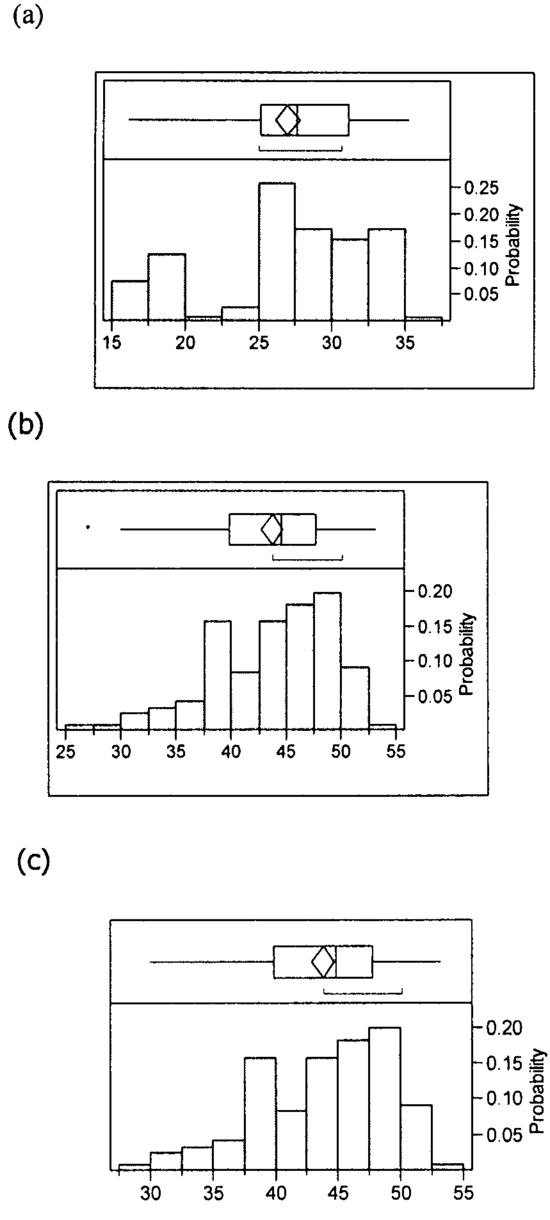


Figure 3.1. Boxplots and histograms of wood-plastic composites bending modulus of rupture (MOR) (a) without coupling agent (MAPP), (b) with coupling agent (MAPP) and outlier, and (c) with coupling agent (MAPP) without outlier.

Table 3.2 shows the log likelihood and AIC scores of select models for the bending MOR without MAPP, the bending MOR with MAPP including one outlier, and the bending MOR with MAPP excluding the one outlier. For these data, the lowest score obtained for the without MAPP and with MAPP including the outlier subsets is for the smallest extreme value (SEV) distribution. The next two lowest scores for these two subsets are for the Weibull and normal distributions, respectively. For the bending MOR excluding the outlier data, the best AIC scores obtained are for the Weibull, SEV, normal, and logistic distributions, respectively. These results are consistent with the probability plots shown in Figures 3.2, 3.3 and 3.4.

Table 3.2. Selected model scores for the wood-plastic composites bending modulus of rupture (MOR) without coupling agent (MAPP), with coupling agent (MAPP) including outlier, and with coupling agent (MAPP) excluding outlier.

Model Fit	Bending MOR without MAPP		Bending MOR with MAPP Including Outlier		Bending MOR with MAPP Excluding Outlier	
	Log Likelihood	AIC	Log Likelihood	AIC	Log Likelihood	AIC
Exponential	-644.2	1292.4	-573.3	1150.6	-568.9	1141.8
Frechet	-501.1	1006.2	-404.6	813.2	-391.6	787.2
LEV	-484.1	972.2	-391.2	786.4	-380.9	765.8
Logistic	-467.8	939.6	-371.7	747.4	-364.9	733.8
Loglogistic	-477.2	958.4	-375.7	755.4	-368.2	740.4
Lognormal	-476.5	957.0	-377.6	759.2	-368.5	741.0
Normal	-464.9	933.8	-370.9	745.8	-363.3	730.6
SEV	-455.0	**914.0**	-364.2	**732.4**	-358.3	720.6
Weibull	-457.6	919.2	-364.5	733.0	-358.1	**720.2**

