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Standard Practice for Evaluating Material Property Characteristic Values for Polymeric Composites for Civil Engineering Structural Applications[1]

This standard is issued under the fixed designation D7290; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice covers the procedures for computing characteristic values of material properties of polymeric composite materials intended for use in civil engineering structural applications. The characteristic value is a statistically-based material property representing the 80 % lower confidence bound on the 5th-percentile value of a specified population. Characteristic values determined using this standard practice can be used to calculate structural member resistance values in design codes for composite civil engineering structures and for establishing limits upon which qualification and acceptance criteria can be based.

1.2 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

D883 Terminology Relating to Plastics
D3878 Terminology for Composite Materials
D5055 Specification for Establishing and Monitoring Structural Capacities of Prefabricated Wood I-Joists
D5457 Specification for Computing Reference Resistance of Wood-Based Materials and Structural Connections for Load and Resistance Factor Design
D5574 Test Methods for Establishing Allowable Mechanical Properties of Wood-Bonding Adhesives for Design of Structural Joints
E6 Terminology Relating to Methods of Mechanical Testing
E178 Practice for Dealing With Outlying Observations
E456 Terminology Relating to Quality and Statistics

2.2 *Other Document:*

MIL-Handbook-17 Polymer Matrix Composites, Volume 1, Revision F[3]

3. Terminology

3.1 *Definitions*—Terminology D3878 defines terms relating to high-modulus fibers and their composites. Terminology D883 defines terms relating to plastics. Terminology E6 defines terms relating to mechanical testing. Terminology E456 defines terms relating to statistics. In the event of a conflict between terms, Terminology D3878 shall have precedence over the other documents.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *characteristic value*—a statistically-based material property representing the 80 % lower confidence bound on the 5th-percentile value of a specified population. The characteristic value accounts for statistical uncertainty due to a finite sample size.

3.2.1.1 *Discussion*—The 80 % confidence bound and 5th-percentile levels were selected so that composite material characteristic values will produce resistance factors for Load and Resistance Factor Design similar to those for other civil engineering materials (see Refs **1** and **2**).[4]

3.2.1.2 *Discussion*—The term "characteristic value" is analogous to the term "basis value" used in the aerospace industry where A- and B-basis values are defined as the 95 % lower confidence bound on the lower 1 % and 10 % values of a population, respectively.

3.2.2 *data confidence factor,* Ω—a factor that is used to adjust the sample nominal value for uncertainty associated with finite sample size.

3.2.3 *nominal value*—the 5th percentile value of the data represented by a probability density function.

[1] This practice is under the jurisdiction of ASTM Committee D30 on Composite Materials and is the direct responsibility of Subcommittee D30.10 on Composites for Civil Structures.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from U.S. Government Printing Office Superintendent of Documents, 732 N. Capitol St., NW, Mail Stop: SDE, Washington, DC 20401, http://www.access.gpo.gov.

[4] The boldface numbers in parentheses refer to the list of references at the end of this standard.

3.2.4 *outlier*—an outlying observation, or "outlier," is one that deviates significantly from other observations in the sample in which it occurs.

4. Significance and Use

4.1 This practice covers the procedures for computing material property characteristic values for polymeric composite materials intended for use in civil engineering structural applications. A characteristic value represents a statistical lower bound on the material property structural member resistance factors for civil engineering design codes for composite structures.

4.2 This practice may be used to obtain characteristic values for stiffness and strength properties of composite materials obtained from measurements using applicable test methods.

5. Sampling

5.1 Samples selected for analysis shall be representative of the material property population for which the characteristic values are to be calculated.

5.2 The minimum number of samples shall be specified in design codes that reference this standard.

NOTE 1—Section 5.3.1 of the building code requirements for structural concrete (ACI 318-05) requires at least 30 samples to determine the standard deviation of concrete compressive strength for a new batch plant but allows a reduction to a minimum of 15 samples, provided that a modification factor is used to increase the standard deviation if less than 30 samples are used (Ref **3**). For wood, Specification D5457 requires a minimum of 30 samples for computing the reference resistance of wood based materials and structural connections for Load and Resistance Factor Design, and states that extreme care must be taken during sampling to ensure a representative sample for sample sizes less than 60. The bending capacity of wood I-joists can be determined either by analysis or empirically by testing (Specification D5055). If the capacity is determined by analysis, a minimum of ten confirming tests is required at each of the extremes of flange size, allowable stress, and joist depth. Test Methods D5574 requires 60 samples for establishing allowable tensile and shear stresses of wood-bonding adhesives in structural joints. Fifty-nine of the samples are actually tested, with the last held in reserve.