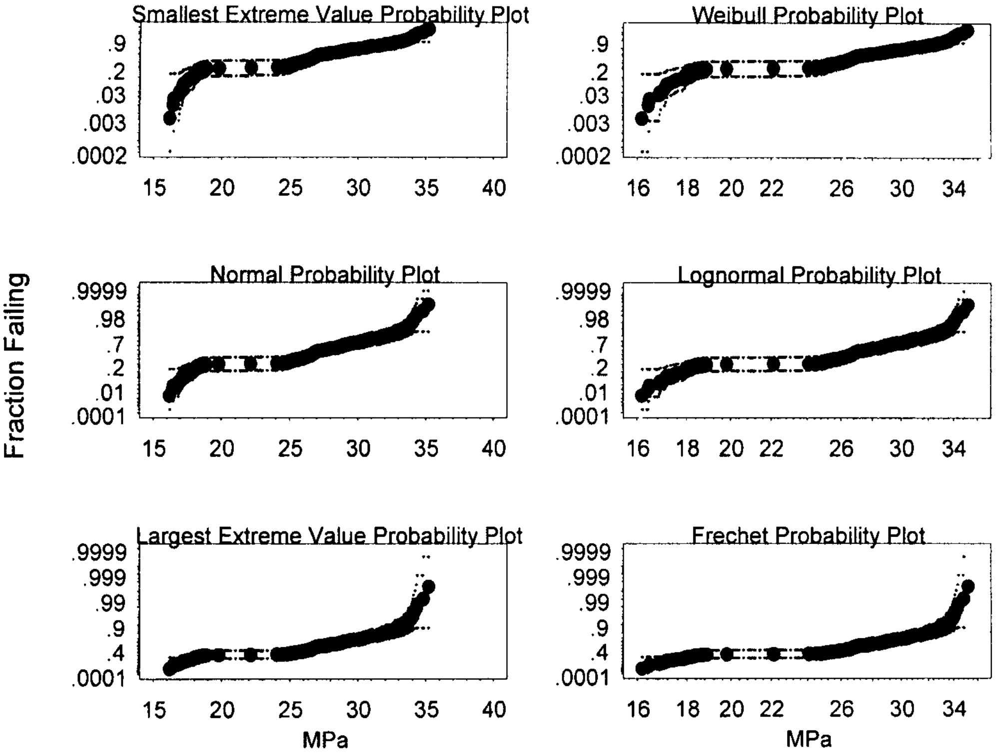


Figure 3.2. Wood-plastic composites bending modulus of rupture (MOR) without coupling agent (MAPP) probability plots from S-PLUS and SPLIDA.

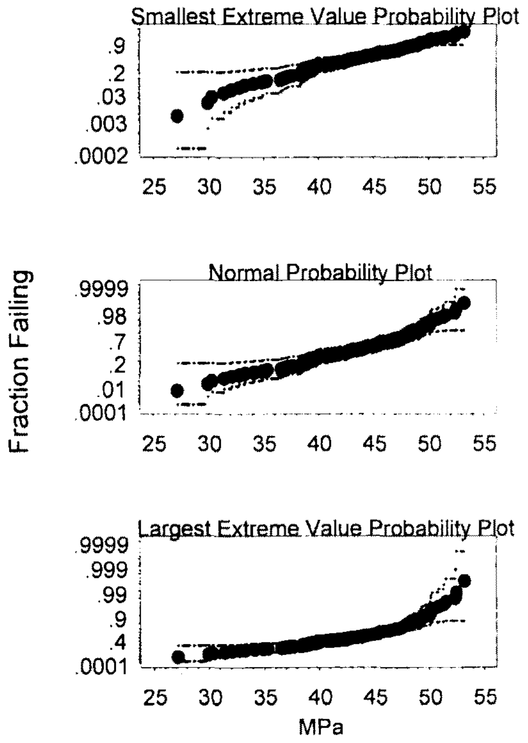
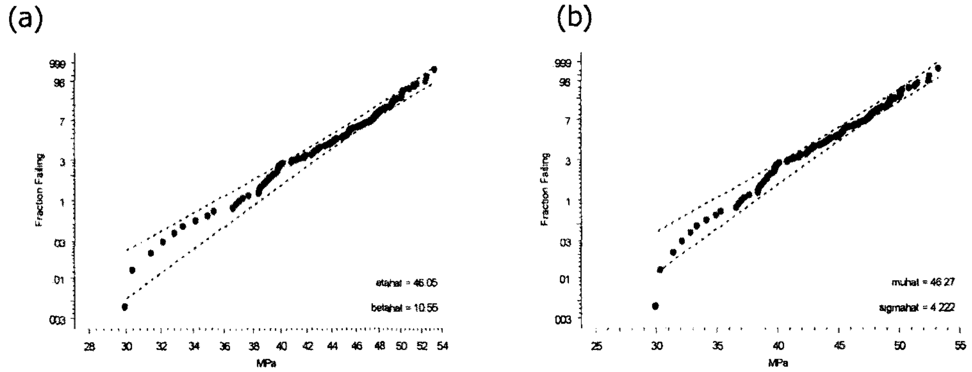


Figure 3.3. Wood-plastic composites bending modulus of rupture (MOR) with coupling agent (MAPP) probability plots from S-PLUS and SPLIDA.



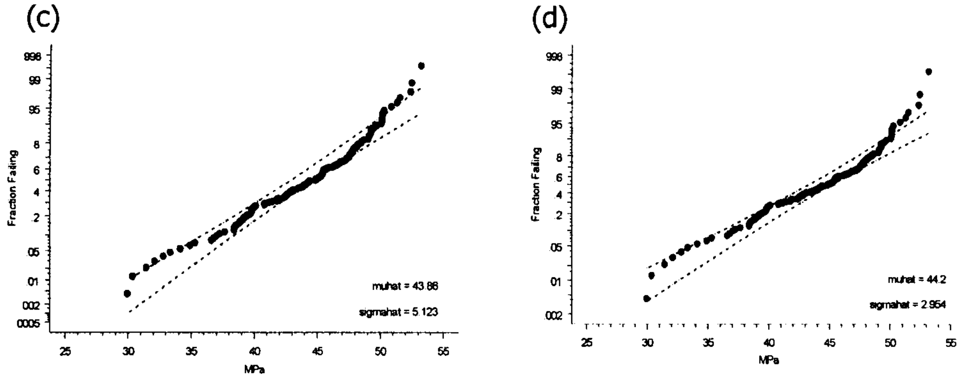


Figure 3.4. Wood-plastic composites bending modulus of rupture (MOR) probability plots with coupling agent (MAPP) and outlier removed from S-PLUS and SPLIDA (a) Weibull distribution, (b) Smallest extreme value distribution, (c) Normal distribution, and (d) Logistic distribution with horizontal axis of MPa and vertical axes of fraction failing.

The Kaplan-Meier plots for the bending MOR data are shown in Figure 3.5. The Kaplan-Meier curves shown are for the bending MOR without MAPP and the bending MOR with MAPP excluding the one outlier. The curve for the bending MOR with MAPP including the outlier was essentially identical to the curve for the bending MOR with MAPP excluding the outlier and is not shown. For the bending MOR without MAPP subset, the probability that the bending MOR will be greater than 27.6426 MPa is 0.50, while the probability that the bending MOR is greater than 33.3801 MPa is 0.10. Statistically, 5% of WPC fails before reaching a pressure of 17.1058 MPa and 95% of WPC fails before attaining a pressure of 33.9585 MPa. The Kaplan-Meier plot for this WPC subset indicates that pressure to failure decreases at increasing rates between 16.1865 and 34.8197 MPa.

In contrast, for the bending MOR with MAPP excluding the one outlier subset, the probability that the bending MOR will be greater than 44.8556 MPa is 0.50, while the probability that the bending MOR is greater than 49.6886 MPa is 0.10. Statistically, 5% of WPC fails before realizing a pressure of 33.3224 MPa and 95% of WPC fails before attaining a pressure of 50.2882 MPa. The Kaplan-Meier plot for this WPC data set indicates that pressure to failure decreases at increasing rates between 29.9419 and 52.4952 MPa.

It is interesting to see that for this WPC data, the addition of a coupling agent not only increases the breaking strength (MOR); it also helps linearize the Kaplan Meier curve. This is readily apparent from the plateau seen in the curve of the bending MOR without MAPP subset at pressures between approximately 18 and 25 MPa. Therefore, the use of MAPP increases the strength of WPC and may allow practitioners to more accurately predict failure probabilities of their manufactured WPC products. Better predictions may also help WPC manufacturers with continuous improvement of product quality and cost reductions.