6. Procedure

6.1 *Mean and Standard Deviation*—Calculate the average value and standard deviation for the measured material property:

$$\bar{x} = \frac{\left(\sum_{i=1}^{n} x_i\right)}{n} \quad (1)$$

$$s_{n-1} = \sqrt{\left(\sum_{i=1}^{n} (x_i - \bar{x})^2\right) / (n-1)} \quad (2)$$

where:

$\bar{x}$ = sample mean (average),
s_{n-1} = sample standard deviation,
n = number of specimens, and
x_i = measured or derived property.

6.2 *Detection of Outlying Observations*—The data being analyzed shall be screened for outliers using the Maximum Normed Residual (MNR) method. A value is declared to be an outlier by this method if it has an absolute deviation from the sample mean which, when compared to the sample standard deviation, is too large to be due to chance. This method detects one outlier at a time; hence the significance level pertains to a single decision.

NOTE 2—Practice E178 provides several methods for statistically analyzing a dataset for outliers. The MNR method is used here because it is a simple method that is unlikely to be miscalculated, misinterpreted or misapplied.

NOTE 3—An outlying observation may be an extreme manifestation of the random variability of the material property value. For such a case, the value should be retained and treated as any other observation in the sample. However, the outlying observation may be the result of a gross deviation from prescribed experimental procedure or an error in calculating or recording the numerical value of the data point in question. When the experimentalist can document a gross deviation from the prescribed experimental procedure, the outlying observation may be discarded, unless the observation can be corrected in a rational manner.

6.2.1 *Outlier Criteria for Single Samples*—For a sample of size n, arrange the data values $\{x_1, x_2, x_3, ...x_n\}$ in order of increasing magnitude with x_n being the largest value. Calculate the MNR statistic as the maximum absolute deviation from the sample mean divided by the sample standard deviation:

$$MNR = \max\left(\frac{|x_i - \bar{x}|}{s_{n-1}}\right) \quad (3)$$

6.2.1.1 Calculate the critical MNR value, CV, based on a 5 % significance level using the following approximation:

$$CV \approx \left(2 - \frac{8}{5\sqrt{n}}\right)^2 \quad (4)$$

6.2.1.2 There are no outliers in the sample of observations if the calculated MNR statistic is smaller than the critical value CV, that is $MNR \leq CV$. If the MNR statistic is found to be greater than the critical value, then the MNR shall be denoted a possible outlier. The possible outlier shall be investigated to determine whether there is an assignable cause for removing it from the data set. If no cause can be found, it shall be retained in the data set. If an outlier is clearly erroneous, it can be removed after careful consideration provided that the subjective decision to remove the value is documented as part of the data analysis report. If an outlier is removed from the dataset, the sample mean and standard deviation shall be recalculated. This process shall be repeated until the sample of observations becomes outlier-free.

NOTE 4—Eq 4 is an approximate nonlinear regression of critical values presented in the MIL-Handbook 17 with a correlation coefficient of 0.998.

6.3 *Material Property Distribution*—For this standard practice, the material property value probability distribution function is assumed to follow the two-parameter Weibull distribution (Ref **2**) expressed in the form:

$$f(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x}{\alpha}\right)^{\beta-1} \exp\left[-\left(\frac{x}{\alpha}\right)^{\beta}\right] \quad (5)$$

where:

β = the shape parameter and is the scale parameter, and
α = the scale parameter.

NOTE 5—The basis for selecting the Weibull distribution is given in Refs **2** and **4**.

6.4 *Maximum Likelihood Parameter Estimation:*

TABLE 1 Data Confidence Factor, Ω, on the 5th-Percentile Value for a Weibull Distribution with 80 % Confidence[A] (Refs 3 and 4)

n	COV							
	0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.50
10	0.950	0.899	0.849	0.800	0.752	0.706	0.619	0.541
11	0.953	0.906	0.860	0.814	0.769	0.725	0.642	0.567
12	0.956	0.913	0.869	0.826	0.783	0.741	0.662	0.589
13	0.959	0.918	0.876	0.835	0.795	0.755	0.679	0.609
14	0.961	0.922	0.883	0.844	0.805	0.767	0.694	0.626
15	0.963	0.926	0.889	0.851	0.814	0.778	0.707	0.641
16	0.965	0.929	0.894	0.858	0.822	0.787	0.719	0.655
18	0.968	0.935	0.902	0.869	0.836	0.803	0.739	0.678
20	0.970	0.940	0.909	0.878	0.847	0.816	0.755	0.698
22	0.972	0.944	0.914	0.885	0.856	0.827	0.769	0.714
24	0.974	0.947	0.919	0.891	0.864	0.836	0.781	0.728
26	0.975	0.949	0.923	0.897	0.870	0.844	0.791	0.741
28	0.976	0.952	0.927	0.902	0.876	0.851	0.800	0.752
30	0.977	0.954	0.930	0.906	0.882	0.857	0.809	0.761
32	0.978	0.956	0.933	0.910	0.886	0.863	0.816	0.770
34	0.979	0.957	0.935	0.913	0.890	0.868	0.822	0.778
36	0.980	0.959	0.938	0.916	0.894	0.872	0.828	0.785
38	0.980	0.960	0.940	0.919	0.897	0.876	0.833	0.791
40	0.981	0.962	0.942	0.921	0.901	0.880	0.838	0.797
42	0.982	0.963	0.943	0.924	0.904	0.883	0.843	0.803
44	0.982	0.964	0.945	0.926	0.906	0.886	0.847	0.808
46	0.983	0.965	0.946	0.928	0.909	0.889	0.851	0.813
48	0.983	0.966	0.948	0.929	0.911	0.892	0.854	0.817
50 or more	0.984	0.967	0.949	0.931	0.913	0.895	0.858	0.821