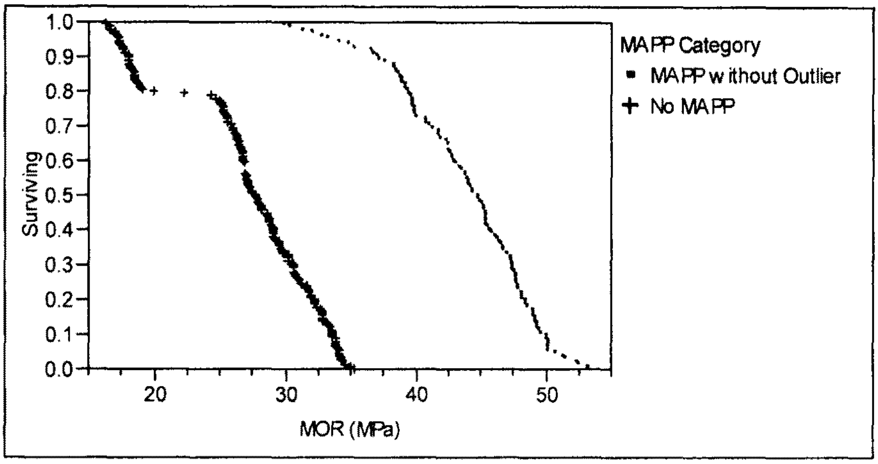


Figure 3.5. Reliability Kaplan-Meier Plot of wood-plastic composites bending modulus of rupture (MOR) without coupling agent (MAPP) and with coupling agent (MAPP) and outlier removed.

4. CONCLUSIONS

Graphically and statistically exploring the reliability of wood-plastic composites as measured by the bending MOE and bending MOR, provides valuable information about WPC. Wood-plastic composites are becoming more important in the forest products industry since they are replacing traditional wood products for many applications, such as decking. The reliability of a deck is directly related to the reliability of the WPC that is used for its construction. The authors are not aware of any other published papers that study WPC reliability via Kaplan-Meier survival curves and related SPLIDA probability plots. The reliability results from this work may directly help WPC manufacturers understand the strength and stiffness measures of the WPC product and facilitate the long term reduction in variation of the product. See Guess and Young (2003) for a similar study on medium density fiberboard.

Probability plot results for the WPC are not substantially altered by the addition of the MAPP coupling agent for either the MOE or MOR data. Kaplan-Meier plots for the MOE data with and without MAPP are almost identical. However, for the MOR data, MAPP does appear to linearize the Kaplan-Meier curve, thereby enabling better prediction of failure probabilities for given applied pressures. MAPP also increases the overall breaking strength, or MOR, of the WPC, which results in improved mechanical properties for many applications.

Descriptive statistics, graphs, and survival plots are powerful and insightful tools that may help us understand the reliability of the data, indicate sources of variation, and suggest opportunities for process improvement. Two software packages were used to validate this analysis from a vast suite of other statistical software packages, compare Deming (1986, 1993). Future work will include assessing additional WPC data and exploring further sources of process and product variation.

ACKNOWLEDGEMENTS

Research Associate Professor Timothy M. Young appreciates funding from the United States Department of Agriculture, Special Wood Utilization Research Grant R112216-100, which is administered by The University of Tennessee Agricultural Experiment Station and the Tennessee Forest Products Center, Dr. Timothy G. Rials, Professor and Director. We thank the University of Maine Advanced Engineering Wood Composites Center (AEWC) for supplying the WPC samples for this study. Also, Graduate Research Assistant Diane G. Perhac is grateful for financial support from The University of Tennessee Agricultural Experiment Station McIntire-Stennis Grant MS-89, as administered by Dr. Larry Wilson, Professor and Interim Head, Department of Forestry, Wildlife and Fisheries. Dr. Frank M. Guess acknowledges funding from Research Associate Professor Young. We thank Dr. Nicolas André, Post-Doctoral Research Associate, for sharing his wisdom, knowledge, and information regarding mechanical testing which generated the data used in this analysis. Finally, we thank Graduate Research Assistant, Leslie Shaffer, for helpfully checking English and journal formatting style on a close to final version of this paper.

REFERENCES

Akaike, H. (1973). Information theory and an extension of the maximum likelihood principle. In B.N. Petrov and F. Csaki (eds.), *Second International Symposium on Information Theory*, Academiai Kiado, Budapest, 267-281.

American Society of Testing and Materials. (2003). *Standard test method for tensile properties of plastics.* ASTM D 638-03. ASTM. West Conshohocken, PA.

American Society of Testing and Materials. (2005). *Standard test methods for flexural properties of unreinforced and reinforced plastic lumber and related products.* ASTM D 6109-05. ASTM. West Conshohocken, PA.

Anonymous. (2003). Principia Consulting website at http://www.principiaconsulting.com/consulting/news.cfm?article=43. Accessed February 17, 2007.

Anonymous. (2006a). Netcomposites website at http://www.netcomposites.net/news.asp?3648. Accessed February 17, 2007.

Anonymous. (2006b). Remodeling Online website at http://www.remodeling.hw.net/industry-news.asp?sectionID=157&articleID=386647. Accessed February 17, 2007.

Bozdogan, H. (2000). Akaike's information criterion and recent developments in information complexity. *Journal of Mathematical Psychology*, **44**(1), 62-91.