[A] Linear interpolation is permitted. For *COV* values below 0.05 ($\hat{\beta} > 24.95$), the values for *COV* = 0.05 shall be used.

6.4.1 Calculate the maximum likelihood estimate, $\hat{\beta}$, of the Weibull shape parameter β by numerically solving the equation:

$$\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}} \ln(x_i)}{\sum_{i=1}^{n} x_i^{\hat{\beta}}} - \frac{1}{\hat{\beta}} - \frac{1}{n}\sum_{i=1}^{n}\ln(x_i) = 0 \tag{6}$$

6.4.2 Calculate the maximum likelihood estimate, $\hat{\alpha}$, of the Weibull scale parameter α using:

$$\hat{\alpha} = \left(\frac{\sum_{i=1}^{n} x_i^{\hat{\beta}}}{n}\right)^{\frac{1}{\hat{\beta}}} \tag{7}$$

where:

n = the number of data values used in the analysis.

6.4.3 Calculate the coefficient of variation of the property from the equation:

$$COV = \frac{\sqrt{\Gamma\left(1+\frac{2}{\hat{\beta}}\right) - \Gamma^2\left(1+\frac{1}{\hat{\beta}}\right)}}{\Gamma\left(1+\frac{1}{\hat{\beta}}\right)} \tag{8}$$

where:

Γ = the gamma function.

6.5 *Nominal Value*—Calculate the nominal value of the sample data as the 5th-percentile of the two-parameter Weibull distribution, using:

$$x_{0.05} = \hat{\alpha}[0.0513]^{\frac{1}{\hat{\beta}}} \tag{9}$$

6.6 *Characteristic Value*—Calculate the characteristic value for the material property as the 80 % confidence bound on the 5th-percentile value using:

$$x_{char} = \Omega\, x_{0.05} \tag{10}$$

In which the data confidence factor, Ω, accounts for the uncertainty associated with a finite sample size. This factor is a function of coefficient of variation, sample size, and reference percentile. Table 1 provides data confidence factors appropriate for lower fifth-percentile estimates.

7. Report

7.1 Report the following information, or references pointing to other documentation containing this information, to the maximum extent applicable:

7.1.1 The sample size and individual data values,

7.1.2 Any data values which were determined to be outliers and excluded from the data analysis, along with the rationale for excluding the outlier,

7.1.3 The sample nominal value and coefficient of variation,

7.1.4 The maximum likelihood estimates of the Weibull shape and scale factors for the sample,

7.1.5 The data confidence factor, Ω, and

7.1.6 The sample characteristic value.

REFERENCES

(1) Ellingwood, B. R., "Toward Load and Resistance Factor Design for Fiber-Reinforced Polymer Composite Structures," *ASCE Journal of Structural Engineering*, Vol 129, No. 4, 2003, pp. 449-458.

(2) Zureick, A., Bennett, R. M., and Ellingwood, B. R., "Statistical Characterization of Fiber-Reinforced Polymer Composite Material Properties for Structural Design," *ASCE Journal of Structural Engineering*, August, 2006, Vol 132 , No. 8, pp. 1320-1327.

(3) ACI 318-05, "Building Code Requirements for Structural Concrete and Commentary," American Concrete Institute, Farmington Hills, MI, 2005.

(4) Zureick, A., Bennett, R. M., and Alqam, M., "Acceptance Test Specifications and Guidelines for Fiber-Reinforced Polymeric Bridge Decks," *Final Report, Volume 2: Determination of Material Property Characteristic Values of Fiber-Reinforced Polymeric Composites*, prepared for the Federal Highway Administration (FHWA), *Structural Engineering, Mechanics, and Materials, Research Report No. 03-6*, School of Civil and Environmental Engineering, Georgia Institute of Technology, http://www.ce.gatech.edu/groups/struct/reports/.