Clemmons, C. (2002). Wood-plastic composites in the United States, the interfacing of two industries. *Forest Products Journal*, **52**(6), 10-18.

Deming, W.E. (1986). *Out of the Crisis.* Massachusetts Institute of Technology's Center for Advanced Engineering Design, Cambridge, MA.

Deming, W.E. (1993). *The New Economics.* Massachusetts Institute of Technology's Center for Advanced Engineering Design, Cambridge, MA.

English, L. P. (1999). *Improving Data Warehouse and Business Information Quality: Methods for Reducing Costs and Increasing Profits.* New York: John Wiley & Sons.

Geng, Y., Kaichang L., and Simonsen, J. (2005). A commercially viable compatibilizer system for wood-polyethylene composites. *Journal of Adhesion Science and Technology*, **19**(15), 1363-1373.

Guess, F.M., Edwards D.J., Pickrell T.M. and Young T.M. (2003). Exploring graphically and statistically the reliability of medium density fiberboard. *International Journal of Reliability and Application*, **4**(4), 97-109.

Guess, F.M., Hollander, M., and Proschan, F. (1986). Testing exponentiality versus a trend change in mean residual life. *Annals of Statistics*, **14**(4), 1388-1398.

Guess, F.M., León, R., Chen, W. and Young, T.M. (2004). Forcing a closer fit in the lower tails of a distribution for better estimating extremely small percentiles of strengths. *International Journal of Reliability and Application*, **5**(4), 129-143.

Guess, F.M., and Proschan, F. (1988). Mean residual life: theory and applications. *Handbook of Statistics: Quality Control and Reliability*, **7**, 215-224.

Guess, F.M., Walker, E., and Gallant, D. (1992). Burn-in to improve which measure of reliability. *Microelectronics and Reliability*, **32**, 759-762.

Guess, F.M., Zhang, X., Young, T.M. and León, R. (2005). Using mean residual life functions for unique insights into strengths of materials data. *International Journal of Reliability and Application*, **6**(2), 79 – 85.

Huang, K-T., Lee, Y. L. and Wang, R. Y. (1999). *Quality Information and Knowledge.* Prentice Hall, New York, NY.

Harper, D.P. and Wolcott, M.P. (2005). Chemical imaging of wood-polypropylene composites. *Proceedings of the Eighth International Conference on Woodfiber-Plastic Composites.* Madison, WI. pp. 153-160.

Kaplan, E.L. and P. Meier. (1958). Nonparametric estimation from incomplete observations. *Journal of the American Statistical Association,* **53**, 457-481.

Kim, J., Matuana, L.M., and McCullough, D.G. (2005). Ash trees infested by emerald ash borers as raw material for wood-based composites. *Forest Products Journal,* **55**(11), 89-92.

Meeker, W. Q. and Escobar, L. A. (1998). *Statistical Methods for Reliability Data.* Wiley & Sons, New York, NY.

Redman, T. C. (1996). *Data Quality for the Information Age.* Artech House Computer Science Library, Boston/Norwood, MA.

Redman, T. C. (2001). *Data Quality: The Field Guide.* Butterworth-Heinemann Digital Press, Boston, MA.

Smith, P.M. and Wolcott, M.P. (2006). Opportunities for wood/natural fiber-plastic composites in residential and industrial applications. *Forest Products Journal, 56*(3), 4-11.

Smith, P.M. and Wolcott, M.P. (2005a). Wood fiber-plastic composite markets and applications. In: Proc. of the 39th Inter. Wood Composites Symposium, Pullman, WA. pp. 289-294.

Smith, P.M. and Wolcott, M.P. (2005b). Wood-plastic composites in emerging products and markets. *In: Proc., 8th Inter. Conf. on Woodfiber-Plastic Composites.* Forest Products Society. Madison, WI. pp. 335-343.

Walker, E. and Guess, F.M. (2003). Comparing reliabilities of the strength of two container designs: A case study. *Journal of Data Science,* **1**, 185-197.

Young, T.M. and Guess, F.M. (1994). Reliability processes and structures. *Microelectronics and Reliability,* **34**, 1107-1119.

Young, T.M. and Guess, F.M. (2002). Mining information in automated relational databases for improving reliability in forest products manufacturing. *International Journal of Reliability and Application,* **3**(4), 155-164.

Zawlocki, M.M., and Hermanson, J.C. (2004). Naval advanced wood composites, characterization of wood-plastic composites by dissipated energy. Prepared for *Office of Naval Research* under Contract N00014-00-C-0488, Project End Report. March 2004.